OPERATIVE DENTISTRY

May/June 2020
Volume 45
Number 3
229–340

Academy of Operative Dentistry • American Academy of Gold Foil Operators • Academy of R.V. Tucker Study Clubs

OPERATIVE DENTISTRY

Volume 45 / Number 3
May/June 2020

www.jopdent.org

Aim and Scope

Operative Dentistry publishes articles that advance the practice of operative dentistry. The scope of the journal includes conservation and restoration of teeth; the scientific foundation of operative dental therapy; dental materials; dental education; and the social, political, and economic aspects of dental practice. Review papers, book reviews, letters and classified ads for faculty positions are also published.

Subscriptions: Fax 317-852-3162

Current pricing for individual, institutional, and dental student subscriptions (both USA and all other countries) can be found at our website: www.jopdent.org, or by contacting our subscription manager via email at editor@jopdent.org. Payment must be in USD and accompany orders. Online payment by credit card (American Express, Discover, Mastercard, and Visa) is available on our website.

Operative Dentistry (ISSN 0361-7734) is published bimonthly by Operative Dentistry, Inc, Indiana University School of Dentistry, Room S411, 1121 West Michigan Street, Indianapolis, IN 46202-5186. Periodicals postage paid at Indianapolis, IN and additional mailing offices. Postmaster: Send address changes to: Operative Dentistry, Indiana University School of Dentistry, Room S411, 1121 West Michigan Street, Indianapolis, IN 46202-5186.

Author Instructions

Please refer to author instructions at www.jopdent.org in the preparation of manuscript submissions and for journal policies.

Journal Policies

The Operative Dentistry Policy Manual which details journal policies, including late fees and claims, is available online at:

https://www.jopdent.com/journal/policies.pdf

Permissions

For permission to reproduce material from Operative Dentistry please apply to Operative Dentistry at the Editorial Office address or via email at editor@jopdent.org.

Online Access

Register for online access, manage subscriptions, save favorite articles and searches, get email alerts, and more at:

http://www.jopdentonline.org/action/registration

Editorial Board

Reviewer names available at: www.jopdent.com/journal/editorial_board.html

We thank all our reviewers for their time and dedication to Operative Dentistry.

On The Cover

"Torres del Paine National Park, sunrise, massif and glacier lake", Torres del Paine National Park, Chile. Photo provided by Lawrence Blank of Corrales, New Mexico, USA. Photo taken with a Canon D6, 50mm f/4 1/100 sec. ISO-200. © Operative Dentistry, Inc.

We welcome the submission of pictures for consideration for use on the cover of Operative Dentistry! All photographs should be submitted via the forms at:

https://www.jopdent.com/journal/journal.html

Editorial Office

The views expressed in Operative Dentistry do not necessarily represent those of the academies or the editors.

Operative Dentistry
Indiana University School of Dentistry, Room S411
1121 West Michigan Street, Indianapolis, IN 46202-5186
Phone 317-350-4371, Fax: 317-852-3162
http://www.jopdent.org

Editorial Staff

©Operative Dentistry, 2020, **45-3,** 229-234

Clinical Technique/Case Report

A Conservative Approach to Ceramic Veneers: A Case Report

C Jurado • H Watanabe • J Villalobos Tinoco
H Ureta Valenzuela • G Guzman Perez • A Tsujimoto

Clinical Relevance

For anterior ceramic veneers, a predictable result can be obtained through a proper diagnostic mock-up followed by the use of reduction guides in tooth preparation. In addition, isolation with a rubber dam is crucial for the success of adhesive protocols.

SUMMARY

Bonding to enamel has been shown to provide reliable results, and thus conservative tooth preparations are key to the success of ceramic bonded restorations. The wax-up is the first diagnostic tool available to evaluate discrepancies between current and ideal tooth proportions. The clinician's diagnostic mock-up provides the patient with a visual perception of the size and shape of the proposed restorations. The use of reduction guides assists the restorative dentist in evaluating the specific amount of tooth structure to be removed during preparation. Furthermore, total isolation with a rubber dam prior to bonding the final restorations is crucial for the success of adhesive protocols. The aim of this report is to demonstrate a conservative approach to tooth preparation with a complete isolation technique prior to bonding eight ceramic restorations.

Carlos A Jurado, DDS, MS, Clinical Dentistry, A.T. Still University Arizona School of Dentistry and Oral Health, Mesa, AZ

*Hidehiko Watanabe, DDS, MS, Department of Restorative Dentistry, Oregon Health and Science University School of Dentistry, Portland, OR, USA

Jose Villalobos Tinoco, DDS, Department of Restorative Dentistry, Centro de Estudios Odontologicos (CEO), Queretaro, Mexico

Heriberto Ureta Valenzuela, CDT, private practice, Culiacan, Mexico

Gerardo Guzman Perez, DDS, private practice, Uriangato, Mexico

Akimasa Tsujimoto, DDS, PhD, Department of Operative Dentistry, Nihon University School of Dentistry, Tokyo, Japan

*Corresponding author: 2730 SW Moody Ave., Portland, OR 97201; e-mail: watanabh@ohsu.edu

https://doi.org/10.2341/19-051-T

INTRODUCTION

Ceramic veneers are well known as a conservative treatment option for anterior teeth presenting wear, fractures, interdental spaces, and facial defects.[1,2] Bonded ceramic veneers have been proven to show reliable outcomes with positive long-term results.[3–5]

The success of ceramic veneer restorations depends on many factors, such as preparation design,[5] adhesive techniques,[6,7] and adequate patient home care.[8] Usually, tooth reduction is needed for ceramic veneers in order to create ideal esthetic results, but excessive reduction can compromise bond strength due to exposure of dentin.[9] With new laboratory techniques and optimal dental materials, it is possible to produce ultrathin ceramic veneers with a thickness of 0.1 to 0.5 mm that can be bonded to tooth structure with minimal or no

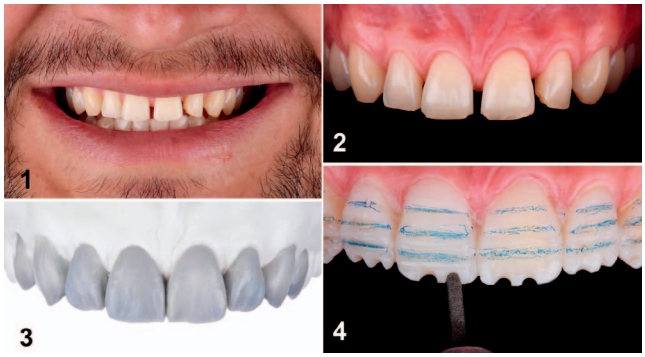


Figure 1. *Preoperative smile view.*

Figure 2. *Preoperative frontal view showing spaces between teeth 6 through 11; uneven incisal edges of teeth 8 through 10; and worn teeth 6, 8, 9, and 10.*

Figure 3. *Diagnostic mock-up with self-cured temporary composite material.*

Figure 4. *Horizontal and vertical depth grooves were cut on the teeth and marked with a blue pencil.*

preparation in order to modify the position, color, and shape of the teeth.[10,11] Currently, the market is offering several ceramic options for the clinician, such as lithium disilicate, feldspathic porcelain, feldspathic porcelain reinforced with leucite, and lithium disilicate reinforced with zirconia.[12–15] These types of ceramics have a high proportion of glassy matrix that produces highly esthetic results and excellent adhesion with resin cement when treated with hydrofluoric acid followed by silane application.[16] Minimal tooth reduction provides a high fracture strength when resin cement is used to bond a veneer to enamel.[17–20] High survival rates have been seen for ceramic veneers bonded to enamel.[21,22]

Ceramic veneer preparations can be challenging for clinicians with little experience, and the lack of good clinical protocols may result in failed restorations. The creation of a diagnostic wax-up is fundamental for the diagnosis and treatment of a potential candidate for veneer restorations.[23] It can provide information related to the discrepancies between current and ideal tooth size, restorative space available, occlusal scheme, and any treatment needed in the opposing arch.[24–26] The diagnostic wax-up can be transferred to the mouth as a diagnostic mock-up, and the patient can participate in a clinical evaluation of the tentative future restorations, allowing one to request any desired changes at this early step. The diagnostic wax-up can also be used as a treatment tool because it can be used to fabricate diagnostic guides and preparation reduction guides.[27] The final preparation can be made on an interim prosthesis placed in the mouth via a putty matrix. Initial depth grooves on the mock-up drive the clinician toward conservative veneer preparations because only a small amount of enamel tissue removal is needed for each tooth.[28,29] Several types of reduction guides can be fabricated from the diagnostic wax-up with either clear or putty matrices. These types of guides allow the clinician to evaluate the interproximal, incisal, and facial reduction on each tooth.[30]

This clinical report describes a conservative approach involving patient evaluation with a diagnostic mock-up, followed by tooth preparation for interim dental prostheses, evaluation of tooth reduction with different guides, and complete isolation for the bonding procedure of eight feldspathic veneers.

CASE REPORT

A 31-year-old male presented to the clinic with the chief goal of closing the spaces between teeth and improving his smile (Figures 1 and 2). After evaluation, the patient was diagnosed with spaces between teeth 6 through 11; uneven incisal edges of teeth 8 through 10; and worn teeth 6, 8, 9, and 10. The patient was offered a combination of orthodontic, tooth whitening, and restorative treatment. However, he rejected the idea of having orthodontic appliances in his mouth and tooth whitening treatments. The patient was informed of the need to have a diagnostic wax-up (GEO Classic, Renfert, Hilzingen, Germany) followed by a diagnostic mock-up with a self-cured temporary composite material (Structur Premium, VOCO GmbH, Cuxhaven, Germany) in order to evaluate the future dimensions of the proposed ceramic restorations (Figure 3). When the diagnostic mock-up was placed in the mouth, the patient was pleased with the result and asked to move forward. The final treatment plan included porcelain ceramic veneers on teeth 6 through 11, and due to the large smile corridor and the patient's request, ceramic veneers on 5 and 12 were included.

At the following clinical appointment, the same previously approved mock-up of the self-cured material was created and placed in the patient's mouth. Horizontal and vertical depth grooves were cut into the teeth with a round diamond bur (801 Spherical, JOTA AG, Rüthi, Switzerland) and marked with a blue pencil (Prismacolor Verithin,

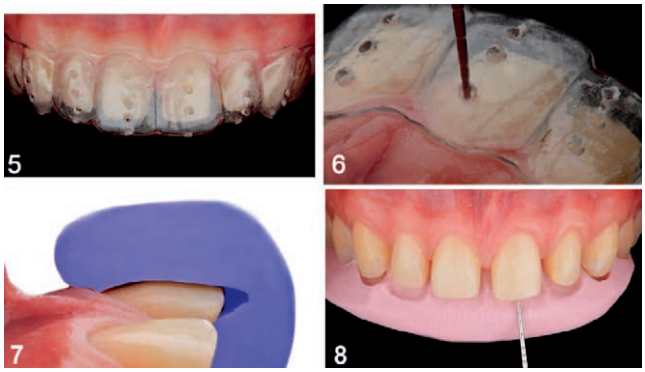


Figure 5. *Insertion of a clear matrix.*

Figure 6. *A periodontal probe was used for measurement of the reduction.*

Figure 7. *A putty reduction guide matrix was fabricated for the evaluation of incisal and facial reduction.*

Figure 8. *A periodontal probe was used to measure the reduction thickness.*

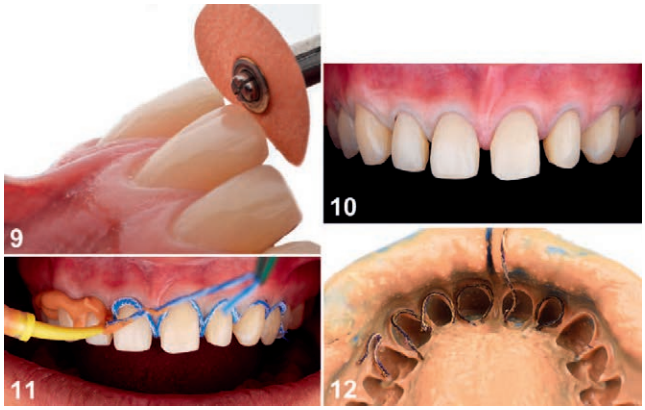


Figure 9. *A sharp corner of the preparation was rounded with a disc.*

Figure 10. *Frontal view of final preparation after first cord packing (00).*

Figure 11. *Removing a second cord (0) followed by injection of light body polyvinylsiloxane.*

Figure 12. *Final impression of eight ceramic veneers.*

Oak Brook, IL, USA) (Figure 4). Tooth reduction was performed with the aid of the clear thermoplastic reduction guide. The clear thermoplastic reduction guide (0.5-mm thickness, Thermoplastics, Keystone Industries, Gibbstown, NJ, USA) was fabricated with a vacuum machine (Pro-Vac, Keystone Industries). It was placed on the anterior teeth, and the conservative tooth preparations were checked with a clear matrix with specific perforations in order to insert a periodontal probe and measure the reduction. The clear matrix also allowed an overall vision of the reduction, including areas not easily accessible, such as the interproximal sites (Figures 5 and 6). In addition, a putty reduction guide matrix (Hydrorise Putty, Zhermack SpA, Badia Polesine, Italy) was fabricated in order to evaluate incisal and facial reduction, again using a periodontal probe to measure the amount of reduction (Figures 7 and 8). After conservative tooth preparations were completed, the teeth were polished and smoothed, and corners were rounded using discs (Soft-Lex Discs, 3M Oral Care, St Paul, MN). This was followed by sandblasting of the teeth with water and 20-micron aluminum oxide particles (AquaCare Aluminum Oxide Air Abrasion Powder, Velopex, London, UK) (Figure 9). A double cord impression technique was used, first packing cord 00 and then 0 (Ultrapak, Ultradent Products Inc, South Jordan, UT, USA), and the final impression was made using light-body and heavy-body consistency polyvinylsiloxane (Virtual 380, Ivoclar Vivadent, Amherst, NY, USA) (Figures 10 through 12).

Master cast and individual dies were fabricated with type IV stone (Fujirock, GC America Inc, Alsip, IL USA). Feldspathic veneers were chosen in order to fulfill the patient's high esthetic demands and for the ability to fabricate very thin restorations. Ceramic veneers were fabricated out of feldspathic porcelain (Noritake Super Porcelain EX-3, Kuraray Noritake Dental Inc, New York, NY, USA) (Figures 13 and 14). Try-in of ceramic restorations was performed with light and neutral try-in pastes (Variolink Esthetic Try-in, Ivoclar Vivadent), and the patient was shown the results (Figure 15). The patient and the clinician decided to use the light shade of cement. Isolation was provided with a rubber dam from 4 through 13, placing clamps on 4 and 13 (Rubber Dam Clamps no. 2, Hu-Friedy, Chicago, IL, USA). In addition, clamps (Hygenic Brinker Clamp B4, Coltene/Whaledent Inc, Cuyahoga Falls, OH, USA) were placed on the specific teeth to which restorations would be bonded (Figures 16 and 17). The placement sequence of the ceramic restorations was first 8 and 9, then 7 and 10, then 6 and 11, and finally 4 and 12. The ceramic restorations received hydrofluoric acid surface treatment (IPS Ceramic Etching Gel, Ivoclar Vivadent) for 60 seconds, followed by rinsing and drying. Restorations were submerged in water and alcohol in an ultrasonic bath (5300 Sweep Ultrasonic Cleaner, Quala Dental Products, Nashville, TN, USA) for five minutes in order to remove any remaining acid. Next, silane (Monobond-S, Ivoclar Vivadent)

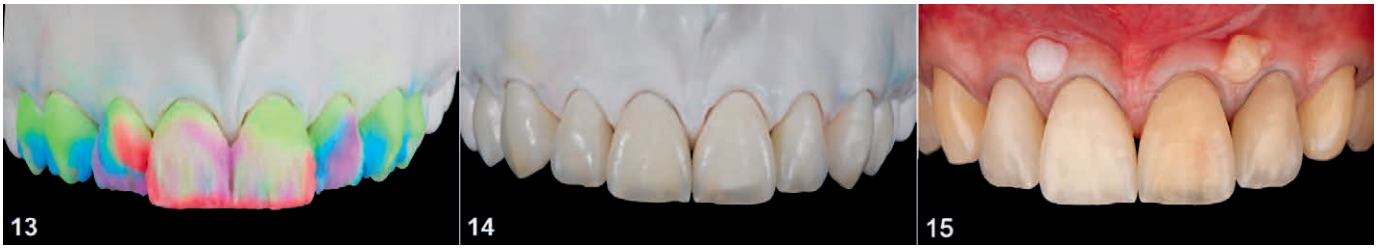


Figure 13. *Porcelain application.*

Figure 14. *Final ceramic restorations.*

Figure 15. *Checking the color of restorations using two different try-in pastes on the left (light) and right (neutral) sides.*

was applied for 60 seconds, and then the restoration was dried. The tooth surface was first treated with 32% phosphoric acid gel (Uni-Etch w/BAC, Bisco Dental, Schaumburg, IL, USA) for 30 seconds, then rinsed, and gently dried. Then primer and adhesive were applied (OptiBond FL, Kerr Dental, Orange, CA, USA) following the manufacturer's instructions and light cured (VALO LED Curing Light, Ultradent Products Inc) for 20 seconds. The light color cement (Variolink Esthetic LC, Ivoclar Vivadent) was applied to both veneers for 8 and 9, which were placed onto the teeth. Excess cement was removed with a microbrush and floss in the interproximal surfaces before light curing for 20 seconds on the facial surface, 20 seconds on the mesial surface, 20 seconds on the distal surface, and 20 seconds on the incisal surface. The same sequence was followed for the teeth and veneers on 7 and 10, then 6 and 11, and finally 5 and 12. Glycerin gel was then applied to the ceramic surfaces in order to prevent an oxygen inhibition layer (Liquid Strip, Ivoclar Vivadent), and the surfaces were again light cured for 20 seconds each. The rubber dam was removed, and excess cement on the cervical area was removed with a no. 12 blade (Surgical Scalpel Blade no. 12, Salvin Dental Specialties, Charlotte, NC, USA). Occlusion, excursive movements, and protrusion were checked. The patient was pleased with the final result (Figures 18 and 19). An occlusal guard was provided to wear at night in order to prevent any damage to the restorations. At the one-year follow-up, the patient was still pleased with the clinical result (Figure 20).

Figure 16. *Rubber-dam isolation of 8 and 9 using clamps.*

Figure 17. *Completion of cementing of eight ceramic veneers. The placement sequence was first 8 and 9, then 7 and 10, then 6 and 11, and finally 4 and 12.*

DISCUSSION

This clinical report describes how a well-planned diagnostic evaluation, thorough treatment planning, controlled tooth preparation, and ideal ceramic selection, can fulfill a patient's high esthetic demands. Initially, an additive wax-up was performed, followed by diagnostic mock-up. The wax-up information transferred to the mouth provides the patient with an opportunity to experience a physical model of the proposed size and shape of the final restoration. On the patient's approval, several types of reduction guides can be fabricated from the diagnostic wax-up. Some reduction guides, such as a clear matrix, can provide the clinician

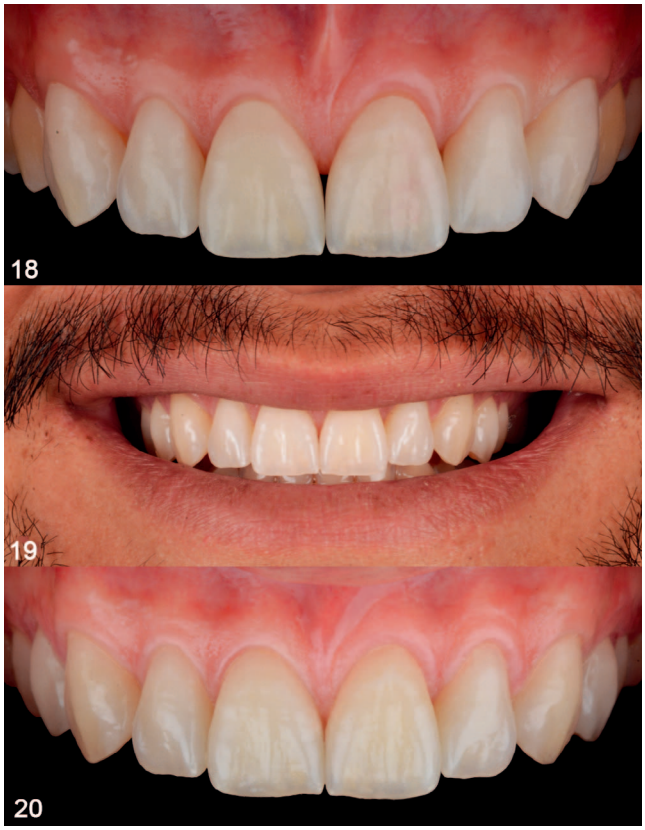


Figure 18. *Frontal view showing eight bonded ceramic veneers immediately after bonding.*

Figure 19. *Final simile view immediately after the delivery of eight ceramic veneers.*

Figure 20. *One-year follow-up of eight ceramic veneers.*

with an overall evaluation of all teeth to be prepped. In contrast, putty matrix guides can provide measurements of individual areas, such as facial and incisal, on specific teeth. Reduction guides provide the clinician with an opportunity to have a well-controlled tooth preparation appropriate to the type of ceramic restorations selected. Experienced restorative dentists may not need any reduction guide in order to achieve ideal tooth reduction, but the authors highly recommend them as one is gaining experience with these restorations. A rubber dam is used for isolation in order to achieve ideal results with the adhesive materials. This article demonstrated a technique in which a rubber dam was placed from the second premolar to the opposite second premolar secured with retainers. Individual retainers were placed on each tooth during the cementation of the ceramic veneer. This type of isolation provides several advantages to the clinician, such as preventing contamination of the working field by saliva, blood, and sulcular fluids. It also improves direct visibility because the rubber dam retracts the tongue, cheeks, and lips while working intraorally. It prevents aspiration and laceration from instruments and speeds up the treatment procedures because the clinician can focus on the clinical steps without worrying about the patient closing their mouth. Isolation between the second premolars provided enough working space for the clinician. Obviously, clinicians can bond final restorations without having total isolation with a rubber dam; however, even minimal contamination may compromise the effectiveness of the bonding agents.

CONCLUSIONS

The use of preparation guides provides the opportunity to verify the amount of tooth reduction needed for conservative veneer preparations. A clear matrix guide provides an overall perspective and can be perforated to measure the depth of specific sites with a periodontal probe. Traditional putty matrix guides are fabricated for more specific evaluation of areas, such as the incisal and facial zones. The goal of any tooth preparation is to maintain the prep in enamel in order to achieve an optimal bonded restoration. Proper tooth isolation is crucial to prevent any saliva or surface contamination during the adhesion of the ceramic restorations. The use of conservative tooth preparation and complete isolation during the bonding procedure should improve the longevity of the restorations.

Regulatory Statement

This study was conducted in accordance with all the provisions of the local human subjects oversight committee guidelines and policies of the OHSU School of Dentistry.

Conflict of Interest

The authors of this article certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

(Accepted 18 May 2019)

REFERENCES

1. Brunton P & Wilson N (1998) Preparations for porcelain laminate veneers in general dental practice *British Dental Journal* **184(11)** 553-556.
2. Nattress B, Youngson C, Patterson C, Martin D, & Ralph J (1995) An in vitro assessment of tooth preparation for porcelain veneer restorations *Journal of Dentistry* **23(3)** 165-170.

3. Shetty A, Kaiwar A, Shubhashini N, Ashwini P, Naveen D, & Adarsha M (2011) Survival rates of porcelain laminate restoration based on different incisal preparation designs: An analysis *Journal of Conservative Dentistry* **14(1)** 10-15.
4. Beier U, Kapferer I, Burtscher D, & Dumfahrt H (2012) Clinical performance of porcelain laminate veneers for up to 20 years *International Journal of Prosthodontics* **25(1)** 79-85.
5. Petridis H, Zekeridou A, Malliari M, Tortopidis D, & Koidis P (2012) Survival of ceramic veneers made of different materials after a minimum follow-up period of five years: A systematic review and meta-analysis *European Journal of Esthetic Dentistry* **7(2)**138-152.
6. Lin T, Liu P, Ramp L, Essig M, Givan D, & Pan Y (2012) Fracture resistance and marginal discrepancy of porcelain laminate veneers influenced by preparation design and restorative material in vitro *Journal of Dentistry* **40(3)** 202-209.
7. Lacy A, Wada C, Du W, & Watanabe L (1992) In vitro microleakage at the gingival margin of porcelain and resin veneers *Journal of Prosthetic Dentistry* **67(1)** 7-10.
8. Della Bona A & Kelly J (2010) A variety of patient factors may influence porcelain veneer survival over a 10-year period *Journal of Evidence Based Dental Practice* **10(1)** 35-36.
9. Ozturk E, Bolay S, Hickel R, & Ilie N (2013) Shear bond strength of porcelain laminate veneers to enamel, dentin and enamel-dentin complex bonded with different adhesive luting systems *Journal of Dentistry* **41(2)** 97-105
10. Carpena G, Ballarin A, & Aguiar J (2015) New ceramics approach for contact lens *Odovtos International Journal of Dental Sciences* **17(1)** 12-18
11. Strassler H (2007) Minimally invasive porcelain veneers: Indications for a conservative esthetic dentistry treatment modality *General Dentistry* **55(7)** 686-694.
12. Maicone P, Lammeti R, & Raffaelli L (2007) An overview of zirconia ceramics: Basic properties and clinical applications *Journal of Dentistry* **35(11)** 819-826.
13. Conrad H, Seong W, & Pesun I (2007) Current ceramic materials and systems with clinical recommendations: A systematic review *Journal of Prosthetic Dentistry* **98(5)** 389-404.
14. Soares P, Spini P, Carvalho V, Souza P, Gonzaga R. Tolentino A, & Machado A (2014) Esthetic rehabilitation with laminated ceramic veneers reinforced by lithium disilicate *Quintessence International* **45(2)**129-133.
15. Trinkner T & Roberts M (2001) Fluorapatite-leucite glass ceramic veneers for aesthetic anterior restorations *Practical Procedures and Aesthetic Dentistry* **13(1)** 37-41.
16. Spear F & Holloway J (2008) Which all-ceramic system is optimal for anterior esthetics? *Journal of the American Dental Association* **139(9)** 19S-24S.
17. Piemjai M & Arksornnukit M (2007) Compressive fracture resistance of porcelain laminate bonded to enamel or dentin with four adhesive systems *Journal of Prosthodontics* **16(6)** 457-464.
18. Gurel G, Sesma N, & Calamita M (2013) Influence of enamel preservation on failure rates of porcelain laminate veneers *International Journal of Periodontics and Restorative Dentistry* **33(1)** 31-39.
19. Peumans M, Van Meerbeek B, & Lambrechts P (2000) Porcelain veneers: A review of the literature *Journal of Dentistry* **28 (3)** 163-177.
20. Edelhoff D & Sorense J (2002) Tooth structure removal associated with various preparation designs for anterior teeth *Journal of Prosthetic Dentistry* **87(5)** 503-509.
21. Sadowsky S (2006) An overview of treatment considerations for esthetic restorations: A review of the literature *Journal of Prosthetic Dentistry* **96 (6)** 433-422.
22. Cotert H, Dundar M, & Ozturk B (2009) The effect of various preparation designs on the survival of porcelain laminate veneers *Journal of Adhesive Dentistry* **11(5)** 405-411.
23. Carlyle L & Richardson J (1985) The diagnostic wax-up: An aid in treatment planning *Texas Dental Journal* **102(2)**10-12.
24. Preston J (1976) A systematic approach to the control of esthetic form *Journal of Prosthetic Dentistry* **35(4)** 393-402.
25. Yuodelis R & Faucher R (1980) Provisional restorations: An integrated approach to periodontics and restorative dentistry *Dental Clinics of North America* **24(2)** 285-303.
26. Phillips K & Morgan R. The acrylic occlusal plane guide: A tool for esthetic occlusal reconstruction (2001) *Compendium of Continuing Education in Dentistry* **22(4)** 302-304, 306.
27. Simon H & Magne P (2008) Clinically based diagnostic wax-up for optimal esthetics: The diagnostic mock-up *Journal of the California Dental Association* **36(5)** 355-362.
28. Coachman C, Gurel G, & Calamita M (2014) The influence of tooth color on preparation design for laminate veneers from a minimally invasive perspective: A case report *International Journal of Periodontics and Restorative Dentistry* **34(4)** 453-459.
29. Pimentel W, Teixeira M, Costa P, Jorge M, & Tiossi R (2016) Predictable outcomes with porcelain laminate veneers: A clinical report *Journal of Prosthodontics* **25(4)** 335-340.
30. Reshad M, Cascione D, & Magne P (2008) Diagnostic mock-ups as an objective tool for predictable outcomes with porcelain laminate veneers in esthetically demanding patients: A clinical report *Journal of Prosthetic Dentistry* **99(5)** 333-339.

©Operative Dentistry, 2020, **45-3,** 235-242

An Improved Direct Injection Technique With Flowable Composites. A Digital Workflow Case Report

C Coachman • L De Arbeloa • G Mahn • TA Sulaiman • E Mahn

Clinical Relevance

Anterior dental restorations often involve difficult and time-consuming procedures. An improved direct injection technique using a digital workflow in the restoration of anterior teeth can be an alternative to save clinical time and yield a predictable and esthetic outcome.

SUMMARY

This article presents a clinical technique based on a case report for restoring the contours and shape of the upper teeth involved in the smile display of a young patient. After planning the treatment for the patient using digital tools (Digital pictures, Digital Smile Design, digital waxup, three-dimensional [3D] printed models, mockup), the upper teeth were restored using an improved injection technique. This improved technique involves the direct injection of flowable composite resin using clear polyvinyl siloxane molds made from 3D-printed models of the patient. The details and benefits of this new technique are described in the article.

Christian Coachman, DDS, CDT, adjunct professor, Department of Preventive and Restorative Sciences, University of Pennsylvania, PA, USA; Well Clinic Dentistry, Sao Paulo, Brazil

Luken De Arbeloa, DDS, DSD Virtual Lab, Madrid, Spain

*Gustavo Mahn, DDS, resident, Operative Dentistry, Department of Comprehensive Oral Health, University of North Carolina at Chapel Hill, Chapel Hill, NC, USA

Taiseer A. Sulaiman, BDS, PhD, Department of Comprehensive Oral Health, University of North Carolina, Chapel Hill, NC, USA

Eduardo Mahn, DDS, DMD, PhD, research professor/director, Esthetic Dentistry Program, Universidad de Los Andes, Santiago, Chile

*Corresponding author: 401 Brauer Hall Campus Box 7450, Chapel Hill, NC 27599, USA; e-mail: gusmahn@email.unc.edu

https://doi.org/10.2341/18-151-T

INTRODUCTION

State-of-the-art oral rehabilitation techniques aim for both esthetic and functional outcomes. Contemporary dental materials, clinical techniques such as Digital Smile Design (DSD), mockups, and integrated treatment planning enables the clinician to both virtually and/or clinically view and assess the treatment plan beforehand. Nevertheless, the process of making direct or indirect final restorations is still very tedious and time-consuming, demanding highly specific skills and attention to meticulous details from the clinician. The traditional process of placing direct anterior restorations is clinically demanding to complete, often involving a tedious

layering process, which limits the ideal indication of them to only a few restorations at a time.[1] Furthermore, traditional direct restorations are not made using preestablished tooth shapes or contours, making the procedure operator dependent and less predictable. When multiple anterior restorations or a smile change is required, indirect restorations are preferred by clinicians. However, fabrication of indirect restorations is often externalized to a dental technician, which increases delivery time and costs.

A clinician's preference for composite resin selection should be based on reported survivability, the composite resins' esthetic ability, and adaptability/handling. Since the 1990s, composite resins have improved vastly both in optical and mechanical properties, making them more versatile within their limitations.[1] Moreover, new techniques for applying composite resins have been introduced, enhancing their application. Mockups using bis-acryl or injecting flowable composite via transparent matrices have become more popular for provisionalizing anterior teeth.[2-5]

The early 1990s hallmarked the use of composite resins in dentistry, especially with the advancements in adhesive bonding. The initial composite resins were usually filled with large quartz particles, resulting in restorations that were rough and difficult to polish. With polishability being a major esthetic concern, newer composite resins emerged in response to the needs expressed by dental practitioners. Most contemporary composite resins fall into one of the following categories: hybrid, nano-filled, microfill, packable, and flowable composite.[6] Composite resins obtain their physical properties/handling characteristics from filler particles' relative amount, size, and shape. As a general rule, the more filler content and the smaller the filler particle, the better. Increasing filler load improves the resistance to functional wear and enhances physical properties. Also, composite resins with smaller particles are inherently more polishable, retain their polish for longer periods of time, and are more resistant to wear. Most composite resins have a putty-like consistency, which is desirable for clinical situations when packing composite resin into cavities. However, there was a need to have a composite resin with lower viscosity for better proximity with the cavity walls. For this reason, a new class of "flowable composite resins" was introduced in late 1996.[7]

Flowable resin-based composites are conventional composites with filler loading reduced to 37%-53% (volume) compared with 50%-70% (volume) for conventional minifilled hybrid composite resin. This altered filler loading modifies the viscosity of these materials. Most manufacturers package flowable composites in small syringes that allow for easy dispensing with very-small-gauge needles. This makes them ideal for use in small preparations or in situations where it would be difficult to fill otherwise. However, the main drawback of flowable composite resins is reduced physical properties and increased polymerization shrinkage compared with conventional composite resin attributed to its low filler content.[8]

A number of studies were conducted to improve the mechanical properties of flowable composite resins by adding nano-filled particles. This addition improved mechanical properties without affecting handling characteristics of the composite.[9] However, laboratory abrasion wear tests have produced contradictory results concerning wear resistance,[10-12] but the clinical wear resistance of flowable composites has yet to be determined. Other studies have concluded that flowable composite resins may have good polishability but less wear resistance, more potential to be eroded under acidic conditions, and more surface roughness over time due to reduced filler loading.[13-15] Therefore, based on the previous studies and due to the decreased filler content, reduced physical properties, and poor wear resistance, it is recommended that flowable composites should only be used in low stress-bearing areas, as liners or in small cavities.

Recently, newer and improved versions of flowable composites have been introduced that may extend their application to be considered in restoring minimally invasive preparations and tooth discolorations.[16-18] No difference in clinical outcomes was concluded when a nanohybrid composite resin was compared with a flowable composite in restoring noncarious cervical lesions during a 24-month observation period.[14] Moreover, when analyzing surface roughness and wear of recent flowable composites compared with conventional nanohybrid composites after toothbrush simulation, similar results were found between the two types of composite resins.[15,19]

Based on these current findings, recent flowable composites imply promising outcomes for esthetic applications. However, due to their lower filler content, they are still considered to be contraindicated for stress-bearing areas. Therefore, it is ultimately the clinicians' responsibility to consider the application of flowable composites in cases where successful and durable outcomes can be anticipated. Direct restorations require attention to meticulous

detail and skills to properly restore a tooth to its proper shape, function, and esthetics. Handling of conventional composites in restoring embrasures and contours can be challenging, and some composite resins' adaptability and sculptability can be complicated. As a result, certain clinical techniques have been introduced to facilitate the application of direct restorative material saving time with optimal esthetic and functional results.

The injection technique using flowable composite[20,21] is an example of a technique that suggests a quick and simple way to restore contours and shape of worn-out/defective teeth. After taking an impression and pouring it with stone, a waxup is made on the model replicating the desired outcome. An impression of this waxup is taken with a clear polyvinyl siloxane (PVS) material. Small access holes are made facially to the incisal edges of the teeth to be restored. Etching and bonding is done for every other tooth while isolating the other teeth with polytetrafluoroethylene tape. After inserting the PVS mold and checking its proper fit, flowable composite is injected through the access holes for the teeth that have been prepared and photopolymerized. This process is repeated for the other teeth that were isolated, and after removing the mold, the final restorations are finished and polished. Because the PVS mold replicates the complete waxup, the space between the mold and the natural tooth is inevitable, and injecting the flowable composite into one tooth space can cause the flowable composite to leak into this space and polymerize on the adjacent tooth. This can be difficult to clean and reshaping the teeth time-consuming, diminishing the very purpose of this technique: saving time with a favorable result.

A more accurate approach based on the injection technique is proposed by making a waxup on the cast of every other tooth, then taking an impression with the clear PVS. This will be the first mold. Then the waxup is completed for the other teeth, and a second PVS mold is made for the full waxup of the teeth. After isolation, etching, and bonding as previously described, the first PVS mold is secured in the patients' mouth. There should be a tight seal between the waxed and unwaxed teeth to seize the flowable composite from flowing into the embrasures and onto the adjacent teeth, accurately polymerizing the flowable composite into the confined space of the first waxup. The second PVS mold is placed, and the process is repeated. Accuracy and finishing time should be advantageous with this approach vs the conventional injection technique. However, it may be challenging to achieve symmetry, shape, and contouring of the teeth. Clinicians and technicians need to consider that it is very difficult to make two identical manual waxups, especially considering that one of them will have waxed every second tooth. Therefore, a digital workflow version of this procedure is introduced in the following clinical case, which can solve the drawbacks mentioned previously.

Computer-aided design and computer-aided manufacturing (CAD/CAM) technologies applied to dentistry have given the clinician a vast diversity of tools to handle clinical scenarios. Restorative dentistry is one of the fields that has benefited the most. The accuracy and consistency of intraoral scanners and milling units have allowed CAD/CAM restorations to be more predictable and durable. The CAD phase offers the clinician the ability to simulate the outcome without even changing a tooth intraorally. Based on an intraoral scan, a digital waxup can be made. Using the "adding tool" of the design software, the volume and shape of a tooth can be changed gradually on the screen and even corrected as many times as needed. Every step in the process can be reversible and modified as a single shape, making a digital waxup both versatile and retrievable. If a "digitally waxed" tooth is not looking according to the expectations, that tooth can be erased, and the process can start again from scratch. After the digital waxup is finished, each tooth can remain as a single shape as well. This means that each digitally waxed tooth can be later modified or visualized individually. This feature presents an incomparable advantage over traditional waxing techniques, where the waxed models are delicate and irreversible. Another advantage is that the digital workflow allows three-dimensional (3D) printing of the models, which is not only easy and inexpensive but also more durable. This sequential digital workflow is crucial to assure proper shape and ease the clinical procedures as described in the following case report.

CLINICAL CASE REPORT

A 28-year-old female patient presented for a screening appointment with concerns about spacing and malaligned and discolored teeth. Tooth #7 was slightly retruded with a lower gingival zenith, lateral incisors were smaller in proportion to central incisors, tooth #10 had a mesial and distal diastema, and the tooth shade of the maxillary teeth was unequal in chroma. She was also dissatisfied with her smile display, complaining about having an uneven gingival line (Figure 1). To begin the

Figure 1. *Pre-operative portrait picture of the patient.*

Figure 2. *DSD photographic protocol of the patient and occlusal scan of upper model.*

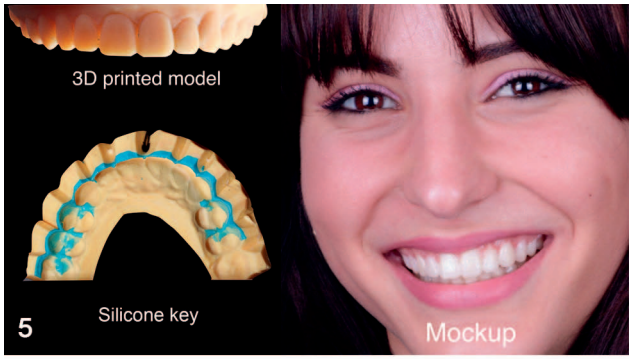
Figure 3. *Digital 2D simulation of the new smile with proposed tooth shape.*

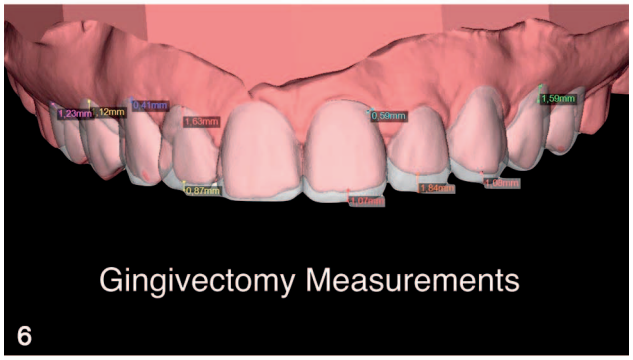
Figure 4. *Digital 3D wax-up design on the digital model and overlapped in the portrait picture of the patient.*

documentation of the findings, the DSD photographic protocol[22] was used, consisting of frontal portrait pictures with and without lip retraction; profile pictures in resting position and full smile; 12-hour picture (picture is taken from the back of the patient, angled from the overhead toward the anterior portion of the chin, focusing on the anterior maxillary flare of the incisors; and occlusal picture (in this case, the digital scan of the model; Figure 2).

A new smile proposition was simulated digitally with the DSD application, which provided the clinician and the patient with a helpful insight of treatment possibilities (Figure 3). Subsequently, the 3D design was created with the NEMO Smile design 3D software (Nemotec Company, Madrid, Spain) and overlapped with the patient's smile (Figure 4). From this simulated mockup, a 3D-printed model was created, and a PVS impression was made as a mold. A traditional additive mockup was made with a bis-acryl temporary material to visualize how the digitally designed teeth appear in the patients' mouth and determine whether the patients' expectations were met (Figure 5). Another aim of this mockup was to check if the occlusal function was kept with the proposed design. The goals were to provide protrusive guidance with all incisors participating in it and to keep canine guidance as lateral excursion pattern toward both sides.

Subsequently, after the occlusion was checked and the viability of the design confirmed, the digital scan of the model and the digital waxup were overlapped revealing tooth shape, alignment, and contours (Figure 6). After the final design was approved, a surgical stent for guiding the gingivectomy procedure was fabricated (Figures 6 and 7) The anticipated outcome of gingival zenith height, alignment, and contour were achieved (Figure 8). After four months of soft tissue healing, the teeth were bleached (Figure 9). Two models were 3D printed: the first was based on a waxup of every other tooth, and the second model was based on the complete waxup. As previously mentioned, this first design can be achieved using the design software by activating or deactivating the superimposed tooth with the digital waxup, because each tooth is an individual overlapped image (Figure 10). A translucent custom tray was used with a clear PVS impression material to take an impression of the models and then placed in a 1.5-bar pressure pot. This process ensured the optimum fit, accuracy of surface details, and contours (Figure 11). Access holes the size of the flowable composite tip were made through the tray and impression material slightly facial to the incisal





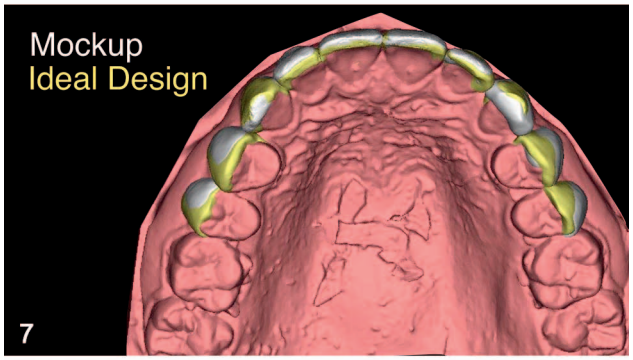


Figure 5. *Traditional additive mock-up on the patient based on a 3D printed model of the digital wax-up.*

Figure 6. *Estimated measurements planned for the gingivectomy procedure.*

Figure 7. *Occlusal view of the ideal mock-up design, which led to the fabrication of a surgical stent.*

Figure 8. *Clinical picture after the gingivectomy was completed.*

edge of each tooth that was to be restored (Figures 12 and 13). Isolation of every other tooth that was not included in the first waxup design was achieved with polytetrafluoroethylene tape due to its minimal thickness, it would not interfere with the seating of the clear PVS mold. However, care was taken when placing the tape around the teeth, because it folds very easily and can leave undesired wrinkles in the contour of the restored teeth. The teeth to be restored were etched with 38% phosphoric acid and rinsed, and the adhesive was applied according to manufacturer's instructions (Adhese Universal, Ivoclar Vivadent, Schaan, Liechtenstein) (Figure 14). The first mold was placed and checked for proper fit. The flowable composite (Tetric Evoflow Bleach L, Ivoclar Vivadent) was injected through the holes filling the entire facial surface, followed by photopolymerization using a Bluephase G2 device (Ivoclar Vivadent) (Figures 15 and 16) with an output of 1200 mW/cm^2. Considering the thickness of the tray and the PVS material, it was favorable to double the polymerization time recommended by the manufacturer to ensure sufficient delivery of energy to achieve optimal polymerization.[23,24] Other authors even suggest applying three times the recommended curing time when the distance between the composite resin and the light tip is more than 4 mm, because of LED design and light scattering.[25]

After light polymerization of the first set of teeth, finishing and polishing were performed. Finalizing contours and embrasures were completed with a #12 blade. Finishing and polishing were achieved with finishing burs, rubber cups, Sof-Lex discs (3M ESPE, St Paul, MN, USA), and polishing wheels and pastes (Figure 19). Subsequently, the second mold of the full waxup design was placed, and the same procedure was repeated for the remaining teeth (Figures 17 and 18). In this case, no changes in the occlusion were made. Protrusive, lateral movements, and occlusal contacts in maximum intercuspation remained intact. The final portrait pictures can be seen in Figure 20.

The improved version of the injection technique presented in this case report depicts a real treatment option, especially for patients that cannot afford traditional full-mouth indirect restorations and are seeking esthetic improvements. However, careful treatment planning and occlusal considerations have to be taken into account to assure good prognosis and long-term success of the restorations. The use of a flowable composite will make these restorations last for a couple of years and will make them more prone to degradation than traditional composites. The longevity of the treatment needs to be addressed with the

Figure 9. *Portrait picture after whitening of teeth and gingivectomy were performed.*

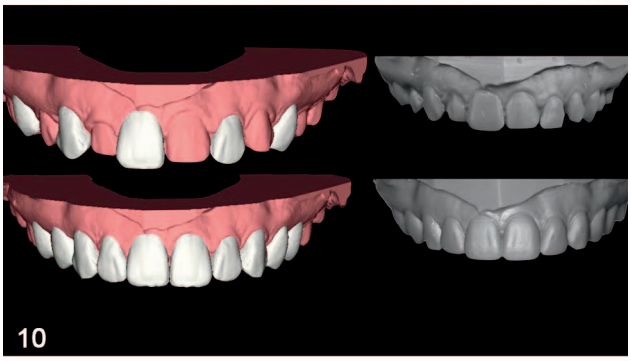


Figure 10. *First digital wax-up and 3D printed model created with the software after the deactivation of every other tooth from the complete wax-up.*

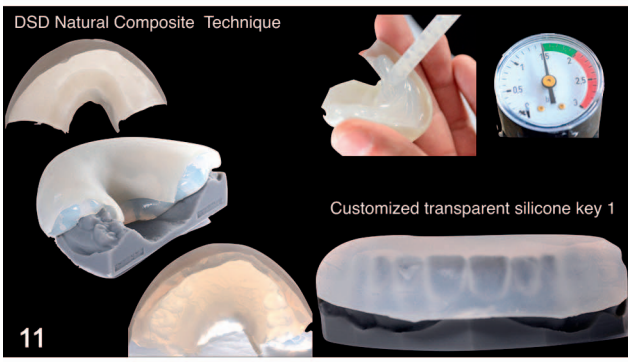


Figure 11. *Fabrication process of the first transparent silicone key.*

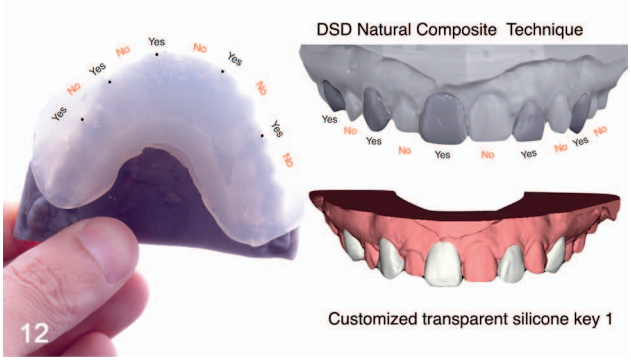


Figure 12. *Detail of the partial digital wax-up, 3D printed model and first silicone key fabricated.*

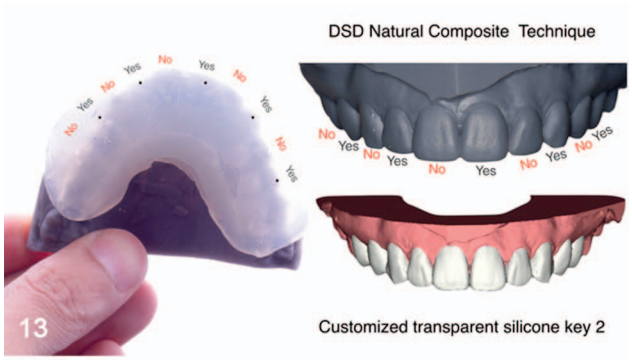


Figure 13. *Detail of the complete digital wax-up, 3D printed model and second silicone key fabricated.*

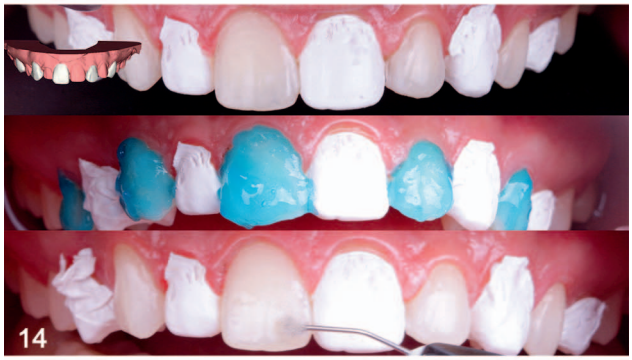


Figure 14. *Etching and bonding procedures for the first set of teeth to be restored.*

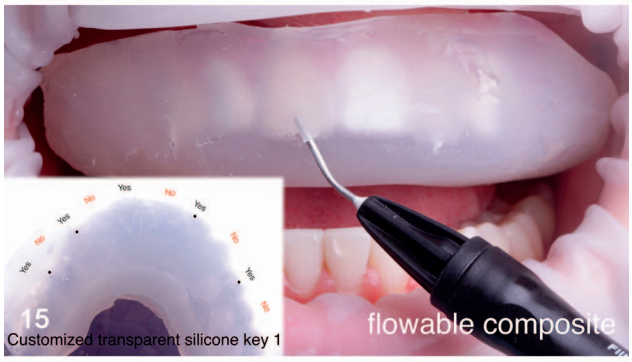


Figure 15. *Injection of flowable composite resin for the restoration of the first set of teeth through the first silicone key.*

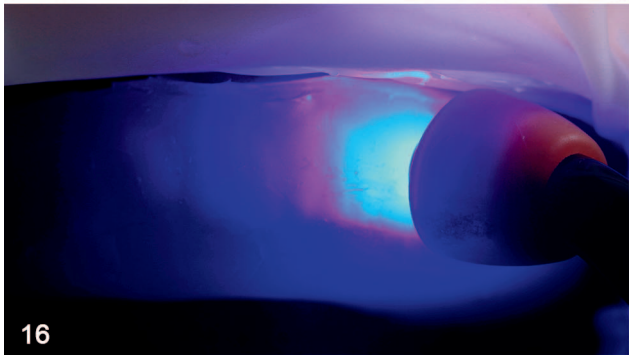
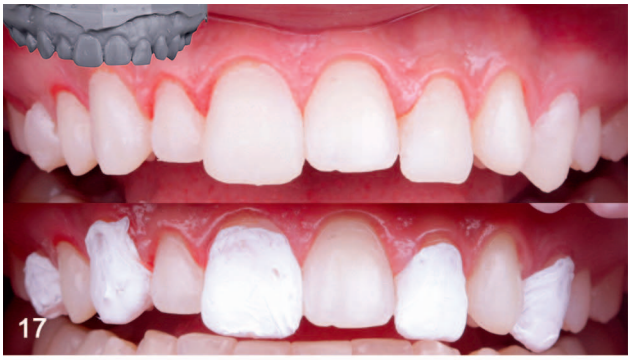
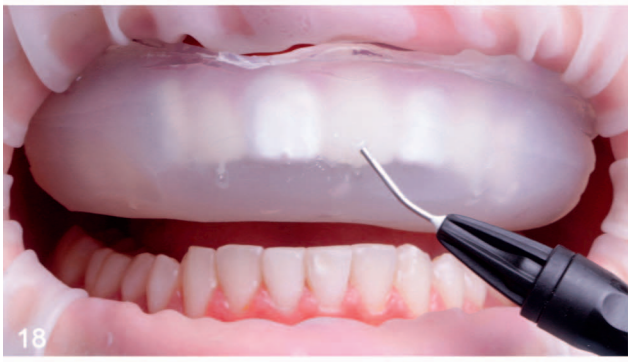


Figure 16. *Photopolymerization of the composite resin through the silicone key.*





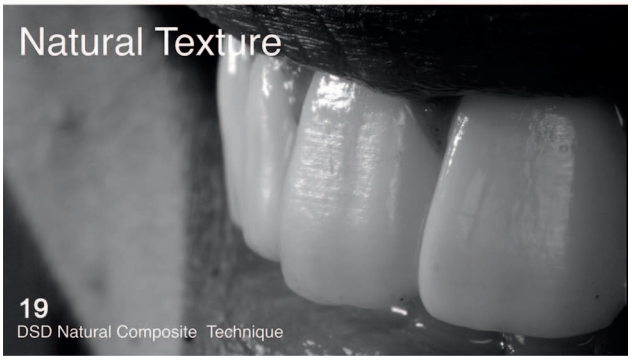


Figure 17. *Clinical picture after the first set of teeth are restored, finished and polished.*

Figure 18. *Injection of flowable composite resin for the restoration of the second set of teeth through the second silicone key.*

Figure 19. *Detail of the texture created after finishing and polishing of the restored teeth.*

Figure 20. *Set of portrait pictures of the patient from the pre-operative view to the final post-operative view.*

Figure 21. *Informal portrait pictures showing the final outcome.*

patient, informing them about its semipermanent characteristics. This technique, unlike restoring anterior teeth directly and manually, might be more cost-effective and does not require high-end clinical skills, making it more predictable and affordable. The digital workflow, however, has a learning curve and requires state-of-the-art hardware/software. It will appear daunting at the beginning, but after the workflow is assimilated by the working team, it might become more convenient to complete a treatment plan than a traditional approach. Similar digital attempts in the field of prosthodontics have been proven to be more cost-effective than the traditional approach.[26] The authors of this paper believe that scientific research should focus more on identifying which clinical situations can get the greatest benefits from applying a digital workflow and that esthetic dentistry might be one of them. This technique also allows for treating patients that need additive restorations without the necessity of preparing the teeth. In fact, a final intraoral impression or scan can be taken to save it for future purposes like converting those shapes to a more durable composite resin or to deliver indirect veneers/crowns. This technique can also be used for subtractive or additive/subtractive (mixed) restorations, but a preparation needs to be performed prior to the waxup and the delivery of the restorations. In

summary, when applying this technique, patients may receive a predictable result with reduced cost, effort, and time and acceptable durability and viability for future treatments.

Regulatory Statement

This study was conducted in accordance with all the provisions of the local human subjects oversight committee guidelines and policies of the University of North Carolina at Chapel Hill.

Conflict of Interest

CC is the current CEO of DSD Company (Sao Paulo, Brazil). LDA is the head of DSD Education of Nemotec Company (Madrid, Spain).

(Accepted 28 August 2019)

REFERENCES

1. Baroudi K & Rodrigues JC (2015) Flowable resin composites: a systematic review and clinical considerations *Journal of Clinical and Diagnostic Research* Jun; **9(6)** ZE18-ZE24.
2. Gouveia THN, Theobaldo JD, Vieira-Junior WF, Lima DANL, & Aguiar FHB (2017) Esthetic smile rehabilitation of anterior teeth by treatment with biomimetic restorative materials: a case report *Clinical, Cosmetic and Investigational Dentistry* **11(9)** 27-31.
3. Sancho-Puchades MM (2015) Advanced smile diagnostics using CAD/CAM mock-ups *International Journal of Esthetic Dentistry* **10(3)** 374-391.
4. Magne PP (2015) A new approach to the learning of dental morphology, function, and esthetics: the "2D-3D-4D" concept *International Journal of Esthetic Dentistry* **10(1)** 32.
5. Gurrea JJ (2014) Wax-up and mock-up. A guide for anterior periodontal and restorative treatments *International Journal of Esthetic Dentistry* **9(2)** 146.
6. Burgess JO, Walker R, & Davidson JM (2002) Posterior resin-based composite: a review of the literature *Pediatric Dentistry* Sep-Oct; **24(5)** 465-479.
7. García AH, Lozano MAM, Vila JC, Escribano AB, & Fos Galve P (2006) Composite resins. A review of the materials and clinical indications *Medicina Oral Patologia Oral y Cirugia Bucal* **11(2)** E215-E220.
8. Unterbrink GL & Lienbenberg WH (1999) Flowable resin composites as "filled adhesives": literature review and clinical recommendations *Quintessence International* **30(4)** 249-257.
9. Balos S, Pili B, Petronijevi B, Markovi D, Mirkovi S, & Sarev I (2013) Improving mechanical properties of flowable dental composite resin by adding silica nanoparticles. *Vojnosanitetski Pregled* **70(5)** 477-483.
10. Dang H & Sarrett D (1999) Wear behaviour of flowable and condensable composite resins *Journal of Dental Research* **78(Spec Issue)** 447.
11. Salerno M, Derchi G, Thorat S, Ceseracciu L, Ruffilli R, & Barone AC (2011) Surface morphology and mechanical properties of new-generation flowable resin composites for dental restoration *Dental Materials* **27(12)** 1221-1228.
12. Garcia FCP, Wang L, D'Alpino PHP, de Souza JB, de Araújo PA, & de LiaMondelli RF (2004) Evaluation of the roughness and mass loss of the flowable composites after simulated tooth brushing abrasion *Brazilian Oral Research Journal* **18(2)** 156-161.
13. Han L, Okamoto A, Fukushima M, & Okiji T (2008) Evaluation of flowable resin composite surfaces eroded by acidic and alcoholic drinks *Dental Materials Journal* **27(3)** 455-465.
14. Karaman EE (2012) Clinical evaluation of a nanohybrid and a flowable resin composite in non-carious cervical lesions: 24-month results *Journal of Adhesive Dentistry* **14(5)** 485-492.
15. Wang RLR (2017) Surface roughness and gloss of novel flowable composites after polishing and simulated brushing wear *Zhonghua Kou Qiang Yi Xue Za Zhi* **52(4)** 243-247.
16. Bonilla ED, Yashur M, & Caputo AA (2003) Fracture toughness of nine flowable composites *Journal of Prosthetic Dentistry* **89(3)** 261-267.
17. Lee IB, Son HH, & Um CM (2003) Rheologic properties of flowable, conventional hybrid, and condensable composite resins *Dental Materials* **19(4)** 298-307.
18. Milnar F (2006) Incorporating flowable composites into the minimally invasive treatment sequence for aesthetic enhancement *Practical Procedures Aesthetic Dentistry* **18(1)** 65-70.
19. Jin J, Takashi R, Hickel R, & Kunzelmann KH (2014) Surface properties of universal and flowable nanohybrid composites after simulated tooth brushing *American Journal of Dentistry* **27(3)** 149-154.
20. Terry D & Powers JM (2014) A predictable resin composite injection technique, Part 1 *Dentistry Today* **33(4)** 96, 98-101.
21. Terry D, Powers JM, Mehta D, & Babu V (2014) A predictable resin composite injection technique, part 2 *Dentistry Today* **33(8)** 12.
22. Coachman C, Calamita MA, & Sesma N (2017) Dynamic documentation of the smile and the 2D/3D digital smile design process *International Journal of Periodontics Restorative Dentistry* **37(2)** 183-193.
23. Corciolani G, Vichi A, & Davidson CL (2008) The influence of tip geometry and distance on light-curing efficacy *Operative Dentistry* **33(3)** 325-331.
24. Price RB, Derand T, & Sedarous M (2000) Effect of distance on the power density from two light guides *Journal of Esthetic Dentistry* **12(6)** 320-327.
25. Xu X, Sandras DA, & Burgess JO (2006) Shear bond strength with increasing light-guide distance from dentin *Journal of Esthetic and Restorative Dentistry* **18(1)** 19-27.
26. Lin XS, Metz MJ, Pollini A, Ntounis A, & Morton D (2014) Digital data acquisition for a CAD/CAM-fabricated titanium framework and zirconium oxide restorations for an implant-supported fixed complete dental prosthesis *Journal of Prosthetic Dentistry* **112(6)** 1324-1329.

©Operative Dentistry, 2020, **45-3,** 243-254

Clinical Research

Clinical Performance of a Glass Hybrid Restorative in Extended Size Class II Cavities

S Gurgan • ZB Kutuk • C Ozturk • R Soleimani • FY Cakir

Clinical Relevance

The clinical effectiveness of a glass hybrid restorative system was as acceptable as composite resin in large size Class II cavities subsequent to 24-month evaluation.

SUMMARY

Objective: To evaluate the clinical performance of a glass hybrid restorative compared with a resin composite in the restoration of large and deep Class II cavities after 24 months.

Methods and Materials: A total of 108 extended size, with the width of the proximal box not interfering with the peak of the cusps and the proximal box in occlusion, Class II lesions in 37 patients were either restored with a glass hybrid restorative or with a micro-hybrid composite resin in combination with selective etching by two experienced operators according to the manufacturer's instructions. Two independent examiners evaluated the restorations at baseline and at the six-, 12-, 18-, and 24-month recalls according to the modified US Public Health Service criteria. Negative replicas at each recall were observed under scanning electron microscopy (SEM) to examine surface characteristics. Data were analyzed statistically.

Results: After 24 months, 90 restorations were evaluated in 32 patients (recall rate: 86.5%). Four glass hybrid restorations were missing; three were due to bulk and one was due to proximal fracture at 12 months. Only six restorations were scored as bravo at baseline and at the six-, 12-, 18-, and 24-month recalls for color ($p<0.05$). No significant differences were observed between the two restorative materials for the other criteria evaluated ($p>0.05$). SEM observations exhibited acceptable surface and marginal adaptation characteristics for both restorative materials at 24 months.

Conclusions: Although glass hybrid restorations showed significant mismatch in color, both restorative materials exhibited successful performance for the restoration of large Class II cavities after 24 months.

Sevil Gurgan, DDS, PhD, Department of Restorative Dentistry, Hacettepe University, Ankara, Turkey, Hacettepe University, Ankara, Turkey

*Zeynep Bilge Kutuk, DDS, PhD, Department of Restorative Dentistry, School of Dentistry, Hacettepe University, Ankara, Turkey

Canan Ozturk, PhD, Ministry of Health, Ankara, Turkey

Reza Soleimani, DDS, Department of Restorative Dentistry, School of Dentistry, Hacettepe University, Ankara, Turkey

Filiz Yalcin Cakir, DDS, PhD, Department of Restorative Dentistry, Hacettepe University, Ankara, Turkey

*Corresponding author: Hacettepe University, Ankara, Other 06100, Turkey; e-mail: dt.zeynepbilge@yahoo.com

https://doi.org/10.2341/18-282-C

INTRODUCTION

Dental amalgam has been considered the most commonly used restorative material in posterior teeth for over 150 years, but its use has declined over the past years[1–3] because of the environmental concerns from its mercury content and increased demand for esthetic alternatives. Today's modern restorative dentistry focuses on minimal removal of tooth tissues and on application of adhesive restorative materials that may have a therapeutic effect on demineralized tissues.[3]

Resin-based composites were introduced in dentistry more than 50 years ago[4,5] and have been successfully used for the restoration of Class I and Class II lesions.[6] However, their polymerization shrinkage and associated stresses could affect the resin composite and tooth tissue bond, resulting in bonding failure and microleakage or in deformation of the tooth structure predisposing it to fracture.[7,8]

Glass ionomers (GIs) have been recommended to be used as restorative cements, cavity liners/bases, and luting cements since their introduction in dentistry in the early 1970s.[9] Compared with resin composites, they have certain unique properties that make them favorable. This includes chemical bonding to enamel and dentin, thermal expansion similar to that of tooth structure, biocompatibility, uptake and release of fluoride, and decreased moisture sensitivity.[10]

The survival rates of high-viscosity GIs that were placed in stress-bearing surfaces of both deciduous and permanent teeth as permanent restorative materials were reported as the same as or superior to amalgam restorations.[11] On the other hand, other studies that have evaluated the clinical performance of high-viscosity GIs in multiple-surface permanent restorations showed that the use of these materials did not exhibit successful results.[12,13]

During the past years, GIs have undergone major changes. Advancements in their formulations led to better properties, such as improvement in handling characteristics, wear resistance and strength and decreased setting time, which have widened the indication spectrum of GIs.[14,15]

Recently, a high-viscosity GI processed with a light-cured, nano-filled resin coating has been introduced and marketed as a restorative material in load-bearing Class I and in limited size Class II cavities. Application of this resin coating to the GI restoration after the GI sets is supposed to improve its wear resistance and esthetic appearance.[3]

Clinical studies are of great importance in predicting the longevity of restorations and providing evidence of the safety and efficacy of new techniques. Until now, only a few clinical trials of these GI restoratives have been done,[16–18] and satisfactory clinical performances were reported in Class I and in small Class II cavities.[19,20] However, this material still has not typically been considered as permanent restoration material for the restoration of extended-size Class II cavities.

One very recent development with GIs was the introduction of glass hybrids (GHs). The manufacturer of GH material stated that it is reinforced with smaller and more reactive silicate particles and acrylic acid molecules with higher molecular weights, which increase the matrix cross-linking of the material. This reinforcement is thought to improve the flexural strength of the material, and the manufacturer claims it may be used in larger Class II cavities.[21]

As it remains unclear if GHs may truly be used to restore extended cavities, the present study aimed to evaluate the clinical performance of this GH restorative compared with a micro-hybrid resin composite in the restoration of large and deep Class II cavities after 24 months. The null hypothesis was that the clinical performance of the GH restorative system would be as successful as resin composite in the restoration of extended Class II cavities.

METHODS AND MATERIALS

This was a two-year, double-blind, randomized, and controlled clinical study. The restorative materials tested are shown in Table 1.

Study Population and Sample Size

After recruiting and screening a group of patients seeking routine dental care by the Hacettepe University School of Dentistry's Department of Restorative Dentistry, a total of 37 patients satisfying the inclusion and exclusion criteria were selected. Inclusion criteria were that patients should 1) have two but not more than four extended-size proximal carious lesions in the posterior teeth, 2) have a healthy periodontal status (patients with a gingival index range of 0.28-0.35, plaque index range of 0.08-0.16,[22] and zero bleeding on probing were included[23]), 3) present a good likelihood of recall availability, 4) have teeth in which the restoration must be in occlusion, and 5) be symptomless and vital. Exclusion criteria were 1) partially erupted teeth, 2) potential behavioral problems, 3) unhealthy

Table 1: *Description of Materials Used in This Study*

Brand	Type	Manufacturer (Batch No.)	Composition
EQUIA Forte Fil	Bulk fill, glass hybrid restorative	GC Corp, Tokyo, Japan (1502091)	Fluoroaluminosilicate glass, polyacrylic acid powder, surface-treated glass
EQUIA Forte Coat	Nanofilled resin	GC Corp, Tokyo, Japan (2684031)	Methylmethacrylate, colloidal silica, camphorquinone, urethane methacrylate, phosphoric ester monomer
Cavity Conditioner	Cavity cleaning agent	GC Corp, Tokyo, Japan (1609061)	Polyacrylic acid 20%, aluminum chloride 3%, distilled water
G-ænial Posterior	Micro-filled resin hybrid composite	GC Corp, Tokyo, Japan (140922B)	UDMA, DMA co-monomer, inorganic filler >100 nm; fluoroaluminosilicate, inorganic filler <100 nm; fumed silica, pre-polymerized fillers (16–17 μm); strontium and lanthanoid fluoride filler (wt/vol %): 77/65
G-ænial Bond	one-step self-etch bonding agent	GC Corp, Tokyo, Japan (1411201)	4-MET, UDMA, TEGDMA, phosphoric acid, monomer, acetone, water, silanated colloidal, silica, initiator

Abbreviations: UDMA; urethanedimethacrylate, DMA; di-methacrylate co-monomer, TEGDMA; triethylene glycol dimethacrylate, 4-MET: 4 methacryloxyethyltrimellitate anhydride.

periodontal status, 4) systemic diseases, and 5) absence of adjacent and antagonist teeth. The average age of patients was 24 years (range, 15-37 years). To ensure statistical power, the minimal representative sample size was based on the required number of fillings to evaluate both materials (n=108). All patients participated voluntarily and were required to provide written informed consent.

Restorative Procedures

Two experienced clinicians placed 108 Class II restorations in 37 patients (Table 2). Before treatment, periapical and bitewing radiographs were taken, and electric pulp testing was performed using a pulp sensitivity tester (Parkell Electronics Division, Farmingdale, NY, USA). Cavity preparation was done using a diamond fissure bur (MS Rounded Edged Cylinder Bur [835R-012-4], Diatech, Heerbrugg, Switzerland) at high speed. Carious tissue was removed with hand instruments and slow-speed tungsten carbide bur (C31L-314-012-6.0, DIATECH, Coltène/Whaledent AG, Altstätten, Switzerland). Local anesthesia was applied where needed. The manufacturer of the GH restorative material limited the cavity size with the width of proximal box not interfering with the peak of cusps (Figure 1). So, before restorative treatment, after the caries was removed completely, the depth and width of the cavities were measured with a periodontal probe. If the cavity depth was <3 mm or a carious pulpal exposure was found, the tooth was excluded from the study. Cavities with multiple surfaces (>two surfac-

Table 2: *Distribution of Materials According to Tooth Type, Preparation and Arch*

	EQUIA Forte		G-ænial Posterior		Total
	MO/DO	MOD	MO/DO	MOD	
Maxillary arch					
Premolar	18	2	14	4	38
Molar	9	1	9	2	21
Mandibular arch					
Premolar	12	2	10	2	26
Molar	10	1	7	5	23
Total	49	6	40	13	108

Abbreviations: MO; Mesioocclusal, DO; Distoocclusal, MOD; Mesioocclusodistal

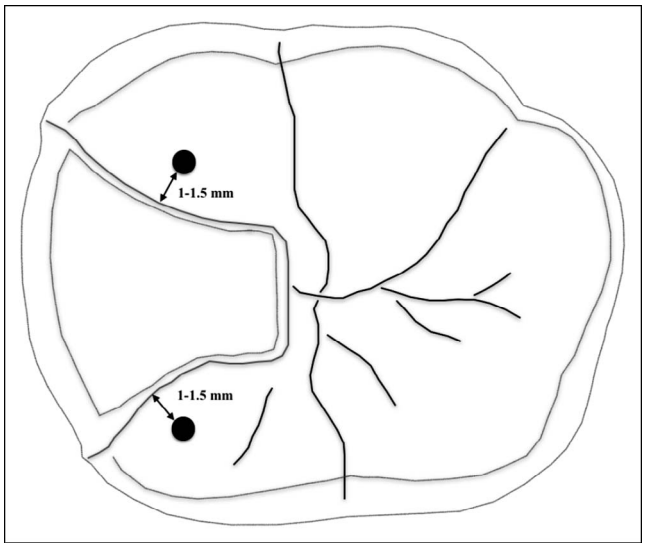


Figure 1. *Recommended Class II cavity size from the manufacturer of EQUIA Forte.*

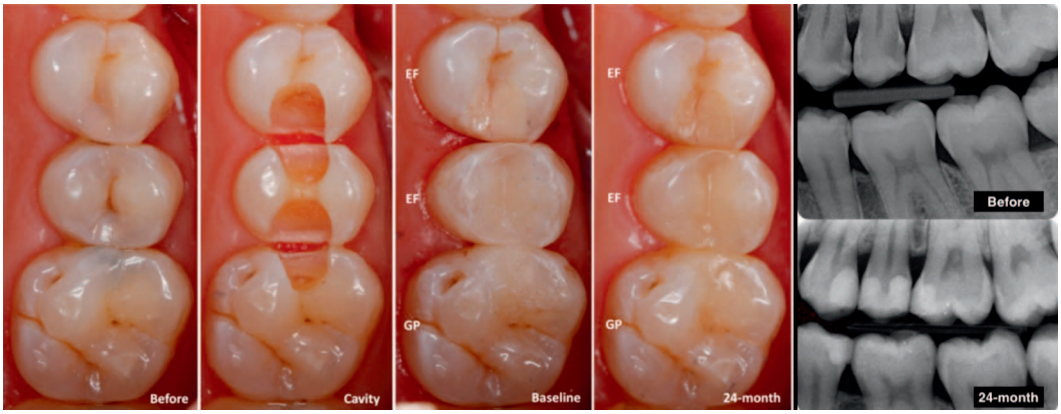


Figure 2. *Clinical and radiologic representatives of EQUIA Forte and G-ænial Posterior. Before restorations (a), cavity preparations (b), restorations at baseline (c), restorations after 24 months (d), bitewing radiograph before treatment (e), bitewing radiograph 24 months after treatment.*

es) were not included, unless unexpected cavity extension to a multiple-surface restoration during treatment occurred. Resin-modified calcium silicate pulp protectant/liner (Theracal LC, BISCO, Inc. Schaumburg, IL, USA) was applied as base material where needed. A sectional matrix system (Palodent, Dentsply, Konstanz, Germany) was used. Cavities were restored with GH restorative (EQUIA Forte, GC Corp, Tokyo, Japan) or micro-hybrid composite resin (G-ænial Posterior, GC Corp) according to the manufacturer's instructions. The restorative materials; EQUIA Forte and G-ænial Posterior, were randomized over two cavity groups using a table of random numbers.

GH Restorations

The cavity was conditioned with 20% polyacrylic acid for 20 seconds (Cavity Conditioner, GC Corp), washed, and briefly dried. Then, EQUIA Forte was mixed automatically for 10 seconds and immediately injected into the cavity. Cotton rolls and saliva ejector were used for isolation. The restoration was finished and polished wet using high-speed fine diamonds (Diatech, Swiss Dental, Heerbrugg, Switzerland) and silicones (HiLusterPLUS, Kerr Corp, Orange, CA, USA) after a setting time of 2.5 minutes. The restoration was briefly dried; then, EQUIA Forte Coat was applied to the surface and light polymerized for 20 seconds using a photo-curing light (Starlight s, Mectron spa, Carasco, Italy) with an irradiance of >1400 mW/cm^2. The output of the light unit was checked after each patient with a radiometer (Demetron, Danbury, CT, USA).

Resin Composite Restorations

G-ænial Bond (GC Corp) was used with a selective etching technique according to the manufacturer's instructions. Enamel was etched with 35% phosphoric acid gel for 10 seconds, rinsed for 5 seconds, and gently dried. Then, G-ænial Bond was applied to the enamel and dentin using a disposable applicator, left undisturbed for 10 seconds, and dried thoroughly for 5 seconds with oil-free air under air pressure. After achieving a frosted glass appearance, G-ænial Posterior was applied with the incremental technique (layers 2 mm thick). Each layer was light-cured for 20 seconds. The restoration was finished and polished with ultrafine diamonds and silicone instruments.

Patients were evaluated for baseline one week after restoration placement. Two independent dentists who were blinded to the restorative materials and patients performed clinical evaluations according to the modified US Public Health Service (USPHS) criteria using mirrors, probes, and bitewing radiographs.[24] The two dentists, with more than 20 years' experience in USPHS criteria evaluation, were calibrated to a predetermined level of inter- and intraexaminer agreement of at least a Kappa value of 95% for each criterion.

Patients were recalled at six, 12, 18, and 24 months for assessments of the restorations using the same criteria as at baseline and using the same two calibrated dentists who examined the restorations at baseline. Final decisions were made by consensus of both examiners if disagreement occurred during the evaluations. Photographs and bitewing radiographs of each restoration were also taken at each recall (Canon macro 100 mm lens, Canon Inc, Tokyo, Japan) (Figure 2).

SEM Analysis

Impressions were taken from one patient selected randomly from each group with polyvinylsiloxane

Table 3: *Recall Rates of Patients*

	Recalls				
	Baseline	**6 Months**	**12 Months**	**18 Months**	**24 Months**
Number of patients (%)	37 (100)	37 (100)	32 (86.5)	32 (86.5)	32 (86.5)

impression material at each recall. The replicas were gold sputter-coated and the surface morphology and marginal integrity of the restorations were examined under SEM (JSM-6400 SEM, JEOL, Tokyo, Japan) at ×10, ×50, and ×200 magnifications.

Statistical Analysis

The statistical analyses were carried out with the IBM SPSS version 22.0 software package (SPSS, Chicago, IL, USA). The Cochran Q test was used to compare the changes according to USPHS criteria across different time points within each restorative material. The changes in each category within the restorative groups were compared using the Fisher exact test (α=0.05).

RESULTS

The distribution of the restorations is shown in Table 2. Forty-four restorations (41%) were placed in molars and 64 restorations (59%) were placed in premolars where as 59 (55%) restorations were placed in the maxillary arch and 49 (45%) restorations were placed in mandibular arch.

The recall rate was 100% at six months and 86.5% at 12, 18, and 24 months (Table 3). At the end of 24 months, 90 restorations were evaluated in 32 patients. Eighteen restorations could not be evaluated because five patients (13.5%) had moved away. The success rate of G-ænial Posterior was 100%. Although the success rate of EQUIA Forte restorations was 93.7% at the 12-month recall, success rate was calculated as 100% at the 24-month recall as three patients with failed restorations at the 12-month recall could not be evaluated at the 24-month recall.

The results of the clinical evaluation of the restorations are presented at Table 4. According to Cochran Q test results, no significant differences were seen between baseline and other evaluation periods for both restoratives ($p>0.05$).

All restorations from the G-ænial Posterior group showed perfect anatomical form at all evaluation periods. None of the restorations from the EQUIA Forte group showed anatomical form deformation until the 12-month evaluation. Two restorations (4.4%) showed slight form deformation at 12 months. These restorations were in need of simple maintenance treatment, and their scores were upgraded to alpha (A).

Six EQUIA Forte restorations (10.9%) showed slight mismatches in color at baseline as well as six (10.9%) at six months, six (13.3%) at 12 months, six (13.3%) at 18 months, and six (13.3%) at 24 months. So, a significant difference was seen between the EQUIA Forte and G-ænial Posterior groups (p=0.011) for color change.

Three (6.3%) EQUIA Forte restorations were lost at 12 months due to bulk fracture (p=0.092). One (2.2%) EQUIA Forte restoration exhibited partial fracture at the proximal contact point of the restoration and was recorded as a failure of the restoration (p=0.429) at the end of 24 months. One EQUIA Forte restoration showed minimal discoloration at the restoration-enamel interface (p=0.429) at 12 months. No differences were observed for the rest of the evaluated criteria (secondary caries, polishability, surface staining, sensitivity, and soft tissue health) ($p>0.05$).

SEM observations of one EQUIA Forte and G-ænial Posterior restoration are shown in Figures 3 and 4. Both materials exhibited acceptable marginal adaptation and surface characteristics during the 24-month evaluation. A slight surface roughness was observed in both restorative materials after 24 months.

DISCUSSION

Adequate strength to resist masticatory and occlusal forces is mainly expected from restorative materials used in the posterior area. Resin composites have been the restorative material of choice for posterior teeth because they offer an extended manipulation time, direct-curing options, reduced number of steps required, and decreased chairside time with the introduction of bulk-fill restoratives partially in deep cavities.[25,26]

Although the merits of GIs, as restorative materials, are clearly shown in the literature,[13] the major drawbacks of conventional GIs have been the relatively low fracture toughness and higher rate of occlusal wear compared with that of other restorative materials, such as amalgam and resin compos-

Table 4: *Clinical Evaluation Scores of the Restorations at Baseline (BL) and at 6, 12, 18, and 24 Months* [a]

Modified USPHS Criteria/Scores	EQUIA Forte					
	Baseline	Six Month	12 Month	18 Month	24 Month	*p*
Anatomic form						
A: Restoration contour is continuous with existing anatomic form and margins.	55 (100)	55 (100)	43 (95.6)	45 (100)	45 (100)	0.406
B: Restoration is slightly overcontoured or undercontoured.	0	0	2 (4.4)	0	0	
C: Marginal overhang or tooth structure (dentin or enamel) is exposed.	0	0	0	0	0	
D: Restoration is missing; traumatic occlusion or restoration causes pain in tooth or adjacent tissue.	0	0	0	0	0	
Secondary caries						
A: No visible caries.	55 (100)	55 (100)	45 (100)	45 (100)	45 (100)	1.000
C: Caries contiguous with the margin of the restoration.	0	0	0	0	0	
Color match						
A: No mismatch in color, shade, or translucency between restoration and adjacent tooth structure.	49 (89.1)*	49 (89.1)*	39 (86.7)*	39 (86.7)*	39 (86.7)*	1.000
B: Mismatch between restoration and tooth structure within the normal range of tooth.	6 (10.9)	6 (10.9)	6 (13.3)	6 (13.3)	6 (13.3)	
C: Mismatch between restoration and tooth structure outside the normal range of tooth.	0	0	0	0	0	
D: Esthetically displeasing color, shade, and translucency.	0	0	0	0	0	
Retention						
A: Present.	55 (100)	55 (100)	45 (93.7)	45 (100)	45 (100)	0.406
B: Partial loss.	0	0	0	0	0	
C: Absent.	0	0	3 (6.3)	0	0	
Marginal adaptation						
A: Excellent continuity at resin–enamel interface; no ledge formation, no discoloration.	55 (100)	55 (100)	45 (100)	45 (100)	44 (97.8)	0.406
B: Slight discoloration at resin–enamel interface; ledge at interface.	0	0	0	0	1 (2.2)	
C: Moderate discoloration at resin–enamel interface measuring 1 mm or greater.	0	0	0	0	0	
D: Recurrent decay at margin.	0	0	0	0	0	
Polishability						
A: Smooth and highly shiny, similar to enamel.	55 (100)	55 (100)	45 (100)	45 (100)	45 (100)	1.000
B: Smooth and satin, highly reflective.	0	0	0	0	0	
C: Rough and shiny, satin, somewhat reflective.	0	0	0	0	0	
D: Rough and dull or satin, not reflective.	0	0	0	0	0	
Surface staining						
A: Absent.	55 (100)	55 (100)	45 (100)	45 (100)	45 (100)	1.000
C: Present.	0	0	0	0	0	
Sensitivity						
Preoperative						
Yes	0	0	0	0	0	1.000
No	55 (100)	55 (100)	45 (100)	45 (100)	45 (100)	
Postoperative						
Yes	0	0	0	0	0	1.000
No	55 (100)	55 (100)	45 (100)	45 (100)	45 (100)	
Soft tissue health						
A: Excellent response-no inflammation.	55 (100)	55 (100)	45 (100)	45 (100)	45 (100)	1.000
B: Slight inflammation of gingival tissue.	0	0	0	0	0	
C: Moderate to severe gingival inflammation.	0	0	0	0	0	
Proximal contact points						
A: Present.	55 (100)	55 (100)	45 (97.8)	45 (100)	45 (100)	1.000
C: Absent.	0	0	1 (2.2)	0	0	

Abbreviation: USPHS, US Public Health Service.

[a] Asterisks indicate that the *p* values in the columns show the difference of restorations in comparison with baseline according to Cochrane Q test for all criteria.

Table 4: *Extended.*

Modified USPHS Criteria/Scores	G-ænial Posterior					
	Baseline	**Six Month**	**12 Month**	**18 Month**	**24 Month**	***p***
Anatomic form						
A: Restoration contour is continuous with existing anatomic form and margins.	53 (100)	53 (100)	45 (100)	45 (100)	45 (100)	1.000
B: Restoration is slightly overcontoured or undercontoured.	0	0	0	0	0	
C: Marginal overhang or tooth structure (dentin or enamel) is exposed.	0	0	0	0	0	
D: Restoration is missing; traumatic occlusion or restoration causes pain in tooth or adjacent tissue.	0	0	0	0	0	
Secondary caries						
A: No visible caries.	53 (100)	53 (100)	45 (100)	45 (100)	45 (100)	1.000
C: Caries contiguous with the margin of the restoration.	0	0	0	0	0	
Color match						
A: No mismatch in color, shade, or translucency between restoration and adjacent tooth structure.	53 (100)*	53 (100)*	45 (100)*	45 (100)*	45 (100)*	1.000
B: Mismatch between restoration and tooth structure within the normal range of tooth.	0	0	0	0	0	
C: Mismatch between restoration and tooth structure outside the normal range of tooth.	0	0	0	0	0	
D: Esthetically displeasing color, shade, and translucency.	0	0	0	0	0	
Retention						
A: Present.	53 (100)	53 (100)	45 (100)	45 (100)	45 (100)	1.000
B: Partial loss.	0	0	0	0	0	
C: Absent.	0	0	0	0	0	
Marginal adaptation						
A: Excellent continuity at resin–enamel interface; no ledge formation, no discoloration.	53 (100)	53 (100)	45 (100)	45 (100)	45 (100)	1.000
B: Slight discoloration at resin–enamel interface; ledge at interface.	0	0	0	0	0	
C: Moderate discoloration at resin–enamel interface measuring 1 mm or greater.	0	0	0	0	0	
D: Recurrent decay at margin.	0	0	0	0	0	
Polishability						
A: Smooth and highly shiny, similar to enamel.	53 (100)	53 (100)	45 (100)	45 (100)	45 (100)	1.000
B: Smooth and satin, highly reflective.	0	0	0	0	0	
C: Rough and shiny, satin, somewhat reflective.	0	0	0	0	0	
D: Rough and dull or satin, not reflective.	0	0	0	0	0	
Surface staining						
A: Absent.	53 (100)	53 (100)	45 (100)	45 (100)	45 (100)	1.000
C: Present.	0	0	0	0	0	
Sensitivity						
Preoperative						
Yes	0	0	0	0	0	1.000
No	53 (100)	53 (100)	45 (100)	45 (100)	45 (100)	
Postoperative						
Yes	0	0	0	0	0	1.000
No	53 (100)	53 (100)	45 (100)	45 (100)	45 (100)	
Soft tissue health						
A: Excellent response-no inflammation.	55 (100)	55 (100)	45 (100)	45 (100)	45 (100)	1.000
B: Slight inflammation of gingival tissue.	0	0	0	0	0	
C: Moderate to severe gingival inflammation.	0	0	0	0	0	
Proximal contact points						
A: Present.	55 (100)	55 (100)	45 (100)	45 (100)	45 (100)	1.000
C: Absent.	0	0	0	0	0	

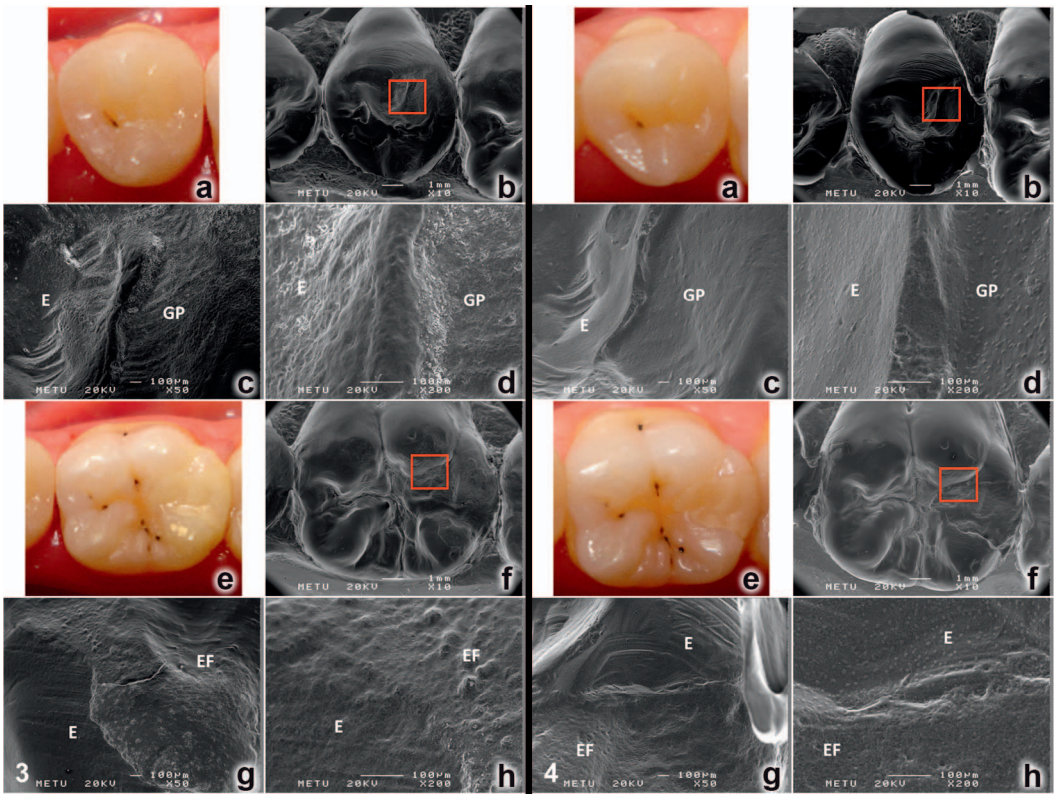


Figure 3. *Representatives of G-ænial Posterior and EQUIA Forte restorations at baseline. Clinical picture of G-ænial Posterior restoration (a), SEM photomicrograph of the G-ænial Posterior restoration ×10 (b), ×50 (c), and ×200 (d). Clinical picture of EQUIA Forte restoration (e), SEM photomicrograph of the G-ænial Posterior restoration ×10 (f), ×50 (g), and ×200 (h). E: enamel; EF: EQUIA Forte; GP: G-ænial Posterior.*

Figure 4. *Representatives of G-ænial Posterior and EQUIA Forte restorations after 24 months. Clinical picture of G-ænial Posterior restoration (a), SEM photomicrograph of the G-ænial Posterior restoration ×10 (b), ×50 (c), and ×200 (d). Clinical picture of EQUIA Forte restoration (e), SEM photomicrograph of the G-ænial Posterior restoration ×10 (f), ×50 (g), and ×200 (h). E: enamel; EF: EQUIA Forte; GP: G-ænial Posterior.*

ites.[27] For this reason, conventional modified GIs were previously not considered materials of choice in Class II restorations, neither in primary nor permanent molars.[12,13] In recent years, further improvements in the composition of GIs have been made to enhance their clinical handling and physical or mechanical properties. Laboratory studies showed that highly viscous GIs could compete with resin composites.[21,28,29]

Although the overall data density on amalgam or composite resin is very high,[30–32] to date, only few studies regarding clinical success of GI-based restorative systems have been reported. These studies were mostly performed on Class I cavities.[17,33] There have been limited data showing their performance in Class II cavities, and clinical trials on Class II cavities were carried out on patients with small to moderate size cavities.[20,34] Although a few clinical studies with different restorative GIs have been carried out,[16,20,34] as far as we could determine, this is the first clinical trial that compared the use of the newly developed GH system in the restoration of extended size Class II cavities. Since no data are available on the clinical success of this new reinforced GH in the restoration of large Class II restorations, the comparison with those of other studies could not be done.

Previously, Scholtanus and Huysmans [12] examined the performance of a high-viscosity GI (Fuji IX, GP Corp) in Class II restorations over six years in a retrospective study. One hundred and sixteen Class II restorations (70 two-surface and 46 three-surface) in 72 patients were made in 1996 and 1997 in general dental practice by two experienced dentists. The authors observed no failures until 18 months; but the survival rate was 93% at 42 months. Failure rate increased after 42 months, and at 72 months the survival rate was reported as 60%. Fracture of the GI in the proximal areas was reported as the reason for replacing restorations. No restorations failed due to the occlusal wear or isthmus fracture. Later, in a prospective clinical study, Frankenberger and oth-

ers[13] examined the clinical performance of a viscous GI (Ketac Molar) in posterior cavities over 2 years and reported that the recall rates were 24% and failure rates were 40% for Class II cavities after 2 years. Bulk fracture at occlusally loaded areas was the main reason for failures.

In 2011, Friedl and others[16] evaluated the clinical behavior of a new GI restorative system, EQUIA in posterior teeth. In this retrospective study, 26 Class I and 125 Class II restorations were placed in permanent molars and premolars of 43 patients in six dental offices. After 24 months, they observed no failures but marginal disintegrities were seen in 1.2% of two-surface Class II cavities and 7.3% of Class II cavities with three or four surfaces. A visible roughness was observed in 14% of two-surface Class II restorations and in 24% of Class II restorations with three or four surfaces. The authors concluded that this system could be used as a permanent restoration material for any size Class I and smaller Class II cavities.

Klinke and others[18] also carried out a multicentered prospective clinical field study with the EQUIA restorative system (EQUIA Fil + EQUIA coat) and examined the clinical performance of this system according to the World Dental Federation criteria. The study was conducted in 144 different private dental clinics in 29 cities. A total of 232 Class II restorations were placed out of 1001 restorations in adult patients aged 20-80 years. However, after four years, they could evaluate only 32 Class II restorations. Eight restorations lost proximal contact or fractured and were found to be clinically poor and needed to be replaced after four years.

Turkun and Kanik[34] reported the clinical performance of EQUIA System over six years. In their long-term clinical trial, 44 Class II cavities out of 256 restorations were restored with the EQUIA system (EQUIA Fil + G Coat). They defined Class II cavities as mostly medium to large in size but not involving any cusps. After 18 months, five Class II restorations (EQUIA Fil + G Coat) had to be replaced, but at the end of six years, they only observed one more restoration that was partially missing and had to be replaced, while six restorations had to be repaired.

In these clinical studies, cavity size in relation to the remaining tooth structure was less considered. However, the manufacturer of the EQUIA Fil restorative system indicated that if used in small to moderate sized Class II cavities; the isthmus width must be less than the half of the intercuspal distance.[18]

Gurgan and others[20] reported another long-term clinical study. Sixty Class II lesions were restored with EQUIA or a micro-hybrid resin composite (Gradia Direct Posterior). In this study, a conservative cavity design was used with the principles of minimally invasive dentistry. None of the cavity preparations involved one or more cusps. Restorations were evaluated yearly according to the modified USPHS criteria. At the end of six years, 45 Class II restorations could be evaluated. Only four Class II EQUIA restorations were lost at three years and another one at four years. No failures were observed at five and six years. However; none of the materials were found to be superior to the other.

The present study was performed on patients with at least two extended size Class II lesions. A new GH restorative system was compared with a resin composite used in the restoration of posterior teeth. In contrast to the previous GI restorative material (EQUIA Fil), the manufacturer of this new GH restorative material (EQUIA Forte) recommended using this material reinforced with ultrafine and highly reactive glass particles for larger and deeper Class II cavities.[35]

As pointed out by American Dental Association, a restorative material intended to be used in posterior teeth needs to have a retention rate of at least 90% after 18 months of clinical service to become fully accepted as a definitive restorative material.[36] In this study, after 24 months, the retention rate of EQUIA Forte Class II restorations was 93.7%. This suggests that the new reinforced GH performs well. So, the null hypothesis is accepted.

None of the restorations showed secondary caries or postoperative sensitivity. Their polishability was successful, and none of the restorations showed surface staining. This may be attributed to the resin coating applied to the surface of restorations. Only a few EQUIA Forte restorations showed slight changes in anatomic form (4.4%) and proximal contact points (2.2%), and three (6.3%) restorations failed during the 12-month follow-up. At the end of 24 months, only one (2.2%) EQUIA Forte restoration had slight discoloration at the restorative material-enamel interface. Much more important were the contact points on lateral ridges, which showed special risk of bulk fractures. Chipping of proximal marginal ridges was reported in earlier studies with conventional reinforced GIs.[12,37] The anatomic form loss seen in the present study in 4.4% of the GH restorations may have been caused by the intrinsic material parameters after abrasion of the surface

coating; the single proximal contact point loss and three failures may be due to the masticatory forces or stresses.

Besides physical properties, the esthetic properties of this material were enhanced by the small glass particles added to the material in different sizes and the application of the coating layer.[35,38] In the present study, color match was seen as the major problem. Six restorations, starting from baseline, showed mismatches in color during all evaluation periods. Controversially, Diem and others[17] reported that 25% of the GI restorations were evaluated as good at baseline but steadily increased to 80% as good at three years. Turkun and Kanik[34] also reported that difference in color was less visible after six years due to the improvement in translucency over time.

This clinical trial also included SEM analyses, as did a previous study, to examine the marginal adaptation and surface characteristics.[20] Twenty-four-month SEM evaluations supported the clinical observations. Both restorations showed acceptable occlusal and marginal characteristics.

On the other hand, the resin composite (G-ænial Posterior) used with a one-step self-etch adhesive (G-ænial Bond) showed clinically successful performance. All G-ænial Posterior restorations performed perfectly in all criteria at all evaluation periods. However, clinical data on resin composites used with self-etch adhesives in selective etch technique for the restoration of Class II cavities are limited, and there have been no long-term results yet. The evaluation period of the present study may not be long enough and further reports of long-term studies are needed to confirm the results of the present study. It should not be ignored that the clinical performance of these materials can also be affected by factors like operator skill.

CONCLUSIONS

The following conclusions may be drawn within the limitations of the present study:

1. Micro-hybrid resin composite showed clinically successful performance in the restoration of large Class II cavities after 24 months;
2. The GH restorative system showed significant mismatches in color and negligible failures, with no significant differences in retention, anatomic form, and proximal contact points;
3. The GH restorative system used could also be a viable option for restoring large Class II lesions.

Regulatory Statement

This study was conducted in accordance with all the provisions of the local human subjects oversight committee guidelines and policies of the Hacettepe University, Ankara, Turkey. The approval code for this study is 2015/KA-15053. This clinical trial was also registered in a clinical trial registry system under ClinicalTrials.gov ID: NCT02991664.

Conflict of Interest

The authors of this manuscript certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

(Accepted 18 February 2019)

REFERENCES

1. Rasines Alcaraz MG, Veitz-Keenan A, Sahrmann P, Schmidlin PR, Davis D, & Iheozor-Ejiofor Z (2014) Direct composite resin fillings versus amalgam fillings for permanent or adult posterior teeth *Cochrane Database of Systematic Reviews* **31(3)** CD005620, http://dx.doi.org/10.1002/14651858.CD005620.pub2.
2. Kielbassa AM, Glockner G, Wolgin M, & Glokner K (2016) Systematic review on highly viscous glass-ionomer cement/resin coating restorations (Part I): Do they merge Minamata Convention and minimum intervention dentistry? *Quintessence International* **47(10)** 813-823.
3. Kielbassa AM, Glockner G, Wolgin M, & Glokner K (2017) Systematic review on highly viscous glass-ionomer cement/resin coating restorations (Part II): Do they merge Minamata Convention and minimum intervention dentistry? *Quintessence International* **48(1)** 9-18.
4. Reichl FX, Durner J, Hickel R, Kunzelmann KH, Jewett A, Wang MY, Spahl W, Kreppel H, Moes GW, Kehe K, Walther U, Forth W, & Hume WR (2001) Distribution and excretion of TEGDMA in guinea pigs and mice *Journal of Dental Research* **80(5)** 1412-1415.
5. Reichl FX, Durner J, Kunzelmann KH, Hickel R, Spahl W, Hume WR, Moes GW, Kehe K, Walther U, & Forth W (2001) Biological clearance of TEGDMA in guinea pigs *Archives of Toxicology* **75(1)** 22-27.
6. Antony K, Genser D, Hiebinger C, & Windisch F (2008) Longevity of dental amalgam in comparison to composite materials *GMS Health Technology Assessment* **13(4)** 1-12.
7. Mahmoud SH, El-Embaby AE, & AbdAllah AM (2014) Clinical performance of ormocer, nanofilled, and nanoceramic resin composites in Class I and Class II restorations: A three-year evaluation *Operative Dentistry* **39(1)** 32-42.
8. Versluis A & Tantbirojn D (1999) Theoretical considerations of contraction stress *Compendium of Continuing Education in Dentistry* **(25)** 24-32; quiz S73.
9. Berg JH & Croll TP (2015) Glass ionomer restorative cement systems: An update *Pediatric Dentistry* **37(2)** 116-124.
10. Bonifacio CC, Werner A, & Kleverlaan CJ (2012) Coating glass-ionomer cements with a nanofilled resin *Acta Odontologica Scandinavica* **70(6)** 471-477.

11. Hickel R, Kaaden C, Paschos E, Buerkle V, Garcia-Godoy F, & Manhart J (2005) Longevity of occlusally-stressed restorations in posterior primary teeth *American Journal of Dentistry* **18(3)** 198-211.
12. Scholtanus JD & Huysmans MC (2007) Clinical failure of class-II restorations of a highly viscous glass-ionomer material over a 6-year period: a retrospective study *Journal of Dentistry* **35(2)** 156-162.
13. Frankenberger R, Garcia-Godoy F, & Kramer N (2009) Clinical performance of viscous glass ionomer cement in posterior cavities over two years *International Journal of Dentistry* 2009:781462, http://dx.doi.org/ 10.1155/2009/ 781462.
14. Mickenautsch S (2016) High-viscosity glass-ionomer cements for direct posterior tooth restorations in permanent teeth: The evidence in brief *Journal of Dentistry* **(55)** 121-123.
15. Mickenautsch S & Yengopal V (2015) Failure rate of direct high-viscosity glass-Ionomer versus hybrid resin composite restorations in posterior permanent teeth—A systematic review *Open Dentistry Journal* **22(9)** 438-448.
16. Friedl K, Hiller KA, & Friedl KH (2011) Clinical performance of a new glass ionomer based restoration system: A retrospective cohort study. *Dental Materials* **27(10)** 1031-1037.
17. Diem VT, Tyas MJ, Ngo HC, Phuong LH, & Khanh ND (2014) The effect of a nano-filled resin coating on the 3-year clinical performance of a conventional high-viscosity glass-ionomer cement *Clinical Oral Investigations* **18(3)** 753-759.
18. Klinke T, Daboul A, Turek A, Frankenberger R, Hickel R, & Biffar R (2016) Clinical performance during 48 months of two current glass ionomer restorative systems with coatings: A randomized clinical trial in the field *Trials* **17(1)** 239.
19. Gurgan S, Kutuk ZB, Ergin E, Oztas SS, & Cakir FY (2015) Four-year randomized clinical trial to evaluate the clinical performance of a glass ionomer restorative system *Operative Dentistry* **40(2)** 134-143.
20. Gurgan S, Kutuk ZB, Ergin E, Oztas SS, & Cakir FY (2017) Clinical performance of a glass ionomer restorative system: A 6-year evaluation *Clinical Oral Investigations* **21(7)** 2335-2343.
21. Schwendicke F, Kniess JLM, Paris S, & Blunck U (2017) Margin integrity and secondary caries of lined or non-lined composite and glass hybrid restorations after selective excavation in vitro *Operative Dentistry* **42(2)** 155-164.
22. Casagrande L, Dalpian DM, Ardenghi TM, Zanatta FB, Balbinot CE, Garcia-Godoy F, & De Araujo FB (2013) Randomized clinical trial of adhesive restorations in primary molars. 18-month results. *American Journal of Dentistry* **26(6)** 351-355.
23. Silness J & Loe H (1964) Periodontal disease in pregnancy. II. Correlation between oral hygiene and periodontal condtion. *Acta Odontologica Scandinavica* **22(Feb)** 121-135.
24. Palaniappan S, Bharadwaj D, Mattar DL, Peumans M, Van Meerbeek B, & Lambrechts P (2009) Three-year randomized clinical trial to evaluate the clinical performance and wear of a nanocomposite versus a hybrid composite *Dental Materials* **25(11)** 1302-1314.
25. Leprince JG, Palin WM, Hadis MA, Devaux J, & Leloup G (2013) Progress in dimethacrylate-based dental composite technology and curing efficiency *Dental Materials* **29(4)** 139-156.
26. Jang JH, Park SH, & Hwang IN (2015) Polymerization shrinkage and depth of cure of bulk-fill resin composites and highly filled flowable resin *Operative Dentistry* **40(2)** 172-180.
27. Baig MS & Fleming GJP (2015) Conventional glass-ionomer materials: A review of the developments in glass powder, polyacid liquid and the strategies of reinforcement *Journal of Dentistry* **43(8)** 897-912.
28. Mickenautsch S & Yengopal V (2015) Do laboratory results concerning high-viscosity glass-ionomers versus amalgam for tooth restorations indicate similar effect direction and magnitude than that of controlled clinical trials? A meta-epidemiological study *Public Library of Science One* **10(7)** http://dx.doi.org/10.1371/journal.pone. 0132246.
29. Barata TJE, Bresciani E, Fagundes TC, Cefaly DFG, Lauris JRP, & Navarro MFL (2008) Fracture resistance of Class II glass-ionomer cement restorations *American Journal of Dentistry* **21(3)** 163-167.
30. McCracken MS, Gordan VV, Litaker MS, Funkhouser E, Fellows JL, Shamp DG, Qvist V, Meral JS, & Gilbert GH (2013) A 24-month evaluation of amalgam and resin-based composite restorations findings from the national dental practice-based research network *Journal of the American Dental Association* **144(6)** 583-593.
31. Bernardo M, Luis H, Martin MD, Leroux BG, Rue T, Leitao J, & DeRouen TA (2007) Survival and reasons for failure of amalgam versus composite posterior restorations placed in a randomized clinical trial *Journal of the American Dental Association* **138(6)** 775-783.
32. Opdam NJ, Bronkhorst EM, Loomans BA, & Huysmans MC (2010) 12-year survival of composite vs. amalgam restorations *Journal of Dental Research* **89(10)** 1063-1067.
33. Mickenautsch S & Yengopal V (2016) Caries-preventive effect of high-viscosity glass ionomer and resin-based fissure sealants on permanent teeth: A systematic review of clinical trials *Public Library of Science One* **11(1)** e0146512.
34. Turkun LS & Kanik O (2016) A prospective six-year clinical study evaluating reinforced glass ionomer cements with resin coating on posterior teeth: Quo vadis? *Operative Dentistry* **41(6)** 587-598.
35. Ong JEX, Yap AU, Hong JY, Eweis AH, & Yahya NA (2018) Viscoelastic properties of contemporary bulk-fill restoratives: A dynamic-mechanical analysis *Operative Dentistry* **43(3)** 307-314.
36. Hickel R, Peschke A, Tyas M, Mjor I, Bayne S, Peters M, Hiller KA, Randall R, Vanherle G, & Heintze SD (2010) FDI world dental federation—Clinical criteria for the evaluation of direct and indirect restorations update and

clinical examples *Journal of Adhesive Dentistry* **12(4)** 259-272.

37. Grogono AL, McInnes PM, Zinck JH, & Weinberg R (1990) Posterior composite and glass ionomer/composite laminate restorations: 2-year clinical results *American Journal of Dentistry* **3(4)** 147-152.

38. Lohbauer U, Kramer N, Siedschlag G, Schubert EW, Lauerer B, Muller FA, Petschelt A, & Ebert J (2011) Strength and wear resistance of a dental glass-ionomer cement with a novel nanofilled resin coating *American Journal of Dentistry* **24(2)** 124-128.

©Operative Dentistry, 2020, **45-3,** 255-264

The Dental Amalgam Phasedown in New Zealand: A 20-year Trend

JM Broadbent • CM Murray • DR Schwass • M Brosnan
PA Brunton • KS Lyons • WM Thomson

Clinical Relevance

This research reports how amalgam has reached the verge of elimination from clinical service in New Zealand's dental education system. New Zealand's national school of dentistry is prepared for New Zealand's expected ratification of the Minamata Convention on Mercury.

SUMMARY

Background and Objectives: Information on the choice of material and performance of restorations placed in a dental practice annually is limited. The Minamata Convention on Mercury is likely to affect the use of amalgam worldwide. The objective of this research was to investigate the use of restorative materials at the University of Otago Faculty of Dentistry in New Zealand from 1998 to 2017.

Methods: Data from the Faculty of Dentistry's database from the years of interest were compiled. These data included information on the characteristics of restorations, including information on the material used and number of surfaces involved for each restoration. The tooth in which each restoration was placed was categorized by arch, tooth type, and deciduous or permanent dentition.

Results: Records identified 227,514 permanent restorations placed from January 1998 to December 2017, of which 91.7% were direct restorations. Among direct restorations, composite resin was the most commonly used material, followed by amalgam, glass ionomer, and compomer. The use of amalgam for direct restorations decreased from 52.3% of direct restorations in 1998 to 7.1% in 2017. A corresponding increase was observed in the use of tooth-colored direct restorations, particularly composites. Among indirect restorations, porcelain fused to metal, gold, and stainless steel

*Jonathan M Broadbent, BDS, PGDipComDent, PhD, associate professor, Dental Public Health, Faculty of Dentistry, University of Otago, Dunedin, New Zealand

Colleen M Murray, BChD, BChD(Hons), BDS, PGDipClinDent, BEd, senior lecturer, University of Otago, Dunedin, New Zealand

Donald R Schwass, BSc, BDS, DClinDent, clinical director, Faculty of Dentistry, University of Otago, Dunedin, New Zealand

Mike Brosnan, BDS, MDentSci, Waikato District Health Board, Maxillofacial Oral Surgery and Dental Department, Waikato Hospital, Hamilton, New Zealand

Paul A Brunton, BChD, MSc, PhD, pro-vice-chancellor, Division of Health Sciences, University of Otago, Dunedin, New Zealand

Karl Lyons, MDS, PhD, acting dean and professor, Prosthodontics, Oral Rehabilitation, University of Otago, Dunedin, New Zealand

Murray Thomson, BDS, MA, MComDent, PhD, professor, Dental Public Health, Faculty of Dentistry, Otago University, Dunedin, New Zealand

*Corresponding author: PO Box 56, Dunedin, Otago 9016, New Zealand; e-mail: jonathan.broadbent@otago.ac.nz

https://doi.org/10.2341/19-024-C

(in pediatric applications) were the materials most frequently used.

Conclusions: Despite having no official policy on reducing the use of dental amalgam, the Faculty of Dentistry is following the global trend in reducing its use, with composite resin now well established as the predominant restorative material used. If the current rate of decline persists unchecked, the Faculty of Dentistry could transition to being amalgam free by 2020, although it seems likely that the characteristics and principles of use of the material (and its removal) will be taught for some time to come. This knowledge is important to planning curriculum changes needed to prepare graduates for clinical practice.

INTRODUCTION

The annual cost of dental care in New Zealand was estimated at $1.1 billion in 2008 (New Zealand Ministry of Health, personal communication, April 15, 2011) and is attributable mostly to the placement and maintenance of dental restorations. The materials used for these dental restorations vary in their range of characteristics, including biocompatibility, longevity, aesthetics, and cost. Despite the important differences among these dental restorative materials, few data have been reported on changing practitioner and patient preferences regarding their use in New Zealand. There is a lack of published information on how many restorations are placed annually in a typical dental practice and what materials are typically used.

Historically, dental amalgam was the material of choice in restorative dentistry worldwide. The use of alternative dental materials was limited by a lack of satisfactory options. Early tooth-coloured restorations were not considered to be as reliable as amalgam, with 10-year failure rates reported as high as 50%.[1] Modern tooth-colored restorations have improved reliability, and clinical experience suggests that amalgam is now giving way to alternatives, but data are lacking on the extent to which these changes have occurred. Many New Zealand dental practices have chosen to become amalgam free and advertise as such, while others continue to use amalgam in a wide range of clinical applications.

A limited number of international studies have reported on changes in the use of dental restorative materials over time. A British study reported on changes at the University College Cork when their dental faculty was in the process of change from dental amalgam to composites as the material of first choice. The investigators noted a substantial shift toward the use of composites in place of amalgam,[2] but since they were making an active transition, this finding is unsurprising. Evidence is lacking on what changes are happening in wider dental practice where an active transition has not been implemented.

New Zealand's signing of the Minamata Convention on Mercury in October 2013 has the potential to substantially affect the use of amalgam in dentistry in this country. New Zealand's eventual ratification of the convention will require dentists (and the dental education system) to take steps to reduce population exposure to mercury. These steps include requirements to

1) set national objectives aiming at dental caries prevention and health promotion, thereby minimizing the need for dental restoration;
2) set national objectives aiming at minimizing use of dental amalgam;
3) promote the use of cost effective and clinically effective mercury-free alternatives for dental restoration;
4) promote research and development of quality mercury-free materials for dental restoration;
5) encourage representative professional organizations and dental schools to educate and train dental professionals and students on the use of mercury-free dental restoration alternatives and on promoting best management practices;
6) discourage insurance policies and programs that favor dental amalgam use over mercury-free dental restoration;
7) encourage insurance policies and programs that favor the use of quality alternatives to dental amalgam for dental restoration;
8) restrict the use of dental amalgam to its encapsulated form; and
9) promote the use of best environmental practices in dental facilities to reduce releases of mercury and mercury compounds to water and land.

Concerns about environmental effects of mercury (as indicated in the Minimata Convention on Mercury), combined with the increasing availability of products with qualities that surpass dental amalgam in most respects, mean it is very likely that dental amalgam will be phased out of use in the foreseeable future. Indeed, the phasedown of the use of dental amalgam as part of the Minimata Convention on Mercury is one of the five main projects of the

World Health Organization's Oral Health Workplan 2018-2020. The World Health Organization intends to provide assistance to low-income countries to accelerate their phasedowns of amalgam use over the timeline of April 2018 to December 2023.

The aim of this research was to identify whether patterns changed in the use of dental amalgam relative to other dental materials during the period 1998-2017 at New Zealand's only dental faculty and to compare this with available data from private clinical dental practice. The authors hypothesized that the use of amalgam would have decreased considerably in favor of tooth-colored alternatives, even in the absence of an active effort to reduce the use of amalgam. This research was conducted to inform possible teaching and curriculum changes at the faculty and to promote debate on the how the New Zealand dental profession should prepare for the imminent amalgam-free future of dentistry.

METHODS

Data on restorations placed at the University of Otago Faculty of Dentistry were obtained by extracting this information from the faculty's database (Titanium, Spark Dental Ltd, Auckland, New Zealand). Data were managed and analysed in Intercooled Stata 15.1 (Statacorp LP, College Station, TX, USA). Data on nonrestorative procedures were not included in analyses. Restorations with a valid recorded date of completion between January 1998 and December 31, 2017 were included.

Information on the material used for each restoration was categorized based on the service code recorded for each restoration. Where recording was ambiguous and it was not possible to ascertain the material used, the restoration was included in counts of total number of restorations but excluded from the specific restoration material category. Restorations of unknown material types are reported in summary data and totals. All temporary restorations were excluded from analyses. Where glass ionomer cement restorations were not coded as temporary restorations, they were included in analyses of glass ionomer cement restorations. Inlay, onlay, veneer, and crown restorations were included, but restorations involving tooth replacement (such as fixed partial dentures bridges and implant crowns) were excluded.

The number of surfaces involved in a given restoration was categorized based on the restoration surface code. Student year of study was categorized; analyses of student output were restricted to the years of undergraduate study to avoid misclassification of work completed by individuals returning to the faculty for postgraduate study or as staff. Teeth were categorized by arch, tooth type, and dentition (permanent vs deciduous). Where data were missing on the specific tooth that had been restored, those restorations were excluded from the analyses.

As part of a survey of dentists conducted in New Zealand during 2016, we included some questions on their use of dental materials. The survey sample included 353 New Zealand oral health practitioners (65.7% dentists and the remainder allied oral health practitioners) and methods used for that research have been described previously.[3] As part of the questionnaire, participants were asked to estimate the percentage of restorations they had placed during the past year using a range of restorative materials (composite, amalgam, glass ionomer cement, ceramic, other) and to rank their relative preference for restorative material to work with. These data were contrasted with faculty results for 2016 to provide wider context of the use of dental materials in New Zealand dental practice.

RESULTS

Records were available for 311,306 restorations placed from 1998 to 2017. This number included 83,792 temporary restorations, leaving a total of 227,514 permanent restorations, of which 91.7% were direct and the remainder indirect. Most indirect restorations were gold (of which over 90% were crowns and the remainder inlays or onlays), stainless steel (deciduous) crowns, and porcelain-fused-to-metal crowns, as well as a number of cast core restorations and all-ceramic crowns (Table 1). During the 20 years, over half of direct restorations were placed using composite resin, while amalgam was used for just under a third, while the remainder included glass ionomer cement, compomer, nonmetallic materials of unspecified type and unspecified materials. Wide differences in the use of dental materials were observed over time. The use of amalgam for dental restorations became less common, decreasing from over half of direct restorations placed in 1998 to fewer than one in 10 restorations placed in 2017 (Figure 1).

Respondents to the survey of New Zealand dental practitioners estimated that an average of 14.5% of direct restorations they had placed within the previous year were amalgam (Figure 1). Among dentists (n=158), 63.5% rated composite as their most preferred restorative material, while amalgam was favored by 12.6%. Among dental therapists

Table 1: *Restorations Placed by Material Type by Year as a Percentage of Total Restorations Placed per Year*

Year	% of Total Direct Restorations						
	Amalgam	Composite	Glass Ionomer Cement[a]	Compomer[b]	Nonspecific Material	Nonspecific Nonmetallic	Total Number of Direct
1998	52.3	47.5	0.0	0.0	0.2	0.0	**9760**
1999	48.3	50.8	0.0	0.6	0.3	0.0	**9911**
2000	47.4	51.1	1.0	0.3	0.3	0.0	**10,725**
2001	43.0	47.7	8.5	0.6	0.3	0.0	**11,744**
2002	39.3	44.1	13.1	1.1	2.3	0.1	**11,471**
2003	36.2	41.8	17.4	1.1	2.9	0.6	**10,607**
2004	34.3	38.7	15.1	0.9	7.4	3.7	**10,232**
2005	36.4	38.5	13.9	0.5	6.5	4.3	**11,173**
2006	34.5	45.9	13.3	2.7	0.2	3.4	**10,564**
2007	33.4	48.0	12.6	2.4	0.6	3.0	**10,020**
2008	30.4	51.0	12.7	3.2	0.0	2.7	**10,957**
2009	30.1	52.3	12.8	2.2	0.0	2.7	**10,358**
2010	26.7	55.6	13.0	2.1	0.0	2.7	**11,218**
2011	28.2	54.0	14.0	1.5	0.0	2.3	**10,030**
2012	24.2	56.3	15.0	2.4	0.0	2.1	**10,137**
2013	21.5	58.0	15.5	2.6	0.0	2.5	**10,838**
2014	16.5	61.4	15.4	3.3	0.2	3.2	**10,135**
2015	14.4	59.2	16.9	0.9	3.9	4.7	**10,122**
2016	11.7	63.8	16.4	0.1	3.8	4.3	**9286**
2017	7.6	67.9	16.1	0.0	4.1	4.4	**9376**

[a] *Prior to 2001 placement of glass ionomer cement restorations may not have always been recorded.*
[b] *After 2015, compomer restorations started to be coded as nonspecific material restorations and are recorded as a "nonspecific material." It is likely that these are compomer, but data are unavailable.*

(n=70), composite was most preferred by 31.4% and amalgam by 15.7%.

The number of single surface composite resin restorations placed annually remained relatively constant through the 20-year period, but the number of 2- and 3+-surface restorations for which composite resin was used increased markedly. In particular, the latter increased from 10% of 3+-surface restorations in 1998 to 90% of those in 2017. By contrast, there was a decrease in the use of dental amalgam for direct restoration of all sizes (Figure 2).

Major changes were seen in the student learning experience in recent years. Prior to 2013, nearly every Bachelor of Dental Surgery (BDS) student placed at least one amalgam restoration on a patient during each year of study, and most had placed a complex (3+ surfaces) restoration. However, complex amalgam restorations were placed by only 19.5% of BDS3, 38.2% of BDS4, and 80.2% of BDS5 students during 2017, and a small number of students had gone through all years of education having placed amalgam only in a "simulation clinic" context without placing any amalgam restorations at all in a clinical setting (Figure 3). Within the BDS graduating class of 2017, an average of 77.6 restorations had been placed throughout their clinical education (BDS years 2-5); of those, an average of 7.8 were amalgam (10.1%), an average of 3.1 being complex 3+ surface amalgam restorations. On the other hand, among those in BDS5 during 2003, the average total number of restorations was 121.4; of those, an average of 53.3 were amalgam (43.9%), of which 20.0 were complex 3+ surface amalgam restorations. These differences were statistically significant ($p<0.0001$, Wilcoxon rank-sum test).

By tooth type, the greatest decline in the use of dental amalgam was in its use as a restorative material for deciduous teeth, dropping from over 80% in 1998 to 0% in 2017. Dental amalgam was used for over 80% of restorations in permanent molars in 1998, but this decreased to fewer than 20% in 2017 (Figure 4).

DISCUSSION

This descriptive study reports a marked decrease in the use of dental amalgam at New Zealand's only dental faculty over the 20-year period 1998-2017.

Table 1: *Restorations Placed by Material Type by Year as a Percentage of Total Restorations Placed per Year (ext.)*

Year	% of Total Indirect Restorations						
	Gold	Porcelain	Porcelain Fused to Metal	Belle Glass or Acrylic	Stainless Steel	Cast Core	Total Number of Indirect
1998	20.4	5.7	38.1	0.5	24.7	10.7	**778**
1999	16.9	4.3	34.8	1.5	36.5	6.1	**1007**
2000	19.3	4.8	27.9	0.9	39.2	8.0	**1019**
2001	16.8	3.6	32.2	1.8	37.6	8.1	**916**
2002	18.2	3.5	29.1	1.5	39.6	8.0	**1020**
2003	19.7	5.3	33.5	1.4	32.1	8.0	**865**
2004	21.2	3.0	38.5	0.8	26.9	9.7	**920**
2005	24.2	10.8	37.8	0.0	20.1	7.1	**986**
2006	25.1	9.1	41.4	0.0	18.4	6.0	**1048**
2007	28.4	6.8	39.7	0.1	17.7	7.4	**843**
2008	28.4	5.8	43.5	0.3	15.5	6.5	**904**
2009	28.9	9.4	46.2	0.0	10.6	4.9	**1251**
2010	27.2	6.2	38.3	0.0	22.8	5.6	**1307**
2011	27.4	7.1	30.3	0.0	30.2	5.1	**1015**
2012	27.3	5.1	37.2	0.0	26.8	3.6	**889**
2013	34.6	3.8	30.8	1.3	25.8	3.9	**955**
2014	37.2	9.0	29.0	0.1	22.0	2.7	**996**
2015	32.2	9.0	26.2	0.7	29.2	2.6	**832**
2016	31.1	8.3	24.8	0.0	33.0	2.9	**701**
2017	34.6	10.5	20.9	0.0	31.9	2.0	**598**

Although the total number of restorations placed per year remained relatively constant, the choice of dental material used, specifically amalgam, shifted markedly with the passage of time. The pace of increase in the use of composite resin appeared to be greater after 2005.

Before considering the implications of these findings, it is important to consider the relative strengths and limitations of this research. One limitation is the change in coding of dental restorations over time, affecting the comparability of data from 1998 to 2001 with the data from subsequent years; however, categories were similar and this is unlikely to have had any impact on the research findings. Another change in coding made surface-level data less accessible after 2015. Variation in the number of students (particularly those enrolled in postgraduate programs) and staff may have affected the service mix for certain years, and this has not been considered in this analysis. The period 2002-2005 featured a large number of restorations that were coded using identifiers from which it was not possible to identify the restorative material type used; these were mostly one- and two-surface restorations and were likely to have used composite or amalgam. Notwithstanding these limitations, the study has a number of strengths, chief of which is the fact that no similar information is available.

The scope of this study did not include survival rates of those restorations included in the analysis; details of techniques used, such as dental dam use, bonding system, curing protocols, and case selection; or the specific brands that had been used.

In the past, the choice of dental material was generally based on operator and patient preferences, which relate to factors such as an individual's caries risk, lesion size and location, and material-related factors such as strength, wear resistance, moisture tolerance, and stability. New Zealand's signing (and expected future ratification) of the Minamata Convention on Mercury will play an important role in this decision making in the future, hastening an existing global change within the dental profession, which, to date, has largely been in response to the growing evidence base for (and continuing clinical experience with) the use of composite resins.

It is important that dental education be informed by high-quality research and also consider the future environment in which graduates will practice. Crucial to this approach will be that new cohorts of dental students are taught considering both the

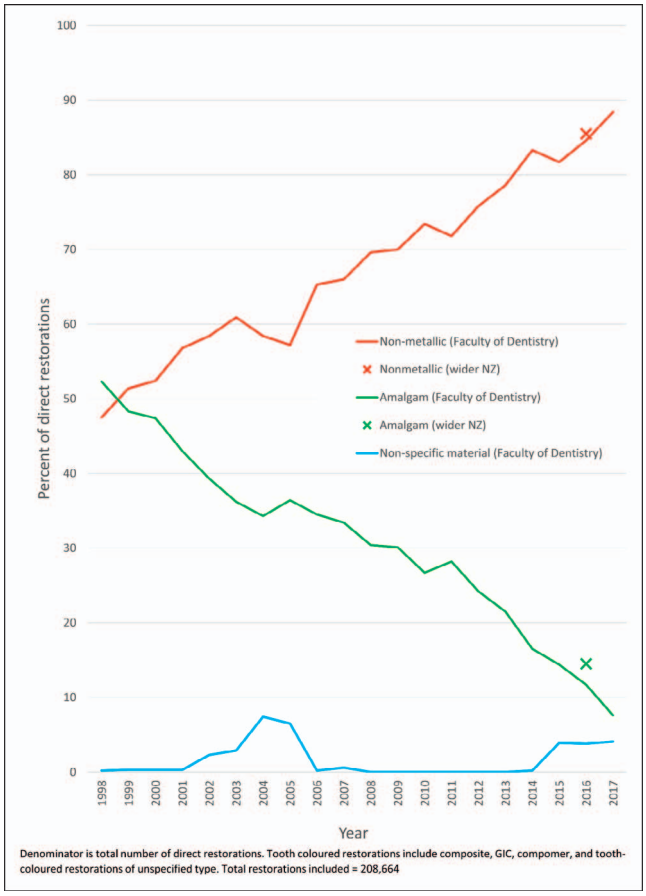


Figure 1. *Annual placement of direct restorations by material type.*

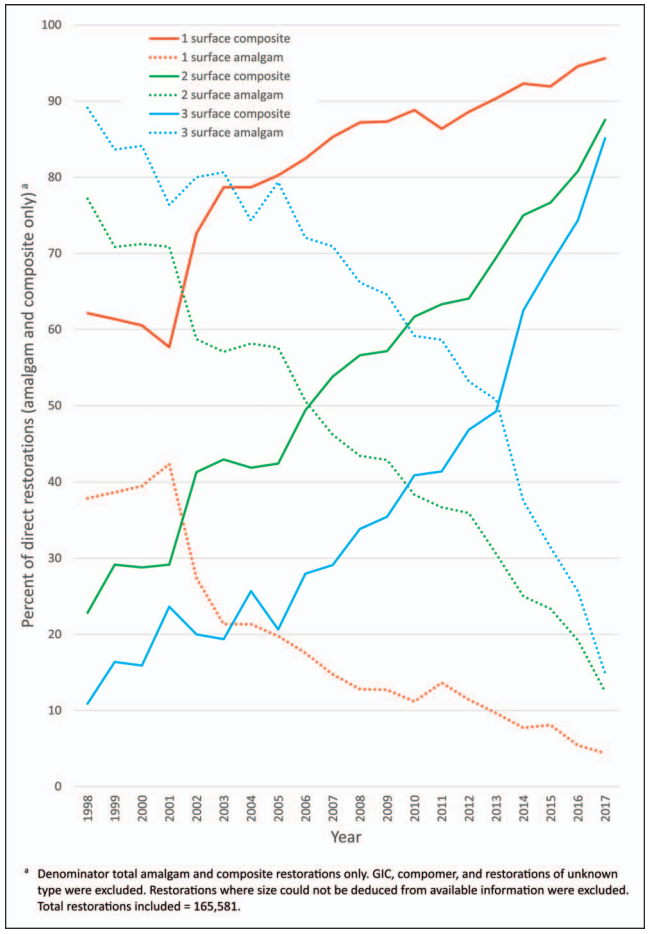


Figure 2. *Percent of restorations placed per year by material type and restoration size.*

obligations outlined in the Minamata Convention and the requirement for evidence-based clinical practice: theoretical teaching needs to be matched to clinical teaching. Based on a projection from the current decline in the use of dental amalgam (Figure 1), the material is unlikely to be used at all by the early 2020s. The teaching curriculum needs to be updated accordingly to enable teaching to adapt to this likely outcome.

Dental education can influence both material selection and the associated techniques used by future members of the dental profession. Experience suggests that some new dental graduates initially continue to use the materials and techniques with which they have become familiar and competent during their dental education. Moreover, the provision of continuing professional education courses by the faculty may affect material selection decisions by established practitioners. Such an approach should be informed by research into the contemporary material selection and techniques used by New Zealand dental practitioners.

Median survival times for amalgam restorations have been reported to be as long as 22.5 years,[4] meaning that amalgam restorations have historically been considered the benchmark by which to compare composite restorations. The use and clinical performance of composite resin restorations placed in posterior permanent teeth have improved greatly. Some consider that composite now performs better than amalgam. Although composite resin has many disadvantages—such as marginal staining and poorer wear strength, fracture resistance, and compressive strength than amalgam—it does have a number of important advantages. Cavity preparation for the restoration of a carious lesion with composite resin can be more conservative than with dental amalgam because mechanical retention does not need to be incorporated into the cavity design. This lowers the biological cost to the tooth. It also has superior esthetics and the ability to bond to both enamel and dentin (via a suitable adhesive system), thus sealing the tooth-restorative interface and reducing occlusal

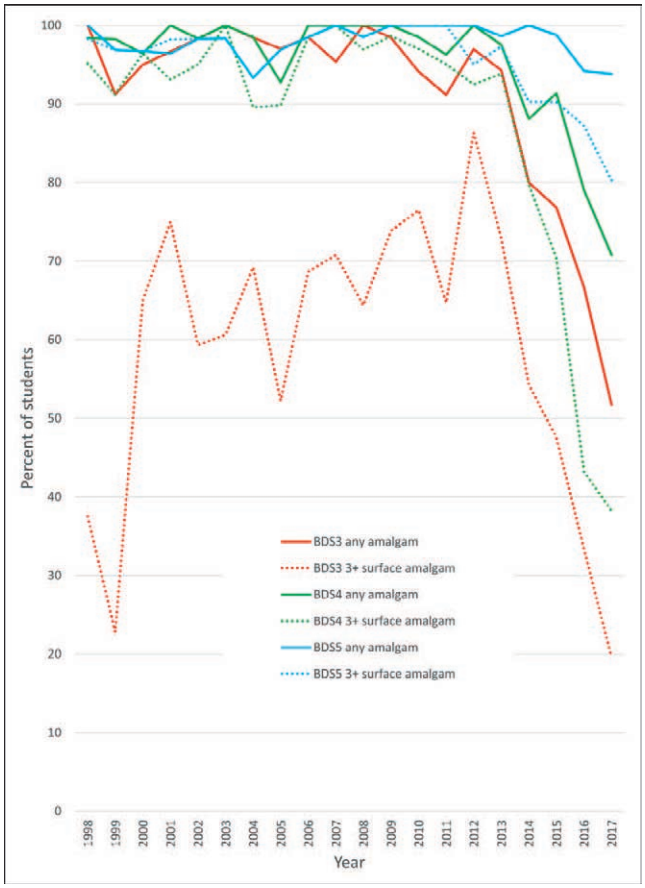


Figure 3. *Percent of students to have placed one or more amalgam restorations during each year of study. Solid lines = any; dotted lines = three+ surfaces.*

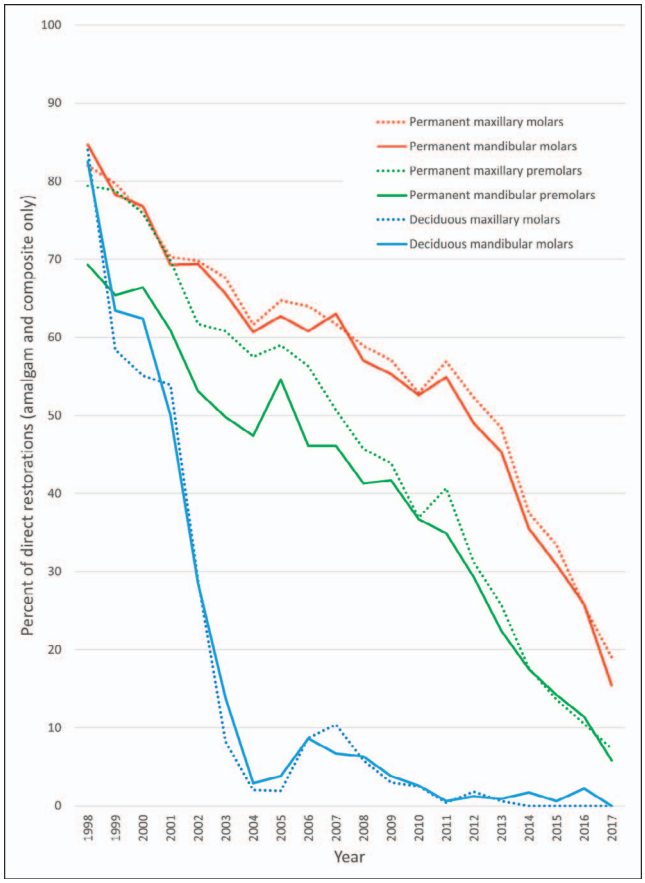


Figure 4. *Percent of restorations placed using amalgam per year by tooth type.*

stresses on both the composite resin and the restored tooth.[5] Although composite resin restorations may require more frequent repair,[6] the ability to successfully repair and/or refurbish a restoration avoids its complete removal and the associated further loss of tooth structure.

In deciduous teeth, short crown heights affect the retention of intracoronal restorations, as does a child's ability to cope with treatment. Preformed metal crowns show very high success rates, with greater longevity and lower rates of retreatment than amalgam restorations in primary molars.[7] They are of particular use in teeth that are extensively broken down or have severe enamel defects. Although amalgam is a forgiving material where moisture control is a problem and it can be placed without using dental dam, the National Health and Medical Research Council of Australia (1999) has recommended that placing or removing amalgam from children's dentitions be avoided. While effective moisture control is essential in the placement of high-quality composite restorations, those can be successful in class I and class II restorations in children. According to the 2014 guidelines of the American Academy of Pediatric Dentistry, there are not enough data comparing compomers to other restorative materials in children's permanent teeth for them to be considered the treatment of choice; however, they can be used as an alternative to other restorative materials in class I and class II restorations in primary teeth. A review of the evidence concluded that amalgam, resin-modified glass ionomers, and compomers showed similar longevity in primary teeth but that conventional glass ionomers showed significantly shorter longevity.[8] Conventional glass ionomers should be used only as either a temporary measure to stabilize a carious dentition in the early stages of treatment or an interim restoration when a tooth is close to exfoliation. For amalgam, its material physical properties are least often the source of problems, with most failures attributable to lack of attention to cavity design or handling of the material in use.[9]

Although dentists are often more concerned with the disadvantages of composite resin, patient concerns about the risks of amalgam toxicity and their greater esthetic awareness may supersede these concerns. When preferences for the choice of material differ between patient and dental professional, dentists tend to defer to patient choice in favor of composite resin.[10] Norwegian dentists tend to favor composites when treating younger patients, except where more complicated restorative challenges are encountered. In such cases, dentists are more likely to select amalgam as the restorative material.[11] Experience from practice suggests that where direct placement of composite resin is problematic due to the extensive nature of the preparation, many dentists may now select an indirect tooth-colored restoration rather than default back to dental amalgam. In the past, high caries risk was often considered a contraindication to the use of composite resins. In an amalgam-free clinical service, material choice is no longer a factor. Instead of relying on case selection to identify high-caries patients where composite is not appropriate, clinicians must instead focus solely on managing caries risk. Good caries risk management is now the single most important factor in determining the long-term success of direct restorations. Some practitioners place very extensive direct composite resin restorations with satisfactory clinical results, at least in the short term.

More research is required to investigate the long-term success of these types of treatments. A recent Cochrane systematic review of restoration performance found that composite restorations are associated with a higher risk of failure and greater risk of secondary caries than amalgam restorations,[12,13] and long-term evidence supporting composite performance is weak. Mechanical causes of failure, such as fractures, start appearing from about the two-year mark, reflecting the appropriateness of decisions made to use the material for individual situations and limitations with respect to the physical properties of these materials in terms of compressive strength, tensile strength, and fracture toughness. Biological causes of failure, such as dental caries, tend to increase more gradually over time.[14] Marginal failure at the bond interface is associated with a significant proportion of these infection-related failures reported. With the rapid evolution of successive generations of resin bonding systems, findings from clinical trials quickly become obsolete as technology advances supersede the limitations of previous product generations. Although it is expected that continued advances in dental materials should inform improved bonded restoration longevity, direct evidence demonstrating so remains relatively weak considering dentin to resin bonds degrade much faster than clinical restorations take to fail.[15]

Larger composite restorations have a higher risk for failure, with each additional surface involved increasing the risk by 30%-40%.[14] A systematic review and meta-analysis indicated annual failure rates of 2.4% for posterior composite restorations after 10 years,[14] informing cause for optimism to expect favorable performance over the medium to long term. Clinician skill is considered very important when placing composite restorations, with younger practitioners more likely to have had a greater proportion of their training focused on placing composite resins rather than amalgam.[16]

Since this study has examined the changing patterns in the use of dental amalgam in favor of tooth-colored alternatives in a dental school setting in New Zealand, it is important to look at what is happening in teaching facilities elsewhere. Much of the available literature is dated, with surveys of the teaching of posterior composites in dental schools worldwide carried out from the late 1980s to the mid-2000s.[17-24] More recently, however, a survey of 100 dental schools was conducted to obtain information on preclinical teaching and material preferences for the restoration of posterior teeth as well as expected future changes.[25] All 46 respondents reported that they taught composite resin for restoring posterior teeth, with nearly two-thirds of these not teaching amalgam as the preferred material and one Swedish school not having taught amalgam use since 2005.

The increasing use of composite resin observed at the University of Otago Faculty of Dentistry is similar (although more marked over the long term) to that which was reported by an Israeli dental school where the use of composite resin increased from 36.8% of restorations placed in 2004-2005 to 48.5% in 2008-2009.[26] That study found that the preferred dental material among younger dental instructors was composite resin, but veteran instructors were more likely to select amalgam. This pattern is mirrored in general dental practice,[22] and older practitioners may be less likely to opt for a more contemporary restorative material.

The current New Zealand government intends to ratify the Minamata Convention on Mercury, but more pressing legislative priorities mean this is unlikely to occur before the end of 2019 (New

Zealand Ministry for the Environment, personal communication, November 23, 2018). Thus, New Zealand's dental education system does not yet have an obligation to phase down dental amalgam; however, considerable progress in advance of its future obligations under the Minamata Convention have already been made. The University of Otago Faculty of Dentistry is arguably already engaged in all the nine strategies identified in the text of the convention that are likely to reduce the use of mercury dental amalgam in New Zealand. For example, the faculty is involved in dental caries prevention and health promotion training and research (objective 1) and conducts a considerable amount of research on the properties of amalgam alternatives (objective 2), while research and development of mercury amalgams has effectively ceased (objectives 3 and 4), students receive more training on amalgam alternatives than amalgam (objective 5), publicly funded services (particularly pediatric dental care) allow for the use of amalgam alternatives (objectives 6 and 7), the use of amalgam is restricted to its encapsulated form (objective 8), and appropriate environmental strategies are employed to minimize the environmental release of mercury (objective 9). It would appear that the Faculty is already meeting these obligations, although action in certain areas may be enhanced.

The University of Otago Faculty of Dentistry is following global trends in the phasedown of dental amalgam, and available private practice data suggest that this is also occurring throughout New Zealand. Dental composites have replaced dental amalgams as the major alternative material of choice. Ongoing curriculum changes are recommended to ensure that graduates are prepared for contemporary clinical practice, and ongoing training of teaching staff is necessary to ensure that experienced practitioners adapt their teaching with the changing curriculum.

Regulatory Statement

This study was conducted in accordance with all the provisions of the local human subjects oversight committee guidelines and policies of the University of Otago. The approval codes for this study are D16/065 and HD15/017.

Conflict of Interest

The authors of this article certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

(Accepted 2 May 2019)

REFERENCES

1. Raskin A, Michotte-Theall B, Vreven J, & Wilson NH (1999) Clinical evaluation of a posterior composite 10-year report *Journal of Dentistry* **27(1)** 13-19.
2. O'Sullivan CO, McKenna GJ, & Burke FM (2012) Trends in material choice for direct restorations by final year students from University College Cork 2004-2009 *European Journal of Prosthodontics and Restorative Dentistry* **20(1)** 31-34.
3. Hong CL, Lamb AW, Broadbent JM, De Silva HL, & Thomson WM (2017) An update on New Zealand oral health practitioners' preparedness for medical emergencies *New Zealand Dental Journal* **113(4)** 5-12.
4. Soares AC & Cavalheiro A (2010) A review of amalgam and composite longevity of posterior restorations *Revista Portuguesa de Estomatologia, Medicina Dentária e Cirurgia Maxilofacial* **51** 155-164.
5. Burgess JO, Walker R, & Davidson JM (2002) Posterior resin-based composite: Review of the literature *Pediatric Dentistry* **24(5)** 465-479.
6. Soncini JA, Maserejian NN, Trachtenberg F, Tavares M, & Hayes C (2007) The longevity of amalgam versus compomer/composite restorations in posterior primary and permanent teeth: Findings from the New England Children's Amalgam Trial *Journal of the American Dental Association* **138(6)** 763-772.
7. Randall RC, Vrijhoef MM, & Wilson NH (2000) Efficacy of preformed metal crowns vs. amalgam restorations in primary molars: A systematic review *Journal of the American Dental Association* **131(3)** 337-343.
8. Qvist V, Poulsen A, Teglers PT, & Mjor IA (2010) The longevity of different restorations in primary teeth *International Journal of Paediatric Dentistry* **20(1)** 1-7, 10.1111/j.1365-263X.2009.01017.x
9. Harris RK (1992) Dental amalgam: Success or failure? *Operative Dentistry* **17(6)** 243-252.
10. Espelid I, Cairns J, Askildsen JE, Qvist V, Gaarden T, & Tveit AB (2006) Preferences over dental restorative materials among young patients and dental professionals *European Journal of Oral Sciences* **114(1)** 15-21, 10.1111/j.1600-0722.2006.00282.x
11. Vidnes-Kopperud S, Tveit AB, Gaarden T, Sandvik L, & Espelid I (2009) Factors influencing dentists' choice of amalgam and tooth-colored restorative materials for class II preparations in younger patients *Acta Odontologica Scandinavica* **67(2)** 74-79, 10.1080/00016350802577800
12. Moraschini V, Fai CK, Alto RM, & Dos Santos GO (2015) Amalgam and resin composite longevity of posterior restorations: A systematic review and meta-analysis *Journal of Dentistry* **43(9)** 1043-1050, 10.1016/j.jdent.2015.06.005
13. Rasines Alcaraz MG, Veitz-Keenan A, Sahrmann P, Schmidlin PR, Davis D, & Iheozor-Ejiofor Z (2014) Direct composite resin fillings versus amalgam fillings for permanent or adult posterior teeth *Cochrane Database of Systematic Reviews***(3)** CD005620, 10.1002/14651858.CD005620.pub2
14. Opdam NJ, van de Sande FH, Bronkhorst E, Cenci MS, Bottenberg P, Pallesen U, Gaengler P, Lindberg A,

Huysmans MC, & van Dijken JW (2014) Longevity of posterior composite restorations: A systematic review and meta-analysis *Journal of Dental Research* **93(10)** 943-949, 10.1177/0022034514544217

15. Carvalho RM, Manso AP, Geraldeli S, Tay FR, & Pashley DH (2012) Durability of bonds and clinical success of adhesive restorations *Dental Materials* **28(1)** 72-86, 10. 1016/j.dental.2011.09.011
16. Kopperud SE, Tveit AB, Gaarden T, Sandvik L, & Espelid I (2012) Longevity of posterior dental restorations and reasons for failure *European Journal of Oral Sciences* **120(6)** 539-548, 10.1111/eos.12004
17. Hayashi M, Seow LL, Lynch CD, & Wilson NH (2009) Teaching of posterior composites in dental schools in Japan *Journal of Oral Rehabilitation* **36(4)** 292-298, 10. 1111/j.1365-2842.2008.01935.x
18. Lynch CD, McConnell RJ, & Wilson NH (2007) Trends in the placement of posterior composites in dental schools *Journal of Dental Education* **71(3)** 430-434.
19. Lynch CD, McConnell RJ, Hannigan A, & Wilson NH (2006) Teaching the use of resin composites in Canadian dental schools: How do current educational practices compare with North American trends? *Journal of the Canadian Dental Association* **72(4)** 321.
20. Lynch CD, McConnell RJ, & Wilson NH (2006) Teaching the placement of posterior resin-based composite restorations in U.S. dental schools *Journal of the American Dental Association* **137(5)** 619-625.
21. Lynch CD, McConnell RJ, & Wilson NH (2006) Teaching of posterior composite resin restorations in undergraduate dental schools in Ireland and the United Kingdom *European Journal of Dental Education* **10(1)** 38-43, 10. 1111/j.1600-0579.2006.00394.x
22. Wilson NH & Mjor IA (2000) The teaching of class I and class II direct composite restorations in European dental schools *Journal of Dentistry* **28(1)** 15-21.
23. Mjor IA & Wilson NH (1998) Teaching class I and class II direct composite restorations: Results of a survey of dental schools *Journal of the American Dental Association* **129(10)** 1415-1421.
24. Wilson NH & Setcos JC (1989) The teaching of posterior composites: A worldwide survey *Journal of Dentistry* **17(Supplement 1)** S29-S33; discussion S47-S52.
25. Liew Z, Nguyen E, Stella R, Thong I, Yip N, Zhang F, Burrow MF, & Tyas MJ (2011) Survey on the teaching and use in dental schools of resin-based materials for restoring posterior teeth *International Dental Journal* **61(1)** 12-18, 10.1111/j.1875-595X.2011.00003.x
26. Ben-Gal G & Weiss EI (2011) Trends in material choice for posterior restorations in an Israeli dental school: Composite resin versus amalgam *Journal of Dental Education* **75(12)** 1590-1595.

©Operative Dentistry, 2020, **45-3,** 265-275

Literature Review

Effect of Bleaching Gel Concentration on Tooth Color and Sensitivity: A Systematic Review and Meta-analysis

MMA Pontes • JML Gomes • CAA Lemos • RS Leão
SLD Moraes • BCE Vasconcelos • EP Pellizzer

Clinical Relevance

The use of low-concentration bleaching gels will promote in the patient a favorable whitening effect compared to high concentrations while at the same time being responsible for a lower dental sensitivity, promoting patient comfort.

SUMMARY

Objective: The aim of this systematic review and meta-analysis was to evaluate a high concentration of hydrogen peroxide (35%) regarding tooth sensitivity and color change in tooth bleaching in comparison to low concentrations (6% to 20%).

Methods and Materials: This review was conducted using the criteria of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses and is registered on the Prospective Register of Systematic Reviews (CRD42017064493). The PICO question was "Does a concentration of hydrogen peroxide ≥35% using in-office bleaching procedure contribute to greater tooth sensitivity?" A search was made in PubMed/MEDLINE, Scopus, and the Cochrane Library.

Results: Fourteen studies were selected for the qualitative analysis and seven for quantitative analysis. A total of 649 patients were evaluated (mean age: 36.32 years; range: 13.9 to 31 years),

Mônica Maria de Albuquerque Pontes, adjunct professor, School of Dentistry, Pernambuco University, Camaragibe, Brazil

*Jéssica Marcela de Luna Gomes, postgraduate student, Aracatuba Dental School, São Paulo State University, São Paulo, Brazil

Cleidiel Aparecido Araujo Lemos, postgraduate student, Department of Dental Materials and Prosthodontics, University of Estadual Paulista, Araçatuba, Brazil

Rafaella de Souza Leão, postgraduate student, Faculty of Dentistry, University of Pernambuco, Camaragibe, Brazil

Sandra Lúcia Dantas de Moraes, adjunct professor, School of Dentistry, Pernambuco University, Camaragibe, Brazil

Belmiro Cavalcanti do Egito Vasconcelos, associate professor, School of Dentistry, Pernambuco University, Camaragibe, Brazil

Eduardo Piza Pellizzer, full professor, Department of Dental Materials and Prosthodontics, São Paulo State University, Araçatuba, Brazil

*Corresponding author: Department of Dental Materials and Prosthodontics, José Bonifácio Street, 1193, Vila Mendonça, Araçatuba, São Paulo 16010-380, Brazil; e-mail: jessicamgomes@hotmail.com

https://doi.org/10.2341/17-376-L

and the follow-up period ranged from one week to 12 months. The meta-analysis demonstrated that tooth sensitivity was higher in the patients submitted to treatment involving a high concentration of hydrogen peroxide (0.67; 95% confidence interval [CI]: 0.44 to 1.03; p=0.04; I^2: 56%), and a significant difference was found regarding objective color ΔE (1.53; 95% CI: 2.99 to 0.08; p<0.0001; I^2: 82%) but no significant difference was found regarding subjective color ΔSGU (0.24; CI: 0.75 to 1.23; p<0.00001; I^2: 89%).

Conclusions: This study indicated that a lower concentration of hydrogen peroxide causes less tooth sensitivity and better effectiveness in objective color change (ΔE); however, there is no difference between them related to subjective color (ΔSGU).

INTRODUCTION

In-office bleaching is a treatment that offers excellent color stability; moreover, since the procedure is under the control of a dental surgeon, there is less risk of exposure to soft tissue.[1] Hydrogen peroxide (HP) is used in this treatment as a dental oxidizing agent, resulting in effective color change.[2] However, the concentration of HP and the duration of its application can influence its absorption into dental tissues, causing tooth sensitivity.[3]

High concentrations of HP promote evident color change at the first application session.[4,5] The mechanism of bleaching can generate a greater number of by-products capable of causing cell stress, clinically reflected as sensitivity.[6-9] Moreover, the clinical protocols for these products require, on average, 30 to 50 minutes of contact of the bleaching gel with the tooth for each clinical session.[10-12]

To maintain efficacy in color as well as alleviate sensitivity, bleaching gels with lower concentrations of HP[13] are used for in-office bleaching. However, low concentrations may require a greater number of sessions to achieve effective bleaching.[14] The efficacy of low-concentration bleaching gels is also affected by the addition of a semiconductor agent. Nanoparticles of titanium dioxide doped with nitrogen have been introduced with the aim of enhancing safety, providing less damage to the dental structure and tooth sensitivity.[14-16]

Considering the variety of products available on the market, it is challenging for dentists to identify a bleaching gel that is efficient and does not cause discomfort or sensitivity to patients.[17,18] Therefore, the aim of the present study was to conduct a systematic review of the literature to evaluate whether high concentrations of HP (≥35%) used in an in-office bleaching procedure can influence tooth sensitivity and color change in comparison to low concentrations (6%, 15%, and 20%). The first and second null hypotheses, in relation to tooth sensitivity and change in tooth color, respectively, were that there is no difference between high concentrations (≥35%) and lower concentrations (6%, 15%, and 20%) of HP.

METHODS AND MATERIALS

Registry of Protocol

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses[19] as well as some systematic reviews of the literature.[20,21] The review is also registered with the Prospective Register of Systematic Reviews (CRD42017064493).

Eligibility Criteria

Studies considered eligible for the present review needed to meet the following criteria: 1) randomized clinical trials, 2) prospective studies, 3) in-office bleaching protocol, and 4) studies published in English. The exclusion criteria were 1) retrospective studies, 2) clinical cases, 3) case series, 4) *in vitro* studies, and 5) *in vivo* (animal) studies.

The guiding question was "Does a concentration of hydrogen peroxide ≥35% using an in-office bleaching procedure contribute to greater tooth sensitivity?" The PICO question was employed: Population: individuals submitted to in-office bleaching; Intervention: the use of ≥35% hydrogen peroxide bleaching gel; Comparison: use of <35% hydrogen peroxide bleaching gel; and Outcomes: tooth sensitivity (primary outcome) and color change (secondary outcome).

Search Strategy

The selection of studies was performed by two independent researchers (MMAP and JMLG), with the involvement of a third researcher to resolve cases of a divergence of opinion between the first two. Electronic searches were performed in the PubMed/MEDLINE, Scopus, and Cochrane Library databases for articles published up to September 2017 based on the eligibility criteria. The key words were *tooth bleaching and in office OR tooth bleaching and hydrogen peroxide and concentration OR dental bleaching and in office OR dental bleaching and hydrogen peroxide and concentration OR tooth*

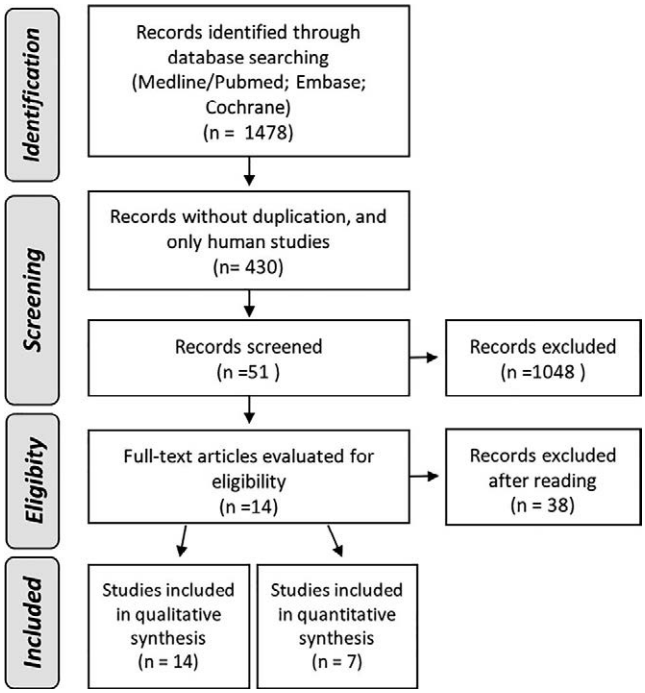


Figure 1. *Flowchart.*

whitening and in office OR tooth whitening and hydrogen peroxide and concentration OR dental whitening and in office OR dental whitening and hydrogen peroxide and concentration. A hand search was also performed in periodicals of major impact in the fields of dentistry and dental materials: *Journal of Dentistry*, *Operative Dentistry*, *Materials Science*, *Journal of Esthetic and Restorative Dentistry*, *Journal of Prosthetic Dentistry*, *American Journal of Dentistry*, *Journal of Dental Research and Dental Materials*.

Summary Measures

One researcher (MMAP) collected the relevant data from the articles, which were checked by two other researchers (BCEV and SLDM). The meta-analysis was based on the inverse variance and Mantel-Haenszel methods. Tooth sensitivity (absolute risk of tooth sensitivity) related to the dichotomous outcomes evaluated using the odds ratio, while subjective (ΔSGU) and objective (ΔE) color changes were considered the continuous outcome and evaluated using mean difference evaluated by inverse variance with a 95% confidence interval (CI). The odds ratio and mean difference values were considered significant when $p < 0.05$. In case of statistical significance ($p<0.10$) for heterogeneity, a random-effects model was used to assess the significance of treatment effects. Where no statistically significant heterogeneity was found, analysis was performed using a fixed-effects model.[22,23] The software Reviewer Manager 5 (Cochrane Group) was used for the meta-analyses.

The kappa statistic was calculated for the determination of the level of agreement between the researchers (MMAP and JMLG) regarding the selection of the studies from the PubMed/MEDLINE, Scopus, and Cochrane Library databases.

Risk of Bias

Two researchers (CAAL and RSL) performed the analysis of the risk of bias using the Cochrane scale for the appraisal of the methodological quality of the randomized clinical trials selected for the present systematic review and meta-analysis.

RESULTS

The search of the databases led to the retrieval of 1478 articles: 722 in Scopus, 597 in PubMed/MEDLINE, and 159 in the Cochrane Library. After the removal of duplicate references, the titles and abstracts of the articles were analyzed regarding the eligibility criteria, and 51 articles were preselected for the reading of the full texts. After the full-text analysis, 14 studies were selected for the qualitative analysis,[2,12-15,24-32] and seven of these were selected for the quantitative analysis[12-15,27,29,31] (Figure 1).

Study Characteristics

Design of the Studies—Table 1 lists the characteristics of the studies. Fourteen randomized controlled trials were selected; four of these studies used a split-mouth design.[14,24,25,31] A total of 649 patients were submitted to bleaching treatment (mean age: 36.32 years; range: 13.9 to 31 years). The most common patient's inclusion criteria in the studies were being caries free,[2,12,15] good oral hygiene,[2,26] absence of periodontal disease,[2] absence of anterior teeth restorations,[12-15,26,28,32] and teeth without bleaching experience.[18,22,26,28,29,31] Three[14,26,31] reported loss of the patient during the follow-ups; this means that 15% of the patients in the included studies dropped out.

The most common patient exclusion criteria in the studies were systemic diseases,[2,26,32] change in tooth structure,[2] smoking,[2] bruxism,[2,12,28] presence of dental sensitivity,[2] poor oral hygiene,[2,12] presence of fluorosis or tetracycline stains,[12-15,28,29,31,32] use of orthodontic treatment,[2,13-15,26,31] taking analgesic or anti-inflammatory drugs,[13,14,31] and pregnancy or breast-feeding.[2,12-15,25,26,32] The follow-up period

Table 1: *Characteristics of the Studies Included*

Reference	Type of Study	Study Design (n per Group)	Patients (n)/ Dropouts (n)	Mean Age (y)	Follow-Up
Bacaksiz and others[2]	RCT	G1: 25% HP with UV light (n=14) G2: 36% HP with LED light (n=14)	28/3	13.9	12 mo
Bezerra Dias and others[24]	RCT	G1: 35% HP (n=3) G2: 6% HP/N-doped TiO_2 (n=3)	6/0	31	1 wk
Bortolatto and others[15]	RCT	G1: 15% HP+TiO_N (n=20) G2: 35% H_2O_2 (n=20)	40/15	G1: 20.7 G2: 21.5	3 wk
Bortolatto and others[13]	RCT	G1: 6% HP+TiO_N (n=24) G2: 35% H_2O_2 (n=24)	48/0	G1: 24.3 G2: 24.0	2 wk
Fernandez and others[25]	RCT (split-mouth)	G1: 6% HP+TiO_N (n=32) G2: 35% HP (n=32)	32/5	24.1	9 mo
Martín and others[26]	RCT	G1: 15%HP+TiO_2+light (n=25) G2: 35% HP+light (n=27) G3: 35% HP (n=36)	88/46	23.03	1 mo
Martín and others[14]	RCT (split-mouth)	G1: 35% HP G2: 6% HP+TiO_N (split-mouth; n=30)	31/1	24.5	1 mo
Martín and others[26]	RCT	G1: 15% H_2O_2 N_TiO2 G2: 35% H_2O_2	70	23.6	1 mo
Mena-Serrano and others[27]	RCT	G1: 20% HP+LED light (n=19) G2: 20% HP (n=19) G3: 35% HP+LED light (n=20) G4: 35% HP (n=19)	77/0	G1: 22.9 G2: 22.0 G3: 23.0 G4: 22.0	1 mo
Moncada and others[28]	RCT	G1: 15% HP+TiO_N+light (n=25) G2: 35% HP+light (n=27) G3: 35% HP (n=35)	87	23.15	1 wk
Reis and others[12]	RCT	G1: 35% HP (n=30) G2: 20% HP (n=30)	60	G1: 29 G2: 25.0	2 wk
Rezende and others[29]	RCT	G1: 20% HP (n=15) G2: 35% HP (n=15) G3: 10% HP (at-home bleaching)	30	G1: 25.9 G2: 24.0	12 mo
Gallagher and others[30]	RCT	G1: 25% HP (n=20) G2: 38% HP (n=20)	21/1	≥18 y	1 wk
Vildsóla and others[31]	RCT (split -mouth)	G1: 6% HP (n=31) G2: 35% HP (n=31)	31/3	24.7 y	12 mo

Abbreviations: ΔE, objective color; ΔSGU, subjective color; RCT, randomized controlled trial; G1, group 1; G2, group 2; G3, group 3; G4, group 4; hydrogen peroxide; N.R., nonreported; TiO_2, titanium dioxide; VAS, visual analog scale; TiO_N, nitrogen-doped titanium dioxide; ARR, absolute risk rate. P1: patient 1; P2: patient 2; P3: patient 3.

ranged from one week to 12 months. The studies compared a higher concentration of HP (35%) to lower concentrations (6% to 20%). Two studies[2,30] performed a comparison of high-concentration HP bleaching gels.

Bleaching Protocol—In-office bleaching was performed in all included studies.[12,13,15,25,26,28,29,31] The bleaching protocol varied according to the concentration of the bleaching gel, and all bleaching protocols are described in Table 1. Some studies mentioned the use of gingival isolation[2,13-15,28] and lip retractor[2,29] and previous prophylaxis before the treatment.[13-15,24,26,27,29,33] The whitening gel was applied on the vestibular surface of the teeth (1 to 2 mm thick) or according to the manufacturer's instructions.[13,15,24] Also, other studies used the LED light associated with two low-level lasers at red (660 nm) or infrared (780 nm) wavelengths,[24] laser of low intensity (808 nm/infrared light),[18] LED light (470 nm),[13,26-28] LED/laser hybrid cold-light,[13,14,31] or infrared laser diodes (830 nm).[26] Only two studies[2,12,30,32] did not report the use of light.

Table 1: *Characteristics of the Studies Included (ext.)*

Reference	In-Office Bleaching Protocol	Outcomes		
		Color Change, ΔE±SD (Spectrophotometer)	Color Change, ΔSGU (Shade Guide Units)	Tooth Sensitivity
Bacaksiz and others[2]	G1: 3×15 min single visit+UV light G2: 3×15 min single visit+LED light	G1: 10.9±4.04 G2: 15.1±2.73	N.R.	Five-Step Scale events: G1: 3; G2: 3
Bezerra Dias and others[24]	G1: 2×12 min in the same session G2: 3×12 min in the same session	G1: P_1: 6.7; P_2: 6.1; P_3: 6.6 G2: P_1: 7.1; P_2: 5.7; P_3: 3.6	G1: $P_{1\text{-}2}$: 0.8; P_3: 1.0 G2: $P_{1:\ 1.5}$; P_2: 0.8; P_3: 4.5	VAS
Bortolatto and others[15]	G1: 3×16 min in three sessions and LED four times/arch per session G2: 3×15 min in three sessions	G1: 8.92±2.36 G2: 6.66±2.73	N.R.	VAS ARR: 52%
Bortolatto and others[13]	G1/G2: 2×12 min in two sessions +LED/laser light (1 min)	G1: 3.03±1.36 G2: 4.96±2.36	N.R.	Verbal scale ARR: 33.4%
Fernandez and others[25]	G1: 2×12 min+LED light in the same session G2: 2×12 min+LED light in the same session	G1: 5.14±3.49 G2: 7.81±2.32	G1: 6.81±2.22 G2: 6.93±2.25	N.R.
Martín and others[26]	G1: 3×15 min+LED light G2: 3×10 min+LED light G3: 1×45 min All groups were treated in the same session	N.R.	N.R.	VAS
Martín and others[14]	G1/G2: 2×12 min+LED laser hybrid light in three sessions	G1: 7.98±2.45 G2: 5.57±3.71	G1: 5.03±2.30 G2: 4.83±2.28	VAS ARR: G1: 36%; G2: 50%
Martín and others[26]	G1: 3×15 min in one session of 45 min G2: 3×12 min one session of 36 min	N.R.	N.R.	VAS
Mena-Serrano and others[27]	G1/G3: 3×15 min in two sessions G2/G4: 3×15 min in two sessions+LED light	G1: 13.2 ±4.1 G2: 11.8±4.0 G3: 12.4±3.7 G4: 14.1±2.9	G1: 6.1±2.6 G2: 8.2±1.3 G3: 8.2±2.5 G4: 8.4±1.4	Five-Point Verbal Scale and VAS ARR: G1: 63%; G2: 73%; G3: 80%; G4: 85%
Moncada and others[28]	G1: 3×15 min per session+30 s light G2: 3×10 min per session+light G3: 3×15 min per session	N.R.	N.R.	VAS
Reis and others[12]	G1: 1×40 min per session G2: 1×50 min per session	N.R.	G1: 1.6±0.7 G2: 3.5±1.0	Five-Point Verbal Scale ARR: G1: 26.7%; G2: 16.7%
Rezende and others[29]	G1: 1×50 min per session G2:1×40 min per session G3: 1×120 min per session (at-home bleaching)	N.R.	G1: 3.1±1.0 G2: 3.2±1.0	Five-Point Verbal Scale Events: G1: 7—ARR: 85% G2: 17—ARR: 47%
Gallagher and others[30]	G1/G2: 3× in one session	G1: 3.23±2.22 G2: 1.46±0.53	N.R.	Questionnaire: 0 to 3 (not sensitive to severely sensitive) Events: 10 (G1 and G2)
Vildsóla and others[31]	G1/G2: 3×12 min per session+LED laser hybrid light in three sessions	G1: 5.1±3.7 G2: 7.3±2.6	G1: 6.8±2.2 G2: 6.9±2.3	N.R.

The bleaching agent at the end was removed with gauze, suction, and/or water.[2] Desensitizing agent was used after the bleaching session in the studies.[2] The patients were instructed to avoid acids and food dyes[2,14,25] and the use of whitening agents.[31]

Tooth-Sensitivity Evaluation—The visual analog scale was used to measure tooth sensitivity.[14,15,24,26,28,29] The degree of tooth sensitivity was measured from 0 to 10, where 0 represents a total absence of pain, 5 moderate pain, and 10 the maximum level of pain.[24] Other measures were also used, such as the Five-Step Scale, which was applied after the bleaching, and the scores were measured with the following criteria: 0: none; 1: mild; 2: moderate; 3: considerable; 4: severe.[2,27] The Five-Point Verbal Scale[12,13,27,29] and a sensitivity questionnaire[30] were used, where four levels were considered: none, mild, moderate, or severe. Tooth sensitivity was evaluated before bleaching and after bleaching and at 24 hours, 48 hours, 72 hours, and one week, according to each study's follow-up. Also, some studies[12-15,27,29] described the absolute risk rate and the number needed to treat.

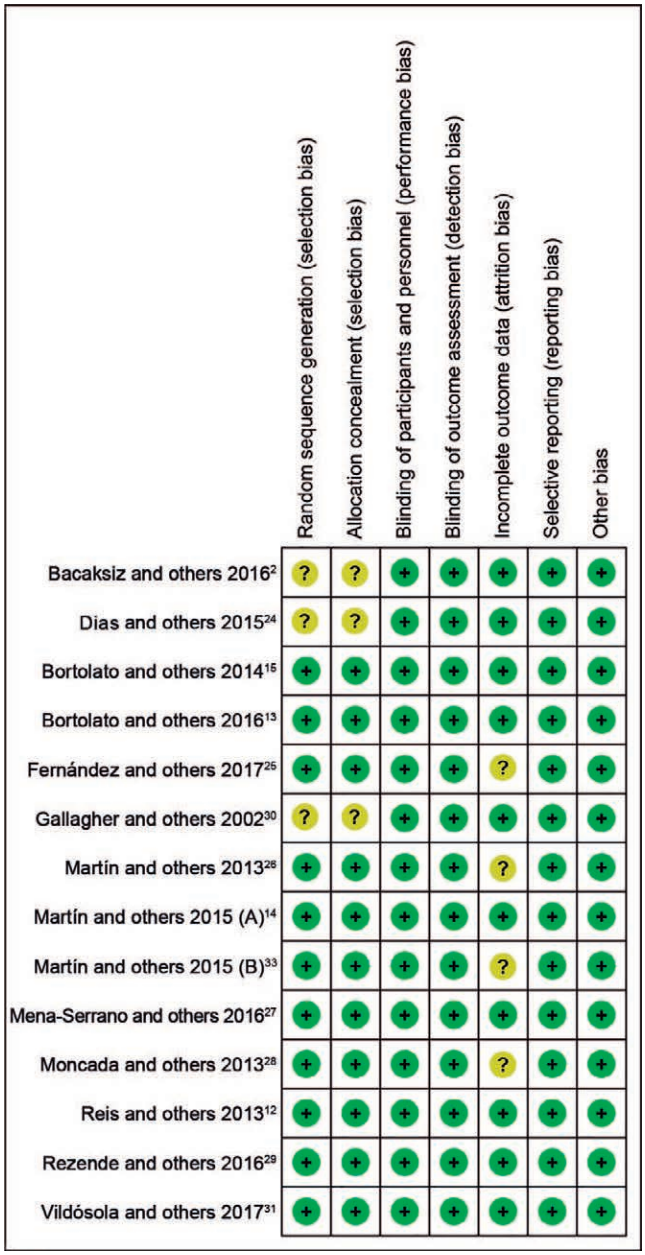


Figure 2. *Analysis of risk of bias, Cochrane scale.*

Color Evaluation—The subjective color analysis was based on shade guide units (ΔSGU), and the analysis was made from the color shade scale in some of the included studies.[12,24,25,27,29] Color was also evaluated in seven studies using an objective color analysis (ΔE) from a spectrophotometer[2,13-15,25,27,30] either by the confection of transparent soft trays with standardized markings[2] or without them in the middle third of the labial surface[24] or by a guide made with high-viscosity silicone putty[13,31] in the periods before bleaching and after bleaching and at 24 hours, 48 hours, 72 hours, one week, one month, six months, and 12 months, according to each study's follow-up. Objective color differences were calculated from the equation $\Delta E = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$.

Risk of Bias—All studies were qualified using the Cochrane Collaboration's tool for the risk of bias (Figure 2) and showed low risk of bias. Some studies were classified as "unclear" for the following items: sequence generation and allocation concealment;[2,24,30] blinding of participants, personnel, and outcome assessor;[24] and incomplete outcome data.[25,26,28]

Meta-Analysis

Tooth Sensitivity—Six studies[12-15,27,29,31] were selected for the quantitative analysis of the concentrations of bleaching gel divided into two groups: lower concentration of HP (6% to 20%) and higher concentration (35%). A significant difference between groups was found, indicating less tooth sensitivity when a lower concentration of HP (6% to 20%) was used (0.67; 95% CI: 0.44 to 1.03; $p=0.04$; I^2: 56%) (Figure 3).

Color Change (ΔE)—About the color change, some studies[13-15,25,27,31] found a significant difference between a high concentration of HP (35%) and a low concentration (6% to 20%) (1.53; 95% CI: 2.99 to −0.08; $p<0.0001$; I^2: 82%) (Figure 4).

Color Change (ΔSGU)—Some studies[12,14,25,27,29,31] performed a subjective evaluation of the change in color, but no significant difference was found between a low concentration (6% to 20%) and a high concentration of HP (35%) (0.24; CI: −0.75 to 1.23, $p<0.00001$; I^2: 89%) (Figure 5).

DISCUSSION

The first null hypothesis, that there is no difference with regard to tooth sensitivity between a high concentration of HP (35%)[34-36] and lower concentrations (6%, 15%, and 20%),[34-36] was rejected. This was because a meta-analysis revealed a significant difference (0.38; 95% CI: 0.16 to 0.92, $p=0.04$; I^2: 56%), revealing less tooth sensitivity for a lower concentration of HP. This agrees with the findings of Moncada and others[28] and other studies[18,26,37] reporting greater tooth sensitivity when high concentrations of HP were used. The major number of dropouts were between the first and second bleaching sections. This is in accordance with the literature[13,25,28] reporting a high level of sensitivity in the early sections.

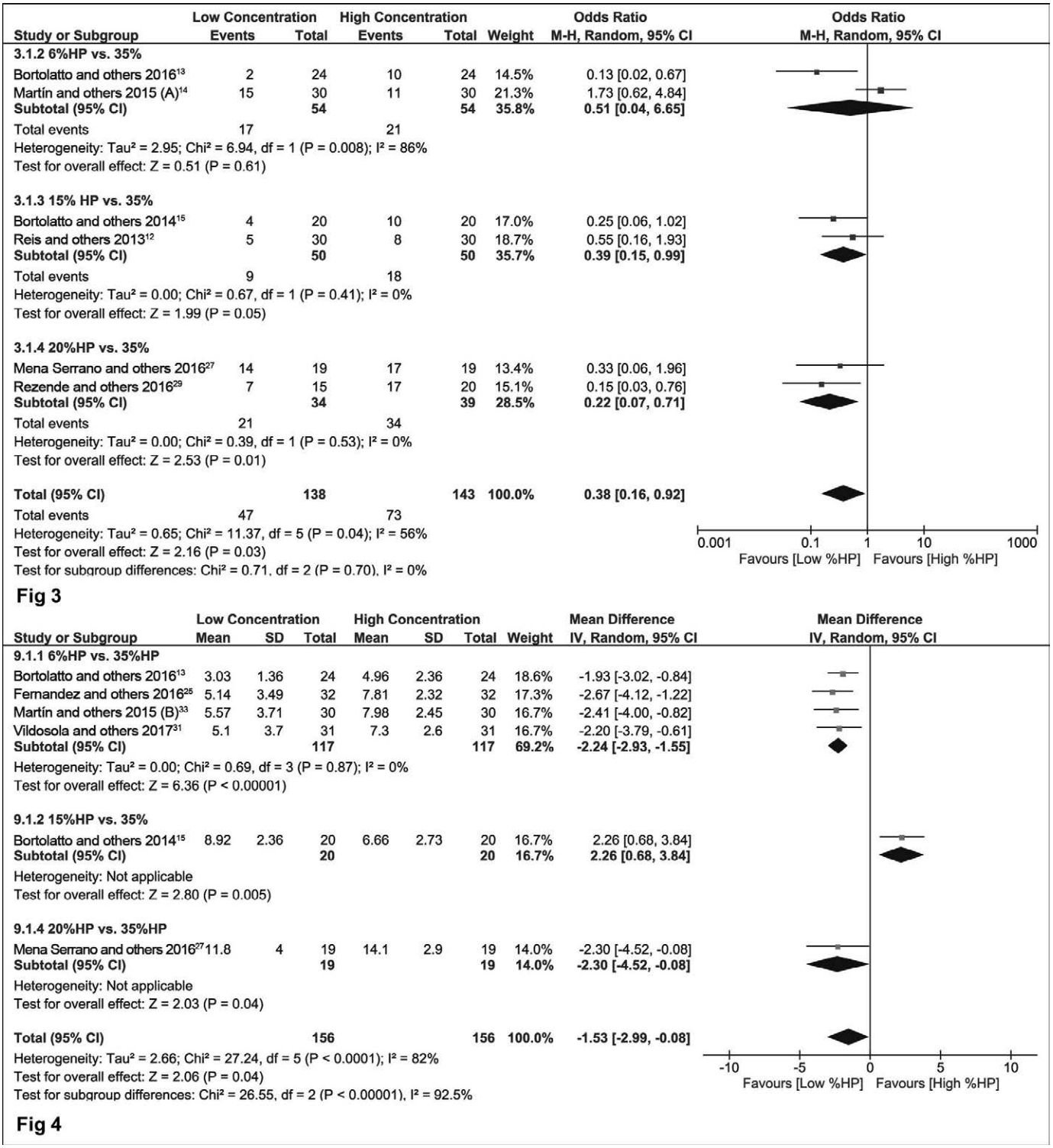


Fig 3

Fig 4

Figure 3. *Outcome: tooth sensitivity (high concentration of HP [35%] vs low concentration of HP [6% to 20%]). M-H, Mantel-Haenszel R.E., random effect.*

Figure 4. *Outcome: color change ΔE (high concentration of HP [35%] vs low concentration of HP [6% to 20%]). IV, inverse variance; R.E., random effect.*

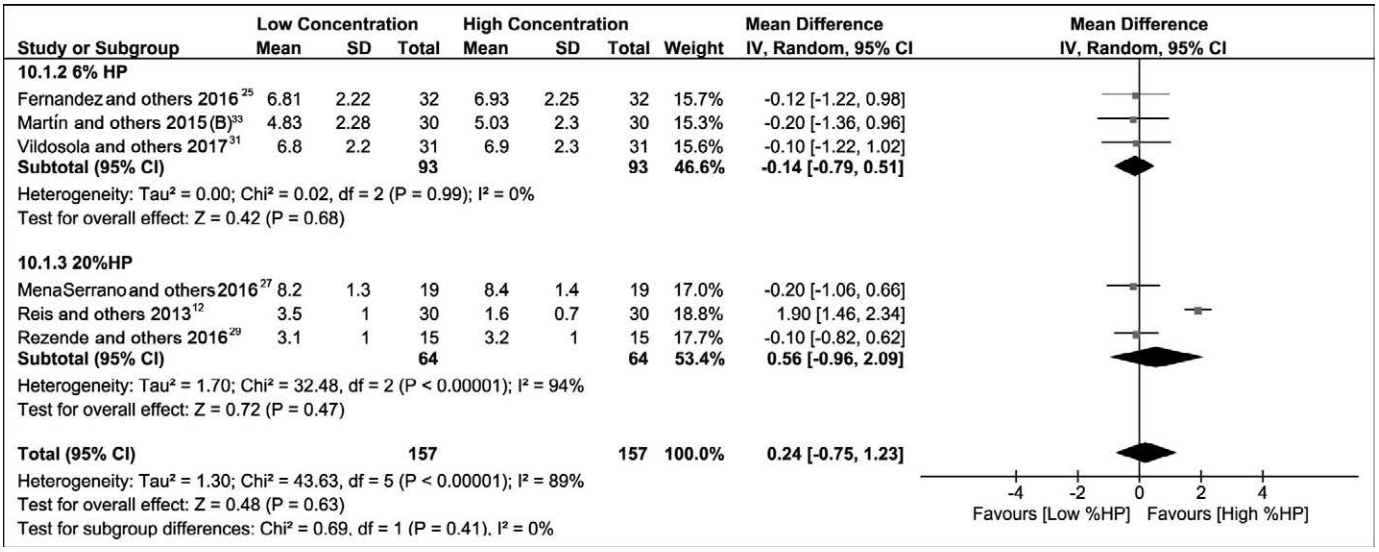


Figure 5. *Outcome: color change ΔSGU (high concentration of HP [35%] vs low concentration of HP [6% to 20%]). IV, inverse variance; R.E., random effect.*

It was not possible to carry out meta-analyses for all studies that were selected for the present systematic review due to a lack of data in some articles. In the evaluation of tooth sensitivity stemming from bleaching sessions, a reduction in sensitivity was reported one week after the procedure. This agrees with the findings of Mondelli and others,[11] who evaluated the effects of high concentrations of HP (35% and 38%) and found that sensitivity increased immediately after treatment and then diminished gradually over the course of a week.

According to Matis and others,[32] tooth sensitivity is related to the contact time of the bleaching gel and not the concentration of HP. In the analysis of bleaching gel application among the studies selected for the present systematic review, either the protocol was found to be the same for low or higher concentrations tested[13,14,25-28] or application was performed with low-concentration gels over a longer period (contact time and/or number of sessions).[15,24,29] This indicates that a longer application time does not exert an influence on tooth sensitivity but enables a low-concentration bleaching gel to perform as effectively as a high-concentration bleaching gel.[13]

The sensitivity caused by low-concentration gel (15%) is lower than that found with high-concentration (35%) gel; this may be related to the association between HP and nitrogen-doped titanium dioxide semiconductor nanoparticles (N_TiO_2). In the presence of visible light, this enables the formation of O_2 without hydroxyl (OH^-) radicals, which are a risk factor in tooth bleaching procedures. Therefore, lower-concentration gels are reported as a less irritating but equally effective tooth bleaching option.[26] However, in the subgroup analysis, when comparing a 6% HP concentration with a 35% HP concentration, there is no difference between them, even with the 6% HP concentration having the N_TiO_2, and it may be related to the use of LED/laser hybrid light in high concentrations (35%), which is reported[33] as an important factor to provide less tooth sensitivity.

In the present systematic review, meta-analysis was performed for both objective color change (ΔE) (−1.53; 95% CI: −2.99 to −0.08; $p<0.0001$, I^2: 82%) and subjective color change (ΔSGU) (0.24; 95% CI: −0.75 to 1.23; $p<0.00001$; I^2: 89%). A statistically significant difference in ΔE was found; however, there was no significant difference for ΔSGU. Hence, the second null hypothesis, which affirms that there is no difference in terms of the change in tooth color between a high concentration of HP (35%)[34-36] and lower concentrations (6% to 20%),[34-36] was partially accepted.

The results used in the meta-analysis to analyze ΔE were acquired from those for the longer follow-up period reported in each study. Researchers[14,38] believe that there is color maintenance after a longer period following bleaching, indicating that the peroxide diffuses through the tissues of the tooth and remains there.[14] Even TiO_2, when used as a catalyst at lower HP concentrations associated with

LED light, presents strong evidence of color rebound.[16,31] These results indicate that color was maintained when lower concentrations of HP were used, in comparison to previous controls (ΔE), for up to one year of follow-up.[2,14,25] Some authors[14,25] also reported that the bleaching protocol is important for color change and maintenance.[14,39,40] A protocol with 120 minutes of contact time would be ideal for complete effectiveness of a bleaching gel with a 6% concentration of HP.[41] However, the time reported in the studies cited was lower yet still presented better results.

Mena-Serrano and others[27] obtained good results by using a 20% concentration of HP with regard to ΔSGU, in comparison to that achieved with 35% HP, but found no difference when color was evaluated using a spectrophotometer (ΔE). This result was obtained in the first 30 days after the bleaching procedure and may be related to the combined use of 35% HP and light. Since 35% HP alone produces radicals in excess, light would not lead to faster bleaching due to the oxidation mechanism of the radicals.[27] Moreover, in the studies with a split-mouth design, the optical effect of the incisors exerted an influence on ΔSGU. The subjective analysis of color depends on physical and environmental variables,[28] which can lead to inconsistencies in the measurement of color. Some researchers,[40,41] when evaluating the color change by people who were not trained after bleaching or even for people who were trained,[41] reported that objective color evaluation using a spectrophotometer is more effective than using visual scales (ΔSGU). Other studies included in the present systematic review[30,42] performed comparisons of bleaching gels with high concentrations of HP (25% to 38%)[1] and demonstrated effectiveness at the 12-month follow-up evaluation.[2] In a study involving adolescent patients (mean age: 13.9 years), Bacaksiz and others[2] found no difference with regard to tooth sensitivity between gels of different concentrations, even when the pulp chambers were wider and more sensitive to irreversible pulpitis.[43]

The risk of bias among the studies included in the present review was low. However, further randomized clinical trials should be performed with uniform bleaching gel application protocols to ensure greater safety for both the operator and the patient and to minimize tooth sensitivity while maximizing the effectiveness of the treatment.

CONCLUSIONS

The findings of the present systematic review and meta-analysis indicate that a lower concentration of HP in tooth bleaching gels results in less tooth sensitivity and more efficacy of objective color (ΔE) as measured by the spectrophotometer, while the same effect between the high and low concentrations was found regarding subjective color (ΔSGU) as measured by the color shade guide.

Conflict of Interest

The authors of this article certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

(Accepted 18 June 2018)

REFERENCES

1. Joiner A (2006) The bleaching of teeth: A review of the literature *Journal of Dentistry* **34(7)** 412-419.
2. Bacaksiz A, Tulunoglu O, & Tulunoglu I (2016) Efficacy and stability of two in-office bleaching agents in adolescents: 12 months follow-up *Journal of Clinical Pediatric Dentistry* **40(4)** 269-273.
3. Torres CR, Wiegand A, Sener B, & Attin T (2010) Influence of chemical activation of a 35% hydrogen peroxide bleaching gel on its penetration and efficacy—In vitro study *Journal of Dentistry* **38(10)** 838-846.
4. Leonard RH, Sharma A, & Haywood VB (1998) Use of different concentrations of carbamide peroxide for bleaching teeth: An in vitro study *Quintessence International* **29(8)** 503-507.
5. de Geus JL, Wambier LM, Kossatz S, Loguercio AD, & Reis A (2016) At-home vs in-office bleaching: A systematic review and meta-analysis *Operative Dentistry* **41(4)** 341-356.
6. Sies H (1993) Strategies of antioxidant defense *European Journal of Biochemistry* **215(2)** 213-219.
7. Martindale JL, & Holbrook NJ (2002) Cellular response to oxidative stress: Signaling for suicide and survival *Journal of Cellular Physiology* **192(1)** 1-15.
8. Coldebella CR, Ribeiro AP, Sacono NT, Trindade FZ, Hebling J, & Costa CA (2009) Indirect cytotoxicity of a 35% hydrogen peroxide bleaching gel on cultured odontoblast-like cells *Brazilian Dental Journal* **20(4)** 267-274.
9. Costa CA, Riehl H, Kina JF, Sacono NT, & Hebling J (2010) Human pulp responses to in-office tooth bleaching *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontics* **109(4)** e59-64.
10. Bernardon JK, Sartori N, Ballarin A, Perdigao J, Lopes GC, & Baratieri LN (2010) Clinical performance of vital bleaching techniques *Operative Dentistry* **35(1)** 3-10.
11. Mondelli RF, Azevedo JF, Francisconi AC, Almeida CM, & Ishikiriama SK (2012) Comparative clinical study of the effectiveness of different dental bleaching methods—Two year follow-up *Journal of Applied Oral Science* **20(4)** 435-443.
12. Reis A, Kossatz S, Martins GC, & Loguercio AD (2013) Efficacy of and effect on tooth sensitivity of in-office

bleaching gel concentrations: A randomized clinical trial *Operative Dentistry* **38(4)** 386-393.

13. Bortolatto JF, Trevisan TC, & Bernardi PS (2016). A novel approach for in-office tooth bleaching with 6% H2O2/TiO_N and LED/laser system-a controlled, triple-blinded, randomized clinical trial *Lasers in Medical Science* **31(3)** 437-444.
14. Martín J, Vildosola P, & Bersezio C (2015) Effectiveness of 6% hydrogen peroxide concentration for tooth bleaching—A double-blind, randomized clinical trial *Journal of Dentistry* **43(8)** 965-972.
15. Bortolatto JF, Pretel H, & Floros MC (2014) Low concentration H_2O_2/TiO_N in office bleaching: A randomized clinical trial *Journal of Dental Research* **93(Supplement 7)** 66s-71s.
16. Vano M, Derchi G, Barone A, Genovesi A, & Covani U (2015) Tooth bleaching with hydrogen peroxide and nano-hydroxyapatite: A 9-month follow-up randomized clinical trial *International Journal of Dental Hygiene* **13(4)** 301-307.
17. Nathanson D (1997) Vital tooth bleaching: Sensitivity and pulpal considerations *Journal of the American Dental Association* **128(Supplement)** 41s-44s.
18. Gokay O, Mujdeci A, & Algn E (2004) Peroxide penetration into the pulp from whitening strips *Journal of Endodontics* **30(12)** 887-889.
19. Moher D, Liberati A, Tetzlaff J, & Altman DG (2009) Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement *British Medical Journal* **339** b2535.
20. Lemos CA, Ferro-Alves ML, Okamoto R, Mendonca MR, & Pellizzer EP (2016) Short dental implants versus standard dental implants placed in the posterior jaws: A systematic review and meta-analysis *Journal of Dentistry* **47** 8-17.
21. Lemos CA, Verri FR, Batista VE, Junior JF, Mello CC, & Pellizzer EP (2017) Complete overdentures retained by mini implants: A systematic review *Journal of Dentistry* **57** 4-13.
22. Chrcanovic BR, Albrektsson T, & Wennerberg A (2015) Immediately loaded non-submerged versus delayed loaded submerged dental implants: A meta-analysis *International Journal of Oral and Maxillofacial Surgery* **44(4)** 493-506.
23. Egger M, & Smith GD. (2003) Principles of and procedures for systematic reviews. In: Egger M, Smith GD, Altman DG (eds) *Systematic Reviews in Health Care: Meta-Analysis in Context* BMJ Books, London 23-42.
24. Dias HB, Carrera ET, Bortolatto JF, Andrade MF, & Rastelli ANS (2016) LED and low level laser therapy association in tooth bleaching using a novel low concentration H_2O_2/N-doped TiO_2 bleaching agent *Laser Physics* **26(1)** 015602.
25. Fernandez E, Bersezio C, & Bottner J (2017) Longevity, esthetic perception, and psychosocial impact of teeth bleaching by low (6%) hydrogen peroxide concentration for in-office treatment: A randomized clinical trial *Operative Dentistry* **42(1)** 41-52.
26. Martín J, Fernandez E, & Bahamondes V (2013) Dentin hypersensitivity after teeth bleaching with in-office systems. Randomized clinical trial *American Journal of Dentistry* **26(1)** 10-14.
27. Mena-Serrano AP, Garcia E, Luque-Martinez I, Grande R, Loguercio AD, & Reis A (2016) A single-blind randomized trial about the effect of hydrogen peroxide concentration on light-activated bleaching *Operative Dentistry* **41(5)** 455-464.
28. Moncada G, Sepulveda D, & Elphick K (2013) Effects of light activation, agent concentration, and tooth thickness on dental sensitivity after bleaching *Operative Dentistry* **38(5)** 467-476.
29. Rezende M, Ferri L, Kossatz S, Loguercio AD, & Reis A (2016) Combined bleaching technique using low and high hydrogen peroxide in-office bleaching gel *Operative Dentistry* **41(4)** 388-396
30. Gallagher A, Maggio B, Bowman J, Borden L, Mason S, & Felix H (2002) Clinical study to compare two in-office (chairside) whitening systems *Journal of Clinical Dentistry* **13(6)** 219-224.
31. Vildosola P, Bottner J, Avalos F, Godoy I, Martin J, & Fernandez E (2017)Teeth bleaching with low concentrations of hydrogen peroxide (6%) and catalyzed by LED blue (450 +/- 10 nm) and laser infrared (808 +/- 10 nm) light for in-office treatment: Randomized clinical trial 1-year follow-up *Journal of Esthetic and Restorative Dentistry* **29(5)** 339-345.
32. Matis BA, Cochran MA, Franco M, Al-Ammar W, Eckert GJ, & Stropes M Eight in-office tooth whitening systems evaluated in vivo: A pilot study *Operative Dentistry* **32(4)** 322-327.
33. Martín J, Ovies N, Cisternas P, Fernandez E, Oliveira Júnior OB, Andrade MF, Moncada G, & Vildósola P (2015) Can an LED-laser hybrid light help to decrease hydrogen peroxide concentration while maintaining effectiveness in teeth bleaching? *Laser Physics* **25(2)** 025608.
34. He LB, Shao MY, Tan K, Xu X, & Li JY (2012) The effects of light on bleaching and tooth sensitivity during in-office vital bleaching: A systematic review and meta-analysis *Journal of Dentistry* **40(8)** 644-653.
35. Tavares M, Stultz J, & Newman M (2003) Light augments tooth whitening with peroxide. *Journal of the American Dental Association* **134(2)** 167-175.
36. Ziemba SL, Felix H, MacDonald J, & Ward M (2005) Clinical evaluation of a novel dental whitening lamp and light-catalyzed peroxide gel *Journal of Clinical Dentistry* **16(4)** 123-127.
37. Benetti AR, Valera MC, Mancini MN, Miranda CB, & Balducci I (2004) In vitro penetration of bleaching agents into the pulp chamber *International Endodontic Journal* **37(2)** 120-124.
38. Bizhang M, Chun YH, Damerau K, Singh P, Raab WH, & Zimmer S (2009) Comparative clinical study of the effectiveness of three different bleaching methods *Operative Dentistry* **34(6)** 635-641.
39. de Almeida LC, Soares DG, Gallinari MO, de Souza Costa CA, Dos Santos PH, & Briso AL (2015) Color alteration,

hydrogen peroxide diffusion, and cytotoxicity caused by in-office bleaching protocols *Clinical Oral Investigations* **19(3)** 673-680.

40. de Paula EA, Nava JA, & Rosso C (2015) In-office bleaching with a two- and seven-day intervals between clinical sessions: A randomized clinical trial on tooth sensitivity *Journal of Dentistry* **43(4)** 424-429.
41. Matis BA, Cochran MA, & Eckert G (2009) Review of the effectiveness of various tooth whitening systems *Operative Dentistry* **34(2)** 230-235.
42. Basting RT, Amaral FL, Franca FM, & Florio FM (2012) Clinical comparative study of the effectiveness of and tooth sensitivity to 10% and 20% carbamide peroxide home-use and 35% and 38% hydrogen peroxide in-office bleaching materials containing desensitizing agents *Operative Dentistry* **37(5)**464-473.
43. Donly KJ, Segura A, Henson T, Barker ML, & Gerlach RW (2007) Randomized controlled trial of professional at-home tooth whitening in teenagers *General Dentistry* **55(7)** 669-674.

©Operative Dentistry, 2020, **45-3,** 276-285

Laboratory Research

Endodontic Access Effect on Full Contour Zirconia and Lithium Disilicate Failure Resistance

J Mallya • N DuVall • J Brewster • H Roberts

Clinical Relevance

Although more investigation is required, replacing adhesively luted, all-ceramic yttria-stabilized zirconium dioxide and lithium disilicate crowns may not be required after endodontic access.

SUMMARY

Objectives: To evaluate the effect of endodontic access on the failure load resistance of both adhesively and conventionally luted, full-contour monolithic yttria-stabilized zirconium dioxide (Y-TZP) and adhesively luted lithium disilicate (LD) crowns cemented on prepared teeth.

Methods and Materials: Seventy-two human maxillary molars were prepared per respective guidelines for all-ceramic crowns with one group (n=24) restored with LD and the other (n=48) receiving Y-TZP crowns. Preparations were scanned using computer-aided design/computer-aided milling (CAD/CAM) technology, and milled crowns were sintered following manufacturer recommendations. All LD crowns and half (n=24) of the Y-TZP crowns were adhesively cemented, while the remaining Y-TZP specimens were luted using a conventional glass ionomer cement (GIC). One LD group, one Y-TZP adhesive group, and one GIC-luted group (all n=12) then received endodontic access preparations by a board-certified endodontist: the pulp chambers were restored with a dual-cure, two-step, self-etch adhesive and a dual-cure resin composite core material. The access preparations were restored using a nano-hybrid resin composite after appropriate ceramic margin surface preparation. After 24 hours, all specimens were loaded axially until failure; mean failure loads were analyzed using Mann-Whitney U test (α=0.05)

Results: Endodontic access did not significantly reduce the failure load of adhesively luted LD or Y-TZP crowns, but Y-TZP crowns with GIC cementation demonstrated significantly less failure load.

Conclusions: These initial findings suggest that endodontic access preparation may not significantly affect failure load resistance of

John Mallya, DMD, MS, 47th Medical Group, Laughlin AFB, TX, USA

Nicholas DuVall, DDS, MS, 96th Dental Squadron, Eglin AFB, FL USA

John Brewster, DDS, MS, USAF Postgraduate Dental School, Keesler AFB, MS, USA

*Howard Roberts, DMD, MS, Division of Restorative Dentistry, University of Kentucky College of Dentistry, Lexington, KY, USA

*Corresponding author: 800 Rose St, D632, Lexington, KY, 40536, USA; e-mail: h.w.roberts@uky.edu or hwroberts1956@gmail.com

https://doi.org/10.2341/18-231-L

adhesively luted Y-TZP and LD crowns. Definitive recommendations cannot be proposed until fatigue testing and coronal seal evaluations have been accomplished.

INTRODUCTION

Full-contour crown restorations are indicated for teeth that have suffered extensive structure loss due to trauma and/or disease, with over 54 million units (crowns, pontics, retainers) reportedly placed in the United States in 2012.[1] Tooth preparation for a complete crown is not a conservative procedure, and. depending on the specific situation, crown preparation may require approximately 24% to 70% of the existing tooth structure to be removed.[2,3] During this procedure, the dental pulp can be subjected to heat and mechanical trauma,[4] and historically it has been suggested that the dental pulp may not fully recover from insults (eg, stressed pulp condition).[5] Hence, a potential chronic pulp inflammation combined with potential insults added during crown preparation[6-9] suggests that vital teeth receiving full metal and porcelain fused to metal crown restorations could be more likely to require future endodontic treatment. Clinical retrospective studies have reporting that crowns requiring endodontic intervention range from 4% to 18% compared with control ranges of 0.5% to 2%.[10-15] Moreover, greater knowledge of identified pulp tissue inflammation biological mechanisms involving heat, mechanical stress, and chemical insult from resin monomer infiltration[4,16-20] that occur during crown preparation and restoration adds emphasis to the idea that crown-restored vital teeth may be more vulnerable to requiring future endodontic intervention.[21-24] Furthermore, an estimated 20% to 50% of nonsurgical root canal treatments are performed via endodontic access through crowns,[25] and surveys report that up to 72% of clinicians prefer to maintain the repaired crown as the definitive post-endodontic restoration.[26,27] As the maintenance of a coronal seal is paramount for long-term success of endodontic treatment,[27-37] concern exists due to the present difficulty with obtaining reliable adhesion and seal with metal and porcelain materials,[35,36] even more so with high-crystalline ceramic surfaces.[37-40]

For all-ceramic crowns, retrospective evaluations report that endodontic intervention ranges from 2.5% to 8.6%.[13,41,42] The effect of endodontic access through all-ceramic restorations on the crown mechanical and physical properties has been a subject of many *in vitro* studies.[42-53] Access preparations through ceramic crowns are usually accomplished with high-speed diamond burs, which produce a machining loading strain process that is said to initiate both surface and subsurface ceramic cracks that lead to structural weakness.[54-59] Accordingly, the all-ceramic crown endodontic access preparation has been suggested as the nidus of following catastrophic complete crown failures,[48,49] while work by Grobecker-Karl and colleagues[60] report that monolithic zirconia is less susceptible to chipping and cracking due to endodontic access. Furthermore, it has been reported that flaw generation is independent of access technique and instruments used, as high-efficiency cutting instruments have been reported to cause ceramic flaws, regardless of the instrument composition.[48] Adhesive technology under *in vitro* conditions have shown some promise in strengthening some ceramic systems,[61,62] but these results are difficult to relate clinically, as *in vitro* ceramic evaluations have yet to correlate with clinical failure patterns.[63-66] Additionally, a recent systematic review could not identify a best practice guideline for endodontic access repair within all-ceramic complete crowns.[67] *In vitro* studies that approximate the clinical conditions involving endodontic access on full-contour ceramic crowns luted on prepared tooth structure are limited. The purpose of this study was to evaluate the effect of endodontic access preparation upon the failure load resistance of adhesively luted lithium disilicate (LD) and monolithic yttria-stabilized zirconium dioxide (Y-TZP) crowns luted both conventionally and adhesively to prepared teeth. The null hypothesis was that there would be no difference in the failure load between intact and endodontically accessed all-ceramic, full-crown restorations.

METHODS AND MATERIALS

Seventy-two freshly extracted human maxillary molars were used in this evaluation. These teeth were removed due to routine clinical indications in local oral and maxillofacial surgery clinics. The teeth were first mounted in autopolymerizing denture base methacrylate resin (Diamond D, Keystone Industries, Gibbstown, NJ, USA). The specimens were then assigned to groups per Figure 1. The specimens were first randomly divided into two groups. One group (n=48) was designated as the Y-TZP (InCoris TZI, Dentsply Sirona USA, York, PA, USA) monolithic crown group, while the second group (n=24) served as the LD (IPS eMax CAD, Ivoclar Vivadent, Amherst, NY, USA) complete crown group. The LD group was further subdivided

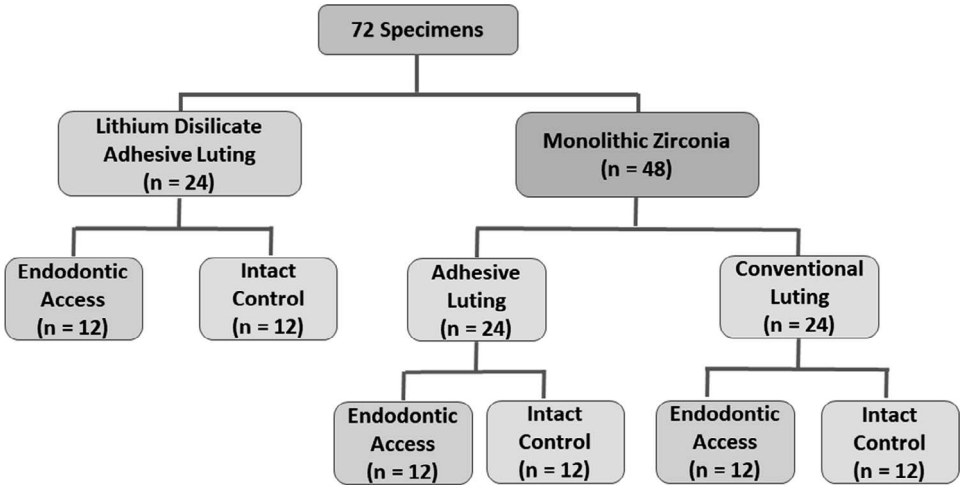


Figure 1. *Study protocol outline.*

into two groups (n=12): one restored group received endodontic access, while the other received no further treatment and served as a control. The Y-TZP group (n=48) was subdivided into two groups (n=24): one group received an adhesively luted complete Y-TZP crown, while the remaining group (n=24) was conventionally cemented using a glass ionomer luting agent. Based on luting strategy, each Y-TZP group was then further subdivided (n=12): one group was prepared with an endodontic access, while the other served as a control.

Specimen occlusal surfaces were ground flat to approximately 1 mm below the marginal ridge and then prepared by one researcher following manufacturer preparation recommendations for each crown substrate. A high-speed electric dental handpiece (EA-51LT, Adec, Newburg, OR, USA) with a diamond bur (8845KR.31.025, Brassler USA, Savannah, GA, USA) was used under continuous water coolant spray. A total occlusal convergence of 10° with a 3 mm occlusogingival axial wall height was standardized by using the handpiece in a fixed lathe arrangement. Preparation features and preparation surface area were confirmed and recorded with a digital recording microscope (KH-7700, Hirox USA, Hackensack, NJ, USA). All scanning and restoration procedures were then completed by a second researcher. The prepared molars were inserted into a quadrant template representing clinical conditions with a digital image captured using a computer-aided design/computer-aided milling (CAD/CAM) acquisition device (inEos Blue, Dentsply Sirona]), while CAD/CAM software (in Lab, version 4.0.0, Dentsply Sirona) was used for restoration design. Restoration contours and anatomy were standardized using a biomimetric copy with the Y-TZP restorations designed with a minimal 1.5 mm occlusal thickness following recommendations at that time, while the LD restorations had 2.0 mm minimal occlusal thickness. The LD groups were milled (MCXL, Dentsply Sirona) and after fit verification were crystallized in a dental laboratory furnace (Programat P700, Ivoclar Vivadent). Each restoration received post-crystallization adjustment and preparation seating verification using disclosing powder (Occlude, Pascal International, Bellevue, WA, USA) followed by steam cleaning and drying with oil-free compressed air. The restoration intaglio surface was treated with 5% hydrofluoric acid (IPS Ceramic Etching Gel, Ivoclar Vivadent) for 20 seconds, rinsed, and dried, which was then followed by ceramic primer application (Clearfil Ceramic primer, Kuraray America, Houston, TX, USA) that was dried using compressed air. All manufacturer recommendations that were current at the time of this evaluation were followed.

The tooth surface was prepared for luting using a pumice water slurry followed by rinsing and drying of the dentin surface. The restoration was then luted with a self-adhesive resin cement (RelyX Unicem2, 3M ESPE, St Paul, MN, USA) to margin closure using digital pressure; excess cement was removed followed by light activation using a Polywave light-emitting diode (LED) visible light curing unit (Bluephase G2, Ivoclar Vivadent) for 20 seconds on the facial, lingual, and occlusal surfaces.

The Y-TZP crowns were milled (MCXL, Dentsply Sirona) followed by sintering in a laboratory furnace (inFire, Dentsply Sirona) following manufacturer recommendations. Sintered restorations were seated and adjusted in the same manner as the LD groups. After cleaning and drying, half (n=24) of the Y-TZP intaglio surfaces were treated using 30 μm silicatized

Table 1: *Mean Preparation Parameters*

Group (n=12 each)	Mean Surface Area (mm^2)	Mean Axial Wall Height (mm)	Mean Total Occlusal Convergence (degrees)	Mean Endodontic Access Opening (mm^2)	Mean Endodontic Access Opening Percentage of Occlusal Surface (%)
1 ZR-KC	115.5 (9.6)	3.03 (0.05)	10.1 (1.01)	NA	NA
2 ZR-KC endodontic access	113.5 (14.9)	3.02 (0.04)	10.3 (0.8)	6.01 (0.64)	11.02 (1.1)
3 ZR-RX	131.3 (13.1)	3.02 (0.05)	10.4 (0.8)	NA	NA
4 ZR-RX endodontic access	112.6 (9.0)	3.03 (0.05)	10.4 (0.6)	8.6 (0.97)	14.2 (1.2)
5 LD-RX	101.8 (7.8)	3.02 (0.03)	10.6 (0.7)	NA	NA
6 LD-RX- endodontic access	102.1 (16.8)	3.02 (0.04)	10.6 (0.5)	9.11 (1.56)	15.5 (2.8)

Abbreviations: LD-RX, lithium disilicate luted with self-adhesive resin cement; NA, nonapplicable; ZR-KC, zirconia luted with conventional glass ionomer cement; ZR-RX, zirconia luted with self-adhesive resin cement.

sand (CoJet System, 3M ESPE) applied with 2-3 bar pressure followed by ceramic primer application (Clearfil Ceramic Primer, Kuraray America) then luted in the same manner as the LD specimens using a self-adhesive resin luting agent (RelyX Unicem 2, 3M ESPE). The remaining (n=24) Y-TZP complete crown intaglio surfaces were treated with 40 μm alumina and were luted with a conventional glass-ionomer luting agent (Ketac Cem, 3M ESPE). All materials were applied following manufacturer recommendations. All specimens were then stored under dark conditions at 37°C ± 1°C and 98% ± 1% humidity. After 24 hours, two of the Y-TZP restored groups and one of the LD restored groups received endodontic access preparation by a board-certified endodontist using diamond burs (Predator Zirconia Bur, Clinicians Choice, New Milford, CT, USA). To somewhat follow clinical conditions, the endodontic access opening area was not standardized but was determined by the endodontist's professional judgment regarding access to and instrumentation of the specimen's canals. Endodontic access opening area and approximate occlusal surface area were measured using a digital recording microscope (7700, Hirox USA).

The pulp chambers were restored using a self-etch, dual-cure adhesive (Clearfil DC, Kuraray America) with a dual-cure, resin core material (Gradia Core, GC America, Alsip, IL, USA). The coronal preparation of the LD specimens was repaired with a nano-hybrid resin composite (Tetric Evo Ceram, Ivoclar Vivadent) after 5% hydrofluoric acid (IPS Ceramic Etching Gel, Ivoclar-Vivadent) treatment of the endodontic access ceramic margin, primer solution application, (Clearfil Ceramic Primer, Kuraray America), and a self-etch, two-step adhesive (Clearfil SE, Kuraray America). The Y-TZP specimen access was repaired in a similar fashion except that the endodontic access marginal area was prepared using silicatized sand (CoJet System, 3M ESPE) followed by ceramic primer application (Clearfil Ceramic Primer, Kuraray America). All materials were used following manufacturer directions. Any required photopolymerization was provided by a Polywave LED visible light curing unit (BluePhase G2, Ivoclar Vivadent) in which performance (1200 mW/cm^2) was periodically assessed with a radiometer (bluephase Meter II, Ivoclar Vivadent). All restored specimens were stored in 100% humidity at 37°C for 24 hours until testing.

Specimens were placed into a fixture mounted on a universal testing machine (RT-5, MTS Corporation, Eden Prairie, MN, USA) and loaded axially until failure at a rate of 0.5 mm per minute using a hardened, 3 mm diameter, stainless steel piston containing a 0.5 m radius of curvature.[66] Mean failure load results were first analyzed with the Shapiro-Wilk and Bartlett tests, which identified both a non-normal data distribution and variance inhomogeneity. Mean data for each material and luting strategy were analyzed using Mann Whitney U test at a 95% level of confidence (α=0.05).

RESULTS

Resultant mean preparation parameters are listed in Table 1. Preparation standardization was reasonably achieved, with surface area covariance ranging from 8% to 16% within each group with an overall coefficient of variation approximating 10% between the groups. Endodontic access openings were less than 10 mm^2 and did not represent greater than 16% of the estimated occlusal surface. The mean failure load results are listed in Table 2. Failure load results found that fracture strength was not significantly affected by endodontic access through both adhesively luted LD and Y-TZP crowns. However, the fracture strength of the conventional glass ionomer

Table 2: *Mean Failure Load Results*

Group (n=12 each)	Failure Load (N)[a]
ZR-KC	7473 (2201)[Y]
ZR-KC endodontic access	5404 (1141)[Z]
p value	0.0068
ZR-RX	5805 (1373)[Y]
ZR-RX endodontic access	4852 (1520)[Y]
p value	0.12
LD-RX	2492 (835)[Y]
LD-RX endodontic access	1787 (487)[Y]
p value	0.078

Abbreviations: LD-RX, lithium disilicate luted with self-adhesive resin cement; ZR-KC, zirconia luted with conventional glass ionomer cement; ZR-RX, zirconia luted with self-adhesive resin cement.

[a] Groups with same capital letter are similar within each group only (Mann Whitney U, p=0.05).

luted Y-TZP crowns were significantly reduced by endodontic access preparation.

DISCUSSION

Clinicians may encounter a tooth restored with a complete ceramic crown that requires endodontic treatment. Current estimates suggest that almost 50% of nonsurgical root canal treatments are performed through full-coverage restorations[26,27] with the repaired crown serving as the definitive restoration approximately three fourths of the time.[27] In contrast to metal, ceramic materials are brittle, and mechanical preparation may induce fractures, defects, and crack initiation.[51-54] Physical and mechanical properties may be impaired, and some authors suggest that the endodontic access is the source of any ensuing catastrophic failure of repaired ceramic crowns.[46] Despite the myriad factors affecting the durability of a ceramic crown containing an endodontic access, a recent systematic review of *in vitro* studies could not identify a best-practice protocol for improving the fracture resistance of ceramic crowns containing an endodontic access.[67]

The present study investigated the effect of endodontic access preparation on the failure load of LD and monolithic Y-TZP all-ceramic crowns luted onto prepared teeth. Adhesive luting protocols were used for both monolithic Y-TZP and LD materials, with additional Y-TZP groups evaluated using a conventional glass ionomer luting strategy. Preparations were accomplished by one researcher using a lathe-type device, which allowed standardization to be reasonably attained with intragroup covariance less than 16% and overall variation between the

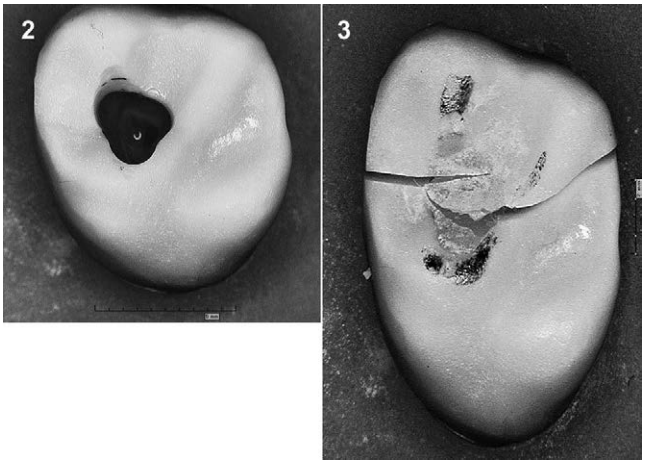


Figure 2. *Zirconia crown with endodontic access.*

Figure 3. *Failed view of the crown depicted in Figure 2.*

groups less than 10%. Conservative endodontic access preparations were also plausibly homogeneous with preparation areas less than 10 mm^2 that involved less than 16% of the occlusal surface area (Figure 2). Although the endodontic access opening and the calculated surface area of the testing probe were similar, anatomy of the molar occlusal surface ensured that the piston contact area was usually outside the access preparation margins, as outlined in Figure 3. Under the conditions of this study, the endodontic access dimension did not significantly decrease the failure load of adhesively luted monolithic Y-TZP and LD crowns. However, this was not observed with conventional glass ionomer cementation of Y-TZP. While adhesive resin techniques have been suggested to ameliorate surface flaws with predominantly glassy ceramics,[61-63] the authors advise caution regarding speculation that resin infiltration was a significant factor in this study, especially when the current status of reliable bonding to Y-TZP is considered.[38-40]

A number of previous studies concerning endodontic access preparations on molar all-ceramic crowns have used resin die substrates instead of prepared tooth surface. While resin die materials allow substrate uniformity, the authors maintain that prepared tooth structure substrates more closely approximate the clinical situation. Even so, Bompolaki and others[46] and Wood and others[47] found that endodontic access significantly weakened LD, laminated Y-TZP core, and alumina crowns, respectively. Qeblawi and others[48] reported that the adhesive cementation did improve endodontically accessed LD fracture resistance compared with those luted with zinc phosphate. Furthermore, a similar LD milled

materials outcome was observed with the findings of Bompolaki and others[46] as endodontic access did not significantly reduce failure load.The results for the LD control group compare favorably with that of Okada and others,[68] Mörmann and others,[69] and Carvalho and others.[70] The results of this study are similar to the recent report by Scioscia and colleagues[71] in that the intact adhesively luted Y-TZP crowns failure load was similar to that found in this study. While the present study's focus did not concern endodontic access repair protocols, different materials were used in contrast to that of Scioscia and others[71] with diverse results. This disparity can be somewhat reconciled in that the present study used a more conservative endodontic access preparation and that thermomechanical loading was not available as well.

The endodontic access preparations were not standardized in this study. To simulate clinical conditions, access cavity dimension was determined by a board-certified endodontist's ability to access all root canals for proper instrumentation. Accordingly, endodontic access cavity preparation size and form within all-ceramic crowns are a topic of interest and controversy. Earlier studies[72-76] have reported some benefits with a conservative (eg, contracted, ninja) endodontic access. Recently, Corsentino and others[77] found that that access cavity size was not a significant factor in fracture strength of endodontically treated molars, which was reinforced by Rover and others[78] and Moore and others.[79] Özyürek and others[80] reported no difference in fracture strength of mandibular first molars between conservative and traditional access preparations, and Jiang and others'[81] using an *in silico* finite element analysis, found no occlusal stress distribution differences between conservative, traditional, and extended endodontic access preparations. Furthermore, Silva and others[82] conducted a systematic review of all *in vitro* studies that concluded that the conservative endodontic access provided no observed advantage. Based on this more recent information, the authors reasoned that the disparity in endodontic access preparation size would have a minimal effect on this study's results.

Under this study's conditions, the null hypothesis was upheld in the situation of adhesive resin cementation. The conservative endodontic access preparation did not significantly reduce the adhesively luted Y-TZP and LD all-ceramic crown failure loads. However, the null hypothesis was rejected as significantly lower failure load resistance was observed with monolithic Y-TZP crowns containing an endodontic access when a conventional glass ionomer cement was used. A curious result of this study was that the Y-TZP crowns luted with a conventional glass ionomer cement luting agent demonstrated greater failure loads compared with the adhesive resin luting method. The authors have no current definitive explanation for this unexpected finding, as the mechanical and physical properties of the self-adhesive resin luting agent are overall greater than that of the conventional glass ionomer cement.[83,84] Since the results were the same for more than one group, the authors strongly suspect that some aspect of the testing conditions was involved, as well as possible difference with supporting tooth structure to a minor extent.

This study contains definite limitations, which are the subject of ongoing studies. Due to technology access constraints, this initial evaluation used axial static loading forces and could not contain an environmental fatigue component, as cyclic loading under wet conditions is suggested to produce failure results that may have more clinical relevance.[85,86] It can also be successfully argued that the failure modes demonstrated during this evaluation did not replicate that usually observed with clinical failure. To wit, retrieved clinically failed ceramics are thought to initiate from internal flaws enabling stress concentrations leading to cracks and defects at the ceramic-cement interface, all of which are accentuated from masticatory occlusal forces. [64,65,87,88]

Some authors suggest that *in silico* finite element analysis methods may provide more clinically pertinent evidence[86,89-92] and allow investigation into such parameters as endodontic access geometry and area, which would be difficult to standardize.[86] Since a preexisting study with similar testing conditions as the current investigation was not available in the current literature, the chosen sample size was an empirical increase to a slightly larger number than that usually observed in most studies. Work is planned using the present findings to establish more robust testing conditions to hopefully proffer future results with improved statistical analytical capability.

Furthermore, this study's results reflect restorations that were prepared using manufacturer recommendations that have recently been updated. Nevertheless, the authors maintain that this initial evaluation provides meaningful information noting that a conservative endodontic access did not significantly decrease the failure load resistance of monolithic Y-TZP and LD crowns. Further ongoing studies in this research series will include updated crown parameter dimensions and employ dynamic environmental functional fatigue testing. Most im-

portantly, clinicians should be strongly cautioned not to be emboldened by these initial results until further investigations have been accomplished.

CONCLUSION

Under this study's conditions, *in vitro* static testing suggests that a conservative endodontic access preparation does not significantly affect the failure load resistance of adhesively luted monolithic Y-TZP and LD crowns. Definitive recommendations cannot be proposed until further studies involving fatigue testing and the ability to establish an effective coronal seal have been accomplished.

Acknowledgement

Any opinions expressed in this work are of the authors only and do not represent the official opinion of the United States Air Force, Department of Defense, or the United States Government.

Regulatory Statement

This study was conducted in accordance with all the provisions of the local human subjects oversight committee guidelines and policies of the 81rst Medical Group. The approval code for this study is: FKE20160007N.

Conflict of Interest

The authors of this manuscript certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

(Accepted 15 December 2018)

REFERENCES

1. Christensen GJ (2013) Too many crowns? *Journal of the American Dental Association* **144(10)** 1174-1176.
2. Edelhoff D & Sorensen A (2002) Tooth structure removal associated with various preparation designs for anterior teeth *Journal of Prosthetic Dentistry* **87(5)** 503-509.
3. Hussain SKF, McDonald A, & Moles DR (2007) In vitro study investigating the mass of tooth structure removed following endodontic and restorative procedures *Journal of Prosthetic Dentistry* **98(4)** 260-269.
4. Chang SW, Lee SI, Bae WJ, Min KS, Shin ES, Oh GS, Pae HO, & Kim EC (2009) Heat stress activates iterleukin-8 and the antioxidant system via Nrf2 pathways in human dental pulp cells *Journal of Endodontics* **35(9)** 1222-1228.
5. Abou-Rass M (1982) The stressed pulp condition: an endodontic-restorative diagnostic concept *Journal of Prosthetic Dentistry* **48(3)** 264-267.
6. Dahl BL (1977) Dentine/pulp reactions to full crown preparation procedures *Journal of Oral Rehabilitation* **4(3)** 247-254.
7. Bergenholtz G (1991) Iatrogenic injury to the pulp in dental procedures: Aspects of pathogenesis, management and preventive measures *International Dental Journal* **41(2)** 99-110.
8. Christensen GJ (1997) Tooth preparation and pulp degeneration *Journal of the American Dental Association* **128(3)** 353-354.
9. Christensen GJ (2005) How to kill a tooth *Journal of the American Dental Association* **136(12)** 1711-1713.
10. Whitworth JM, Walls AW, & Wassell RW (2002) Crowns and extra-coronal restorations: Endodontic considerations: The pulp, the root-treated tooth and the crown *British Dental Journal* **192(6)** 315-320.
11. Cheung GS, Lai SC, & Ng RP (2005) Fate of vital pulps beneath a metal-ceramic crown or a bridge retainer *International Endodontic Journal* **38(8)** 521-530.
12. Valderhaug J, Jokstad A, Ambjørnsen E, & Norheim PW (1997) Assessment of the periapical and clinical status of crowned teeth over 25 years *Journal of Dentistry* **25(2)** 97-105.
13. Ortorp A, Kihl ML, & Carlsson GE (2012) A 5-year retrospective study of survival of zirconia single crowns in a private practice setting *Journal of Dentistry* **40(6)** 527-530.
14. Beier US, Kapferer H, & Dumfahrt H (2012) Clinical long-term evaluation and failure characteristics of all-ceramic restorations *International Journal of Prosthodontics* **25(1)** 70-78.
15. Rinke S, Lange K, Roediger M, & Gersdorff N (2015) Risk factors for technical and biological complications for zirconia single crowns *Clinical Oral Investigations* **19(8)** 1999-2006.
16. Paschalidis T, Bakopoulou A, Papa P, Leyhausen G, Geurtzen W, & Koidis P (2014) *Dental Materials* **30(12)** e405-e418.
17. Lefeuvre M, Amjaad W, Goldberg M, & Stanislawski L (2005) TEGDMA induces mitochondrial damage and oxidative stress in human gingival fibroblasts *Biomaterials* **26(25)** 5095-5266.
18. Chang HH, Chang MC, Wang HH, & Huang GF (2014) Urethane dimethacrylate induces cytotoxicity and regulates cyclooxygenase-2, hemeoxygenase and carboxylesterase expression in human dental pulp cells *Acta Biomaterialia* **10(2)** 722-731.
19. Stanislawski L, Lefeuvre M, Bourd K, Soheili Majd E, Goldberg M, & Périanin A (2003) TEGDMA induced toxicity in human fibroblasts is associated with early and drastic glutathione depletion with subsequent production of oxygen reactive species *Journal of Biomedical Materials Research Part A* **66A(3)** 476-482
20. Gallorini M, Cataldi A, & di Giacomo A (2014) HEMA induced cytotoxicity: oxidative stress, genotoxicity and apoptosis *International Endodontic Journal* **47(9)** 813-818
21. Jackson CR, Skidmore AE, & Rice RT (1992) Pulpal evaluation of teeth restored with fixed prostheses *Journal of Prosthetic Dentistry* **67(3)** 323-325.
22. Goodacre CJ & Spolnik KJ (1994) The prosthodontic management of endodontically treated teeth: A literature

review. Part I. Success and failure data treatment concepts *Journal of Prosthodontics* **3(4)** 243-250.

23. Goodacre CJ, Bernal G, Rungcharassaeng K, & Kan JY (2003) Clinical complications in fixed prosthodontics *Journal of Prosthetic Dentistry* **90(1)** 31-41.
24. Cheung GS, Lai SC, & Ng RP (2005) Fate of vital pulps beneath a metal-ceramic crown or a bridge retainer *International Endodontic Journal* **38(8)** 521-530.
25. Goldman M, Laosonthorn P, & White RR (1992) Microleakage—Full crowns and the dental pulp. *Journal of Endodontics* **18(10)** 473-475.
26. Trautmann G, Gutmann JL, Nunn ME, Witherspoon DE, & Shulman JD (2000) Restoring teeth that are endodontically treated through existing crowns. Part I: Survey on pulpal status on access *Quintessence International* **31(10)** 713-718.
27. Trautmann G, Gutmann JL, Nunn ME, Witherspoon DE, & Shulman JD (2000) Restoring teeth that are endodontically treated through existing crowns. Part II: Survey on restorative materials commonly used *Quintessence International* **31(10)** 719-728.
28. Gillen BM, Looney SW, Gu LS, Loushine BA, Weller RN, Loushine RJ, Pashley DH, & Tay FR (2011) Impact of the quality of coronal restoration versus the quality of root canal fillings on success of root canal treatment: A systematic review and meta-analysis *Journal of Endodontics* **37(7)** 895-902.
29. Pratt I, Aminoshariae A, Montagnese TA, Williams KA, Kaligbinejad N, & Mickel A (2016) Eight-year retrospective study of the critical time lapse between root canal completion and crown placement: Its influence on the survival of endodontically treated teeth *Journal of Endodontics* **42(11)** 1598-1603.
30. Trautmann G, Gutmann JL, Nunn ME, Witherspoon DE, & Shulman JD (2001) Restoring teeth that are endodontically treated through existing crowns. Part IV: Material usage and prevention of dye leakage *Quintessence International* **32(1)** 33-41.
31. Saunders WP & Saunders EM (1994) Coronal leakage as a cause of failure in root-canal therapy: A review *Endodontics Dental Traumatology* **10(3)** 105-108.
32. Madison S & Wilcox LR (1988) An evaluation of coronal microleakage in endodontically treated teeth. Part III. In vivo study *Journal of Endodontics* **14(9)** 455-458.
33. Ray HA & Trope M (1995) Periapical status of endodontically treated teeth in relation to the technical quality of the root filling and the coronal restoration *International Endodontic Journal* **28(1)** 12-18.
34. Heling I, Gorfil C, Slutzky H, Kopolovic K, Zalkind M, & Slutzky-Goldberg I (2002) Endodontic failure caused by inadequate restorative procedures: Review and treatment recommendations *Journal of Prosthetic Dentistry* **87(6)** 674-678.
35. Verissimo DM & do Vale MS (2006) Methodologies for assessment of apical and coronal leakage of endodontic filling materials: A critical review *Journal of Oral Science* **48(3)** 93-98.
36. Schwartz RS & Fransman R (2005) Adhesive dentistry and endodontics: Materials, clinical strategies and procedures for restoration of access cavities: A review *Journal of Endodontics* **31(3)** 151-165.
37. Al-Maqtari AAA & Lui JL (2010) Effect of aging on coronal microleakage in access cavities through metal ceramic crowns restored with resin composites *Journal of Prosthodontics* **19(5)** 347-356
38. Bömicke W, Schurz A, Krisam J, Rammelsberg P, & Rues S (2016) Durability of resin-zirconia bonds produced using methods available in dental practice *Journal of Adhesive Dentistry* **18(1)** 17-27.
39. Khan AA, Al Kheraif AAA, Jamaluddin S, ElSharawy M, & Divakur DD (2017) Recent trends in surface treatment methods for bonding composite cement to zirconia: A review *Journal of Adhesive Dentistry* **19(1)** 7-19.
40. Blatz MB, Vonderheide M, & Conejo J (2018) The effect of resin bonding on long-term success of high-strength ceramics *Journal of Dental Research* **97(2)** 132-139
41. Beier US, Kapferer I, & Dumfahrt H (2012) Clinical long-term evaluation and failure characteristics of all-ceramic restorations *International Journal of Prosthodontics* **25(1)** 70-78.
42. Rinke S, Lange K, Roediger M, & Gersdorff N (2015) Risk factors for technical and biological complications with zirconia single crowns *Clinical Oral Investigations* **19(8)** 1999-2006.
43. Grobecker-Karl T, Christian M, & Karl M (2016) Effect of endodontic access cavity preparation on monolithic and ceramic veneered zirconia restorations *Quintessence International* **47(9)** 725-729.
44. Haselton DR, Lloyd PM, & Johnson WT (2000) A comparison of the effects of two burs on endodontic access in all-ceramic high Lucite crowns *Oral Surgery Oral Medicine Oral Pathology Oral Radiology Endodontics* **89(4)** 486-492.
45. Sabourin CR, Flinn BD, Pitts DL, Gatten TL, & Johnson JD (2005) A novel method for creating endodontic access preparations through all-ceramic restorations: Air abrasion and its effect relative to diamond and carbide bur use *Journal of Endodontics* **31(8)** 616-619.
46. Bompolaki D, Kontogiorgos E, Wilson JB, & Nagy WW (2015) Fracture resistance of lithium disilicate restorations after endodontic access preparation: An in vitro study *Journal of Prosthetic Dentistry* **114(4)** 580-586.
47. Wood K, Berzins D, Luo Q, & Nagy W (2006) Resistance to fracture of two all ceramic crown materials following endodontic access *Journal of Prosthetic Dentistry* **95(1)** 33-41.
48. Qeblawi D, Hill T, & Chlosta K (2011) The effect of endodontic access preparation on the failure load of lithium disilicate glass-ceramic restorations *Journal of Prosthetic Dentistry* **106(5)** 328-336.
49. Kelly R, Fleming G, Hooi P, Palin W, & Addison O (2014) Biaxial flexure strength determination of endodontically accessed ceramic restorations *Dental Materials* **30(8)** 902-909.
50. Cuddihy M, Gorman CM, Burke FM, Ray N, & Kelliher D (2013) Endodontic access cavity simulation in ceramic dental crowns *Dental Materials* **29(6)** 626-634.

51. Sutherland JK & Teplitsky PE (1989) Endodontic access of all-ceramic crowns *Journal of Prosthetic Dentistry* **61(2)** 146-149.
52. Teplitsky PE & Sutherland JK (1985) Endodontic access of cerestore crowns *Journal of Prosthetic Dentistry* **11(12)** 555-558.
53. Cohen BD & Wallace JA (1991) Castable glass ceramic crowns and their reaction to endodontic therapy *Oral Surgery, Oral Medicine, Oral Pathology* **72(5)** 328-326.
54. Kelly RD, Palin WM, Tomson PL, & Addison O (2017) The impact of endodontic access on the biaxial flexure strength of dentine-bonded crown substrates—An in vitro study *International Endodontic Journal* **50(2)** 184-193.
55. Hu KX & Chandra A (1993) A fracture mechanics approach to modelling strength degradation in ceramic grinding processes *Journal of Engineering for Industry* **115(1)** 73-83.
56. Zhang GM, Satish KG, & Ko WK (1994) The Mechanics of Material Removal Mechanisms in Machining Ceramics Technical Report TR 94-22rl *College Park, MD: Institute for Systems Research*.
57. Sindel J, Petschelt A, Grellner F, Dierken C, & Griel P (1998) Evaluation of subsurface damage in CAD/CAM machined dental ceramics *Journal of Materials Science Materials in Medicine* **9(5)** 291-295.
58. Thompson JY, Anusavice KJ, Naman A, & Morris HF (1994) Fracture surface characterization of clinically failed all-ceramic crowns *Journal of Dental Research* **73(12)** 1824-1832.
59. Rekow D & Thompson VP (2007) Engineering long term clinical success of advanced ceramic prosthesis *Journal of Material Science Materials in Medicine* **18(1)** 47-56.
60. Grobecker-Karl T, Christian M, & Karl M (2016) Effect of endodontic access cavity on monolithic and ceramic veneered zirconia restorations *Quintessence International* **47(9)** 725-729
61. Fleming GJP & Addison O (2009) Adhesive cementation and the strengthening of all-ceramic dental restorations *Journal of Adhesion Science and Technology* **23(7-8)** 945-949.
62. Fleming GJ, Hooi P, & Addison O (2012) The influence of resin flexural modulus on the magnitude of ceramic strengthening *Dental Materials* **28(7)** 769-776.
63. Rungruanaganut P & Kelly JR (2012) Insights into "bonding" of all-ceramics influenced by cement, sand-blasting and water storage time *Dental Materials* **28(9)** 939-944.
64. Quinn JB, Quinn GD, Kelly JR, & Scherrer SS (2005) Fractographic analyses of three ceramic whole crown restoration failures *Dental Materials* **21(10)** 920-929.
65. Kelly JR, Giordano RA, Poeber RI, & Cima MJ (1990) Fracture-surface analysis of dental ceramics. Clinically-failed restorations *International Journal of Prosthodontics* **3(5)** 430-440.
66. Kelly JR (1999) Clinically relevant approach to failure testing of all-ceramic restorations. *Journal of Prosthetic Dentistry* **81(6)** 652-661.
67. Gorman C, Ray N, Burke F (2016) The effect of endodontic access on all-ceramic crowns: A systematic review of in vitro studies *Journal of Dentistry* **53(1)** 22-29.
68. Okada R, Asakura M, Ando A, Kumano H, Ban S, Kawai T, & Takebe J (2018) Fracture strength testing of crowns made of CAD/CAM composite resins *Journal of Prosthodontic Research* **62(1)** 287-292.
69. Mörmann WH, Bindl A, Lüthy H. & Rathke A (1998) Effect of preparation and luting system on all-ceramic computer-generated crowns *International Journal of Prosthodontics* **11(4)** 333-339
70. Carvalho AR, Bruzi G, Anderson RE, Maia HP, Giannani M, & Magne P (2016) Influence of adhesive core buildup designs on the resistance of endodontically treated molars restored with lithium disilicate CAD/CAM crowns *Operative Dentistry* **41(1)** 76-82
71. Scioscia A, Helfers A, Soliman S, Krastl G, & Zitzmann NU (2018) Performance of monolithic and veneered zirconia crowns after endodontic treatment and different repair strategies *Operative Dentistry* **43(2)** 170-179.
72. Krishan R, Paqué F, Ossareh A, Kishen A, Dao T, & Friedman S (2014) Impacts of conservative endodontic cavity on root canal instrumentation efficacy and resistance to fracture assessed in incisors, premolars, and molars *Journal of Endodontics* **48(8)** 1160-1166.
73. Clark D & Khademi J (2010) Modern molar endodontic access and directed dentin conservation *Dental Clinics of North America* **54(2)** 249-273.
74. Gluskin AH, Peters C, & Peters OA (2014) Minimally invasive endodontics: Challenging prevailing paradigms *British Dental* Journal **216(6)** 347-353.
75. Ahmed HM & Gutmann JL (2015) Education for prevention: A viable pathway for minimal endodontic treatment intervention *Endodontic Practice Today* **9(4)** 283-285.
76. Bürklein S & Schäfer E. (2015) Minimally invasive endodontics *Quintessence International* **46(2)** 119-124.
77. Corsentino G, Pedullà E, Castelli L, Liguori M, Spicciarelli V, Martignoni M, Ferrari M, & Grandini S (2018) Influence of access cavity preparation and remaining tooth substance on fracture strength of endodontically treated teeth *Journal of Endodontics* **44(9)** 1416-1421.
78. Rover G, Belladonna FG, Bortoluzzi EA, De-Deus G, Silva EJNL, & Teixeira CS (2017) Influence of access cavity design on root canal detection, instrumentation efficacy, and fracture resistance assessed in maxillary molars *Journal of Endodontics* **43(10)** 1657-1662.
79. Moore B, Verdelis K, Kishen A, Dao T, & Friedman S (2016) Impacts of contracted endodontic cavities on instrumentation efficacy and biomechanical responses in maxillary molars *Journal of Endodontics* **42(12)** 1779-1783
80. Özyürek T, Üler Ö, Demiryürek EÖ, & Yimaz F (2018) The effects of endodontic access cavity preparation design on the fracture strength of endodontically treated teeth: Traditional versus conservative preparation *Journal of Endodontics* **44(5)** 800-805.

81. Jiang Q, Huang Y, Tu X, Zhengmao L, Yeng H, & Yang X (2018) Biomechanical properties of first maxillary molars with different endodontic cavities: A finite element analysis *Journal of Endodontics* **44(8)** 1283-1288.

82. Silva EJNL, Rover G, Belladonna FG, De-Deus G, da Silveira Teixeira C, & da Silva Fidalgo TK (2018) Impact of contracted endodontic cavities on fracture resistance of endodontically treated teeth: A systematic review of in vitro studies *Clinical Oral Investigations* **22(1)** 109-118.

83. Scioscia A, Helfers A, Soliman S, Krastl G, & Zitzmann NU (2018) Performance of monolithic and veneered zirconia crowns after endodontic treatment and different repair strategies *Operative Dentistry* **43(2)** 170-179.

84. Attar N, Tam LE, & McComb D (2003) Mechanical and physical properties of contemporary dental luting agents *Journal of Prosthetic Dentistry* **89(2)** 127-134.

85. de la Macorra JC & Pradíes G (2002) Conventional and adhesive luting cements *Clinical Oral Investigations* **6(1)** 198-204.

86. Arola D (2017) Fatigue testing of biomaterials and their interfaces *Dental Materials* **33(4)** 367-381.

87. Cuddihy M, Gorman CM, Burke FM, Ray NJ, & Kelliher D (2013) Endodontic access cavity simulation in ceramic dental crowns *Dental Materials* **29(6)** 626-634.

88. Kelly JR, Campbell SD, & Bowen HK (1989) Fracture surface analysis of dental ceramics *Journal of Prosthetic Dentistry* **62(5)** 536-541.

89. Campos RE, Soares PV, Versluis A, O de Junior, Ambrosano GMB, & Nunes IF (2015) Crown fracture: Failure load, stress distribution, and fractographic analysis *Journal of Prosthetic Dentistry* **114(3)** 447-455

90. Magne P & Tan DT (2008) Incisor compliance following operative procedures: A rapid 3D finite element analysis using micro-CT data *Journal of Adhesive Dentistry* **10(1)** 49-56.

91. Dejak B, Míotkowski A, & Romanowicz M (2003) Finite element analysis of stresses in molars during clenching and mastication *Journal of Prosthetic Dentistry* **90(6)** 591-597.

92. Rodregues FP, Li J, Silikas N, Ballester RY, & Watts DC (2009) Sequential software processing of micro-XCT dental images for 3D-FE analysis *Dental Materials* **25(6)** e47-e55.

©Operative Dentistry, 2020, **45-3,** 286-296

Effects of Bioactive Agents on Dentin Mineralization Kinetics After Dentin Bleaching

ALM Ubaldini • RC Pascotto • F Sato • VO Soares • ED Zanotto • ML Baesso

Clinical Relevance

Dental bleaching treatment significantly decreases dentin bond strength. Bleached dentin remineralization treatment seems to effectively promote mineral formation, increase dentin bond strengths, and improve dentin's chemical affinity with adhesive monomers.

SUMMARY

Objectives: This study evaluated effects of Bioglass 45S5 (BG) and Biosilicate (BS) remineralization on the chemical composition and bond strength of control dentin (CD) and bleached dentin (BD) surfaces.

Methods and Materials: Dentin bleaching treatment was performed using the walking bleaching technique with 0.01 g of sodium perborate and 0.5 mL of 3% hydrogen peroxide for 14 days. Remineralization treatment was carried out by rubbing a remineralization solution (0.015 g of BG or BS diluted in 1.35 mL of distilled water) on the etched dentin surface for 30 seconds. Micro-Raman spectroscopy (MRS) was used to quantitatively analyze the mineral matrix ratios of CD and BD (n=5) after remineralization treatment with BG and BS over 15 days of incubation in artificial saliva. The CD and BD discs (n=10) with and without remineralization treatment with BG and BS were restored using a two-step etch-and-rinse adhesive system (Optibond S, Kerr) and five layers of 1-mm-thick composite resin (Filtek Z250, 3M ESPE). The restored dentin discs were sectioned into nine bonded beams with cross-sectional areas of approximately 0.9 mm^2 and tested for microtensile bond strength (μTBS). The dentin surface of one fractured beam per tooth was submitted to MRS to characterize the physicochemical composition (n=10) at the interface. The data were analyzed using one-way analysis of variance and the Tukey-Kramer post hoc test ($p<0.005$).

Results: MRS bioactive analyses revealed that both BG and BS promoted increased mineral matrix ratios in the CD and BD. Significantly higher μTBS values were found after CD treatment with BG (CD: 57 MPa±11; CD-BG: 78

*Adriana Lemos Mori Ubaldini, DDS, PhD, Department of Dentistry, State University of Maringá, Maringá, PR, Brazil

Renata Corrêa Pascotto, DDS, PhD, Department of Dentistry, State University of Maringá, Maringá, PR, Brazil

Francielle Sato, PhD, Department of Physics, State University of Maringá, Maringá, PR, Brazil

Viviane Oliveira Soares, PhD, Department of Science, State University of Maringá, Goioerê, PR, Brazil

Edgar Dutra Zanotto, PhD, Department of Materials Engineering, Federal University of São Carlos, São Carlos, SP, Brazil

Mauro Luciano Baesso, PhD, Department of Physics, State University of Maringá, Maringá, PR, Brazil

*Corresponding author: Av Mandacaru 1550, 87080-0009, Maringá, PR, Brazil; e-mail: adrianaubaldini@gmail.com

https://doi.org/10.2341/18-272-L

MPa±15) and when BG and BS were applied to the BD (BD: 42 MPa±5; BD-BG: 71 MPa±14; BD-BS: 64 MPa±11) ($p<0.005$). The MRS analysis of the fractured dentin beam showed that the remineralization treatment significantly increased the dentin relative mineral concentration and promoted the appearance of new interface peaks, indicating a chemical interaction ($p<0.005$).

Conclusion: Remineralization of BD is an effective therapy to restore damage caused by dentin bleaching and acid conditioning. This approach not only increases dentin mineral compounds but also improves dentin's ability to interact chemically with the adhesive system.

INTRODUCTION

Restorative procedures for endodontically treated teeth remain challenging in clinical restorative dentistry due to the high risk of biomechanical failure.[1,2] Internal bleaching is a conservative option to improve the esthetics of discoloured endodontically treated teeth; however, it decreases tooth fracture strength and increases the failure rate of restorative procedures. Additionally, internal bleaching agents chemically interact with dentin compounds,[3] thereby promoting changes in the dentin's organic composition by denaturing the collagen proteins[4] and causing demineralization,[5] thus reducing its adhesion to restorative materials.[6]

The hybrid layer is defined as a three-dimensional polymer/collagen network with a continuous and stable bond between the adhesive monomers and dentin.[7] Previous studies have indicated that this ideal relationship is not achieved due to a discrepancy between the depths of dentin demineralization and adhesive infiltration, resulting in unprotected collagen fiber exposure and susceptibility to deterioration.[8,9] Loss of integrity of the hybrid layer may occur because of water-sorption-induced hydrolysis of the adhesive monomers and as a result of acidic conditioning, which activates collagen fibril degradation through endogenous matrix metalloproteinases (MMPs).[10-12]

The use of agents that promote dentin remineralization, such as calcium sodium phosphosilicate glass (Bioglass 45S5 [BG]: 24.5% Na_2O, 24.5% CaO, 45% SiO_2, 6% P_2O_2 — wt%)[13] and a fully crystalline glass-ceramic (Biosilicate [BS]: 23.75% Na_2O, 23.75% CaO, 48.5% SiO_2, 4.0% P_2O_5 — wt%),[14] has been shown to be an effective alternative for preserving adhesive interface integrity.[15,16] These bioactive compounds induce a progressive dehydration mechanism and replace extrafibrillar and intrafibrillar water, restoring the protective function of the collagen apatites[17-19] and promoting the formation of a hydroxyapatite layer on the dentin surface.[20-23]

Considering that no information is available regarding the use of remineralization agents on bleached dentin (BD) during restorative bonding steps, this study aimed to investigate the remineralization abilities of two bioactive materials and their potential therapeutic effects on the resin-dentin bond when they were used as remineralizing agents on BD. The following null hypotheses were tested: 1) no difference exists in the quantities of mineral components of control dentin (CD) and BD in the presence or absence of remineralization treatment, 2) the dentin bond strength is not altered after internal bleaching and/or remineralization treatment, and 3) dentin remineralization does not change the dentin-adhesive interface composition.

METHODS AND MATERIALS

Specimen Preparation

Eighty extracted unerupted human third molars were used following guidelines approved by the Local Ethics Committee (research protocol: 50615715.1.0000.0104). Using a low-speed diamond saw (Diamond Wheel 012"x fine, South Bay Technology Inc, San Clemente, CA, USA) under water cooling, a flat midcoronal dentin disc of 5 mm was prepared from each tooth. From these 70 dentin discs, 60 were set aside for microtensile bond strength (μTBS) testing and posterior physicochemical analysis using micro-Raman spectroscopy (MRS), while 20 were cut into four small pieces (2×2×5 mm) and used for bioactive tests. The specimens were divided into six groups based on the treatment protocol (Figure 1): 1) the CD group; 2) the CD-BG group, CD remineralized with a calcium sodium phosphosilicate glass (BG, Vitreous Materials Laboratory, São Carlos, Brazil); 3) the CD-BS group, CD remineralized with a fully crystalline glass-ceramic (BS, Vitrovita, São Carlos, Brazil); 4) the BD group; 5) the BD-BG group, BD remineralized with BG; and the BD-BS group, BD remineralized with BS.

Dentin bleaching treatment was performed by simulating the walking bleach technique using a paste made with 0.01 g of sodium perborate (Whiteness Perborato, FGM Produtos Odontológicos,

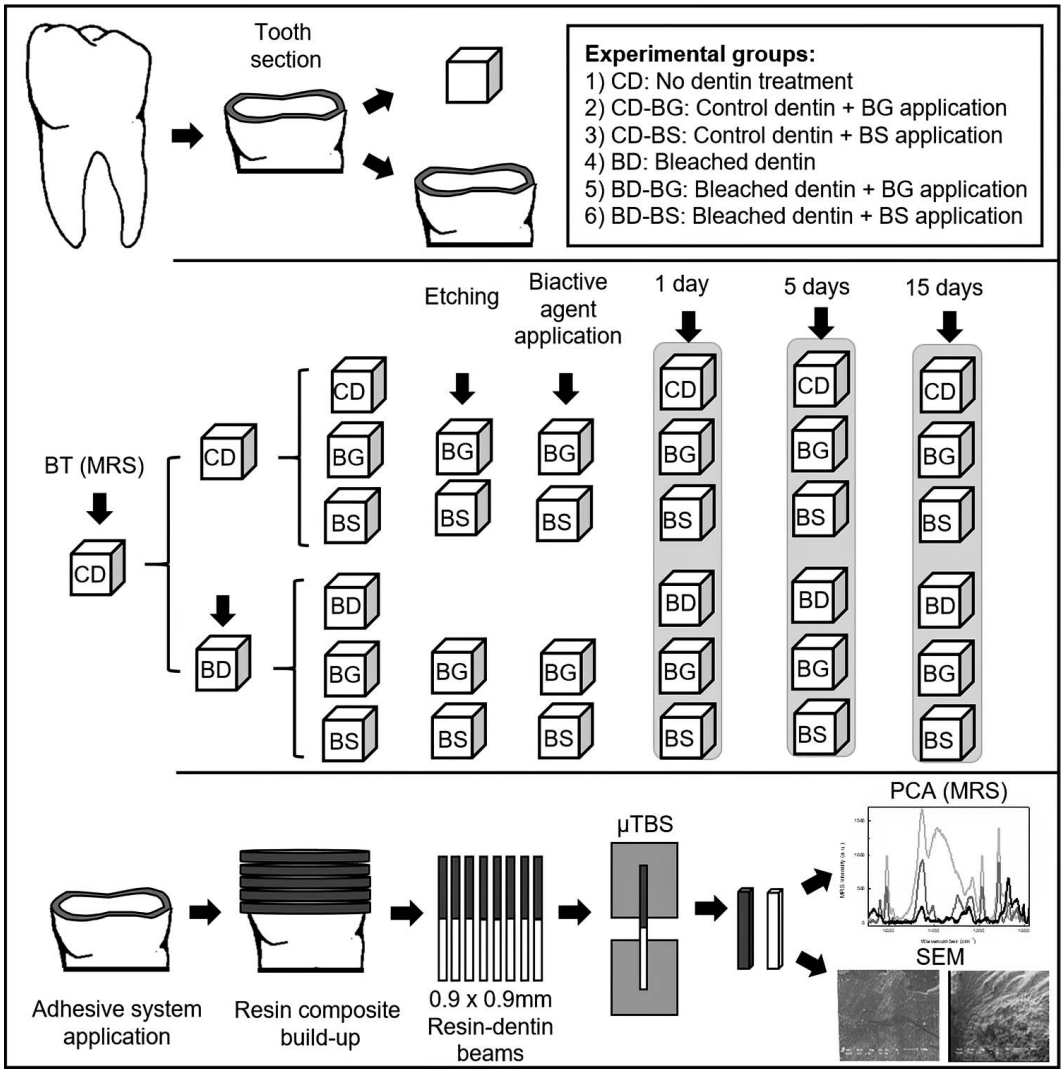


Figure 1. *Diagram illustrating preparation of the specimens and the analysis sequence.*

Joinville, Brazil) and 0.5 mL of 3% hydrogen peroxide (Rioquímica, São Jose do Rio Preto, Brazil). During the 14 days of bleaching treatment, the specimens were stored in an incubator (ProLab, São Paulo, Brazil) with a 95% ± 5% relative humidity at 37°C, and the bleaching agent was replaced after the seventh day. After the bleaching treatment was finished, the dentin surfaces were washed with distilled water and air-dried for 2 seconds.

Remineralization treatment was performed with two different agents, including the gold standard remineralizing agent, BG,[13,24,25] and the experimental remineralizing crystalline glass-ceramic, BS.[24] The CD and BD surfaces were etched with 37% phosphoric acid (Condac37, FGM Produtos Odontológicos) for 10 seconds, followed by a copious water rinse for 1 minute. After acid conditioning, the remineralization treatment was carried out to induce mineral bone formation before adhesive application. The remineralization solutions were prepared by diluting 0.1 mg of the remineralizing agent powder in 1 mL of deionized water immediately before application.[20] A micropipette (Monocanal VVCS-10, Digipet, São Paulo, Brazil) was used to apply 10 μl of this solution to the moist dentin surface. Using a microbrush, the solution was gently rubbed on the dentin for 30 seconds. The surface was then washed with deionized water for 15 seconds and gently dried with filter paper to remove excess water.

Bioactive Test

Bioactive analysis (n=10) was performed to investigate the ability of BG and BS to induce dentin

remineralization before or after bleaching treatment. MRS initial spectra were obtained before treatment (as a control group), after the procedures of bleaching and acid conditioning, and after the remineralization agent was applied. To enable the MRS analysis according to storage time after remineralization treatment, the specimens were adapted to fit into a plastic device and immersed in 25 mL of artificial saliva[9] in a 37°C water bath. Then, long-term analyses were carried out after 1 day, 5 days and 15 days of immersion. Before obtaining the spectra, the specimens were rinsed with distilled water for 30 seconds and air-dried.

Raman spectra were obtained with a confocal Raman microscope (Senterra Bruker Optik GmbH, Ettingen, Germany). After the samples were excited by a 785-nm laser source, spectra were recorded in the spectral range of 450 to 1800 cm^{-1}. The laser (power=100 mW) was focused onto the specimen with a 20× magnification lens. The spatial resolution was 3 to 5 cm^{-1}, and the integration time of the detector was 3 seconds. Each curve resulted from an average of 60 spectra. Reference points were determined on the specimen surface to enable the MRS spectra to be gathered at the same position before and after treatment, as well as during the long-term analyses. Four spectra were obtained for each measurement, and the final result for each specimen was calculated by the average of these four spectra.

The spectra were baseline-corrected, and the integrated areas of the dentin organic (amide I: 1650 cm^{-1}) and mineral compounds (phosphate ν1: 961 cm^{-1}) were calculated. Then, the dentin structural modifications were characterized by the mineral matrix ratio (961 cm^{-1}/1650 cm^{-1}).[22] To standardize the graphic visual analyses, all ratios were normalized by the values of the control spectra. Additionally, the MRS spectra from BG and BS were obtained to characterize their chemical structures.

Restorative Procedures

An adhesive interface was created to enable μTBS and physicochemical analyses. For the groups in which dentin was tested as a control surface, restorative treatment was conducted immediately after specimen preparation. However, for the groups in which the dentin tissue was bleached, restorative treatment was carried out 14 days after the dentin bleaching treatment was completed to eliminate any residual by-products of the bleaching agent. During those 14 days, the BD specimens were stored in an incubator with a 95% ± 5% relative humidity at 37°C. Restorative procedures were performed according to the manufacturer's instructions using a two-step etch-and-rinse adhesive (Optibond S, Kerr, Orange, CA, USA) and five layers of 1-mm-thick composite resin (Filtek Z250, 3M ESPE, AG Dental Products, Seefeld, Germany). Each layer was light-cured for 20 seconds at 1200 mW/cm^2 with a light-emitting diode unit (Radii, Cal-SDI, Bayswater, Australia). Specimens were stored in artificial saliva for seven days at 37°C before testing.

Microtensile Bond Strength Test (μTBS)

The restored dentin blocks (n=10) were longitudinally sectioned across their interfaces in both mesial-distal and buccal-lingual directions to obtain nine bonded beams with cross-sectional areas of approximately 0.9 mm^2. The exact width of each beam was measured with a digital caliper (Zaas Precision; Amatools, São Paulo, Brazil).

The position of the beams was equidistant between the jig claws and perpendicular to the tensile force. Each restoration interface was tested under 0.5 mm/min traction in a universal test machine (EZ Test, Shimadzu, Kyoto, Japan) until the moment of specimen fracture. The tensile force (newtons) was divided by the cross-sectional area in square millimeters to express the bond strength value in megapascals. The μTBS values were computed for each tooth by averaging the values of the nine resin-dentin beams from that tooth. Pretest failures were included in this average by assigning to it the minimum bond strength value found for the corresponding tooth.

The failure modes were evaluated using scanning electron microscopy (Superscan SS-550, Shimadzu) with 100× magnification. The fractured beam surfaces were placed onto aluminium discs and sputter-coated with a gold-palladium alloy (IC-50, Shimadzu). The failure patterns were classified as follows: 1) adhesive fracture when the fracture site was located between the adhesive and dentin; 2) mixed when the fracture involved the dentin-adhesive interface, including cohesive failure of the dentin and composite resin; 3) cohesive dentin fracture; and 4) cohesive fracture in the composite resin.

Physicochemical Analysis of the Fractured Dentin Interface

Physicochemical analysis of the fractured dentin interface was performed on the five tested beams that had the highest μTBS values per experimental group (n=5). The resin-dentin interface modifications due to bleaching and/or remineralization

treatment were analyzed through chemical mapping using the same equipment and configuration described for the bioactive analysis but with a 100×-magnification lens. A scan of the entire area of the fractured dentin (0.9 mm^2) was performed, and MRS mapping was carried out by selecting 10 points on both the X- and Y-axes with a distance of 0.09 mm between them. All spectra were collected systematically under the same conditions.

The MRS spectra were submitted to baseline correction, and an average spectrum was obtained per line on the X-axis of the spectral map. Dentin physicochemical modifications were investigated through analysis of the mineral matrix ratio (961 cm^{-1}/1650 cm^{-1}). Additionally, the Raman spectra of CD, BD and the adhesive system were visually compared with the average spectra obtained from the evaluated fractured interfaces. Comparison of the spectra demonstrated the appearance of three new MRS bands in the dentin interface spectra; these bands were not identified in the CD and BD spectra or in the adhesive spectra. These new MRS bands were centered at 1295 cm^{-1} (C-H bonds),[26] 1405 cm^{-1} (methylene CH_2),[27] and 1637 cm^{-1} (methacrylate monomer).[10] The areas of the new bands were measured and normalized to the area of the amide I band of each respective spectrum.

Statistical Methods

Statistical analyses were performed using R i386 3.0.2 software (R statistical software, R Foundation for Statistical Computing, Vienna, Austria). The ratios obtained by the bioactive test and physicochemical analysis were submitted to descriptive statistics and were presented in graphics with their means and standard deviations. The μTBS data were statistically analyzed with the Shapiro-Wilk normality test, two-way analysis of variance and the Tukey-Kramer post hoc analysis (α=0.05).

RESULTS

MRS ratios obtained from the bioactive test are illustrated in Figure 2A,B. The mineral matrix ratio (961 cm^{-1}/1650 cm^{-1}) demonstrated that remineralization treatment with both agents improved the mineral content of BD after the acid conditioning step. The relative mineral composition of the CD remained constant during the 15 days of incubation (Figure 2A), showing that immersion in artificial saliva did not promote mineral formation on the CD surface. Bleaching treatment promoted a reduction in the dentin relative mineral content, which was not restored to its initial value after 15 days of artificial saliva immersion (Figure 2B). The acid-conditioning step reduced the mineral composition of the CD (Figure 2A) and intensified the loss of the mineral composition of the BD (Figure 2B). Nevertheless, remineralization with BG and BS restored this mineral loss. Mineral deposition on the CD occurred immediately after remineralization treatment with BG (CD-BG), required one day of incubation when BS solution was used (CD-BS), and was stable for both groups after 15 days of artificial saliva incubation (Figure 2A). BD mineral restoration was

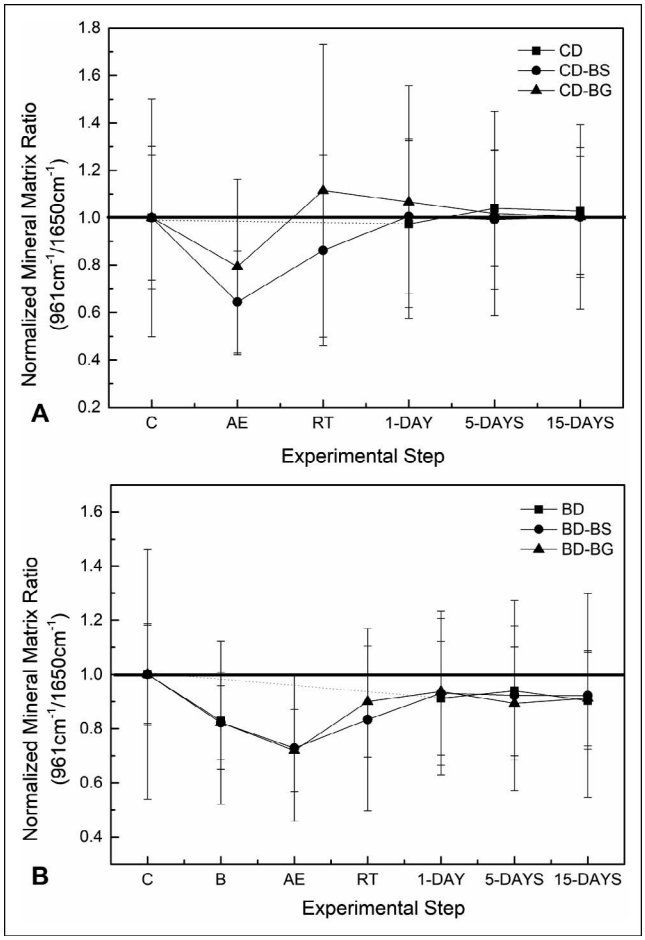


Figure 2. *Mineral matrix ratio (961 cm^{-1}/1650 cm^{-1}) obtained from the bioactive test under different experimental conditions: B. before any treatment, initial measurement; BL, after bleaching treatment; 1-Day, after one day of artificial saliva incubation; 5-Days, after five days of artificial saliva incubation; 15-Days. after 15 days of artificial saliva incubation AE. after etching; RT, right after remineralization treatment;. (A): Remineralization using a calcium sodium phosphosilicate glass. (B):Rremineralization using a fully crystalline glass-ceramic. Bleaching treatment reduced the dentin relative mineral content. Artificial saliva immersion did not change the mineral composition of CD or BD. The acid conditioning step reduced the mineral compositions of CD and BD. Remineralization treatment using BG and BS improved the mineral contents of CD and BD immediately after agent application in groups CD-BG, BD-BG, and BD-BS and required one day of artificial saliva incubation for CD-BS.*

Table 1: *Effect of Bleaching and Remineralization Treatment on Dentin Microtensile Bond Strength (MPa) According to Experimental Groups*

Group	Mean±SD	Premature failure	Total Beams*
CD	57.4±11.3	5	85 AB
CD-BG	78.5±15.2	0	90 C
CD-BS	73.7±14.7	0	90 BC
BD	42.2±5.5	10	80 D
BD-BG	70.9±13.7	3	87 BC
BD-BS	63.8±11.0	5	85 BC

Abbreviations: CD, control dentin; CD-BG, control dentin with bioglass; CD-BS, control dentin with crystalline glass-ceramic; BD, bleached dentin; BD-BG, bleached dentin with bioglass and BD-BS, bleached dentin with crystalline glass-ceramic.
** Different capital letters indicate the significant statistical difference (p<0.05), after two-way analysis of variance and Tukey tests.*

more intense shortly after the BG and BS remineralization treatments (BD-BG and BD-BS) and presented continuous behavior after 15 days of incubation. Although the remineralization approach improved the mineral content of the BD, this treatment was not capable of restoring the dentin mineral components to their initial values (Figure 2B).

Microtensile Bond Strength Test

The μTBS results are shown in Tables 1 and 2 . The statistical analysis indicated that bleaching treatment significantly decreased the dentin μTBS values (CD: 57.4±11.3 MPa; BD: 42.2±5.5 MPa) ($p<0.05$). Remineralization treatment with BG promoted a significant increase in the CD μTBS values (57.4±11.3 MPa; CD-BG: 78.5±15.2 MPa) ($p<0.05$), and both BG and BS treatments resulted in significantly higher BD μTBS values (BD: 42.2±5.5 MPa; BD-BG: 70.9±13.7 MPa; BD-BS: 63.8±11.0 MPa) ($p<0.05$). The 2-way ANOVA (Table 3) indicated a significant effect for the bleaching ($p=0.001$) and the remineralization treatment ($p<0.001$). The interaction term was not significant ($p=0.60$). Scanning electron microscopy analysis of the fractured surfaces revealed that most failures in groups CD, CD-BG, and CD-BS were at the adhesive interface, while the failure patterns were mostly mixed for group BD-BG (Table 2). The types of failures in all experimental groups are illustrated in Figure 3A through D.

Table 2: *Failure Modes Distribution According to Experimental Groups*

Group	Failure Mode, n (%)[a]			
	1	2	3	4
CD	40 (47)	33 (39)	7 (8)	5 (6)
CD-BG	50 (56)	36 (40)	2 (2)	2 (2)
CD-BS	48 (54)	36 (40)	4 (4)	2 (2)
BD	45 (56)	30 (38)	3 (4)	2 (2)
BD-BG	37 (42)	42 (48)	5 (6)	3 (4)
BD-BS	43 (50)	30 (36)	8 (9)	4 (5)

Abbreviations: CD, control dentin; CD-BG, control dentin with bioglass; CD-BS, control dentin with crystalline glass-ceramic; BD, bleached dentin; BD-BG, bleached dentin with bioglass and BD-BS, bleached dentin with crystalline glass-ceramic.
[a] Failure modes: 1, adhesive failure; 2, mixed failure; 3, cohesive failure in the dentin; 4, cohesive failure in composite resin.

Table 3: *Two-way Analysis of Variance*

Source	*df*	Type III Sum of Squares	Mean Square	F	*p**
Bleaching treatment	1	1786.9	1786.9	11.71	0.001
Remineralization treatment	2	6733.21	3366.6	22.06	<0.001
Interaction	3	154.07	77.03	0.5	0.6

Abbreviation: df, *degrees of freedom.*
** p<0.05 indicates significant difference.*

Physicochemical Analysis of the Fractured Dentin Interface

A qualitative comparison of the spectra of the dentin surface, adhesive system, and fractured interface is illustrated in Figure 4. Physicochemical analysis of the fractured dentin beam showed an increased mineral matrix ratio (961 cm^{-1}/1650 cm^{-1}) at the interfaces in groups CD-BG and BD-BS (Figure 5A). The new MRS peak ratio analyses revealed that the C-H band (1295 cm^{-1}) was most evident among the new peaks and presented a higher value in the groups treated with the remineralizing agents (CD-BG, BD-BG, and BD-BS) (Figure 5B).

DISCUSSION

This study showed higher dentin mineral matrix ratios when the CD and BD tissues were treated with both of the tested bioactive agents. Dental bleaching treatment significantly decreased the dentin bond strength; however, the mineral formation induced by remineralization treatment not only increased the BD mineral content but also mediated dentin bond strengths. The fractured dentin surface analysis proved that mineral deposition was improved due to remineralization agent application and demonstrated that the dentin tissue presented a greater chemical affinity with adhesive monomers after the remineralization approach. Remineraliza-

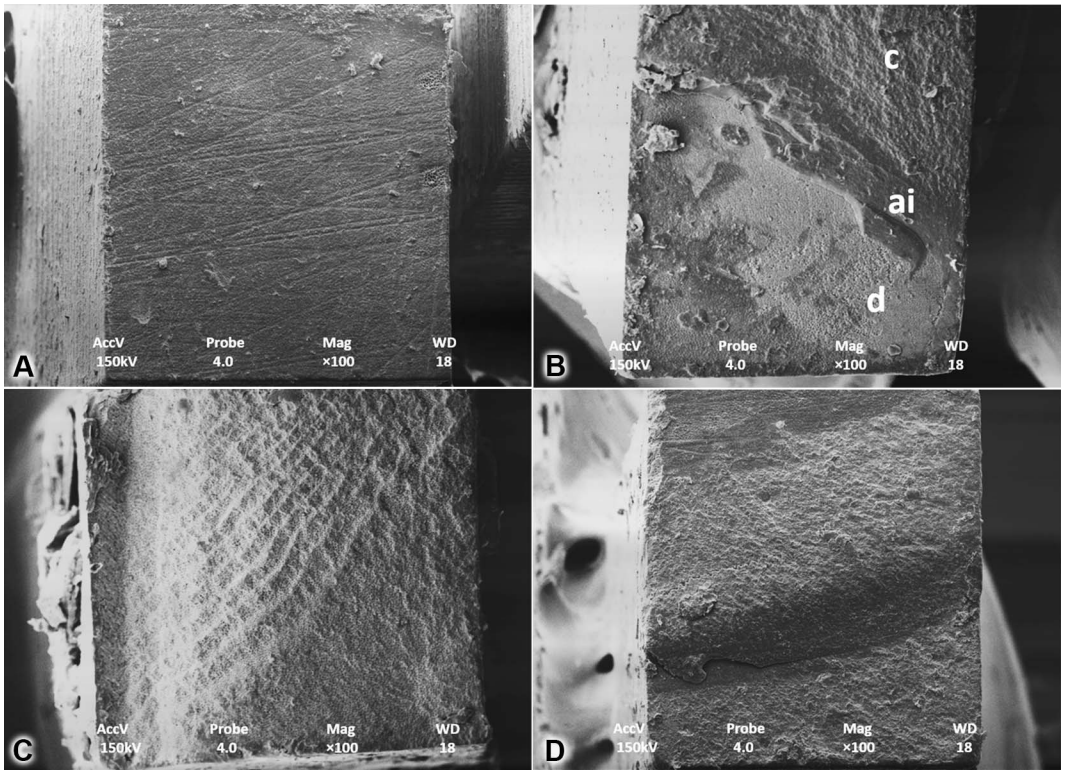


Figure 3. *Scanning electron microscop failure analysis of the fractured specimens (×100). (A) Adhesive failure along the dentin surface for CD-BG. (B) Mixed failure for CD with a fracture at the dentin surface (d) and in the adhesive interface (a), and cohesive failure in the composite resin (c). (C) Cohesive failure within dentin for CD. (D) Cohesive failure within the composite resin for BD-BS.*

tion treatment with BG demonstrated better results as it increased both the CD and BD bond strengths and improved tissue chemical interactions with adhesive monomers. This is the first study to test BD remineralization effects.

Compared with other bioactive materials, BG presents the highest bioactivity index (IB=12.5) and is still considered the gold standard agent.[13,24,25] BS was developed with the goal of combining the high bioactivity of BG with the good mechanical strength and toughness of glass-ceramics.[24] Based on the results of this study, both BG and BS can be used to restore dentin mineral compounds after internal bleaching. The two tested agents promoted mineral deposition on demineralized dentin and BD, increased the BD bond strength, and improved the chemical interactions between this mineral tissue and adhesive monomers. Nevertheless, only BG yielded significant results for CD bond strength and physicochemical interactions with the adhesive system.

Bioactive glass and glass-ceramic remineralization processes involve the exchange of ions ($Si^{4+,}$ OH^{-}, Na^{+}, Ca^{2+}, PO_4^{3-}) between the glass silicate network and the surrounding fluid body.[13,14] This process induces calcium phosphate (Ca/P) precipitation and its subsequent crystallization into hydroxycarbonate apatite on the mineral tissue surface.[13,22,28] Glass dissolution during the remineralization reaction depends on the presence of an aqueous medium.[17,24] Considering that fluoride is not a functional compound for biomineralization,[11] artificial saliva was selected as the aqueous medium to simulate the oral environment because its ionic composition is comparable to that of plasma.[29]

Dentin consists of a heterogeneous tissue with high water content, and its remineralization is a challenging process not only because of its mineral and organic composition but also because of its tissue design, that is, the intrafibrillar orientation of the minerals in the collagen network.[14] Improvement of the dentin mechanical properties depends on extrafibrillar deposition, particularly intrafibrillar minerals, as a consequence of biomimetic remineralization.[30] Mineral deposition around the denuded collagen fibrils protects the resin-dentin interface from water and enzymatic degradation, restores dentin mineral compounds, and consequently improves tissue dynamic behavior.[31]

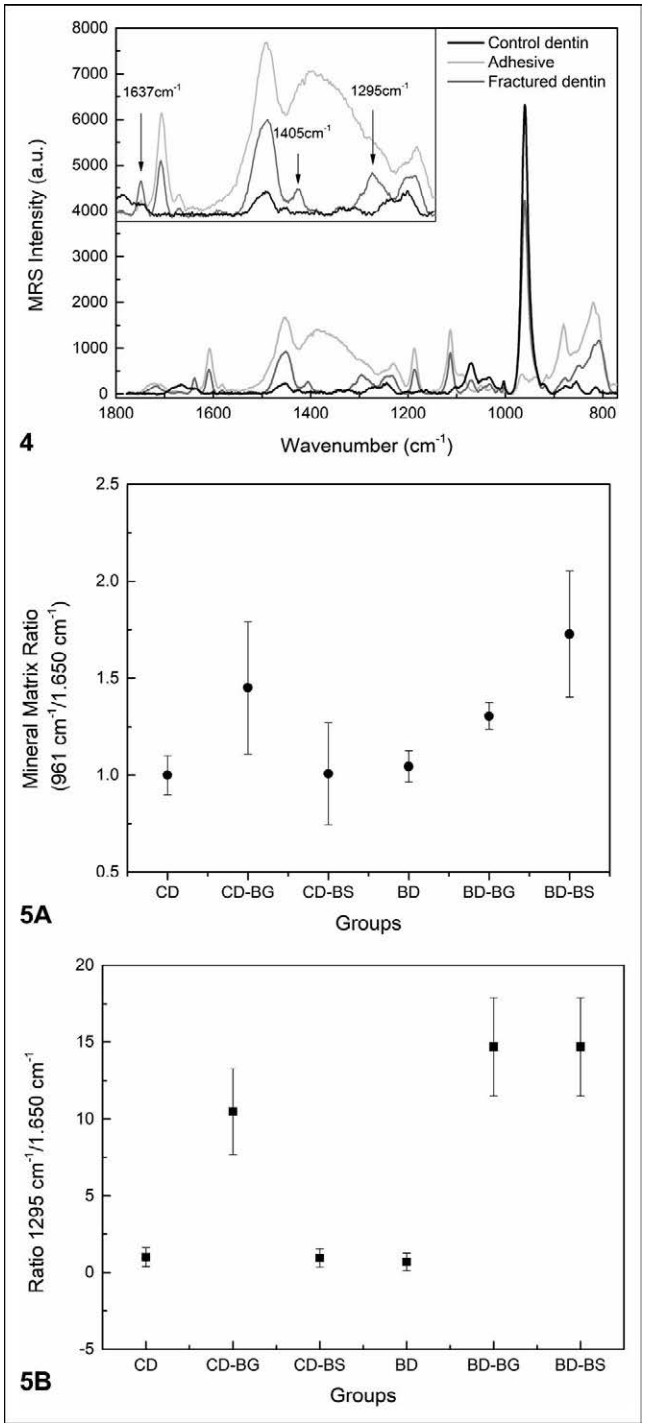


Figure 4. *Comparison of the MRS spectra of the adhesive system, CD and fractured dentin (interface average spectrum). The new MRS bands are indicated by the black arrows, C-H (1295 cm^{-1}), CH_2 of methylene (1405 cm^{-1}) and C=C of methacrylate bonds (1637 cm^{-1}).*

Figure 5. *The mean values (DP) of the fractured dentin MRS physicochemical composition. The vertical axis represents the normalized intensity of the assessed rates, and the horizontal axis presents the experimental groups. (A): Mineral matrix ratio (961 cm^{-1}/1650 cm^{-1}). When all groups were compared, the dentin mineral composition was higher for CD treated with BG and BD remineralized with BS. (B): New MRS peak ratio (1295 cm^{-1}/1650 cm^{-1}). These peak ratio analyses showed that the new band was more evident in CD treated with BG and that BD was remineralized with both BG and BS. The results of both ratio analyses corroborate the microtensile bond strength findings, indicating that when dentin mineral compounds are more intense, the substrate more readily interacts with adhesive monomers, increasing resin-dentin bond strength.*

The bioactive test results led to rejection of the first null hypothesis of the study as the CD and BD remineralization treatments with BG and BS demonstrated increases in the dentin mineral contents. The mineral content of the CD specimens was reduced after the etching step; however, this loss was restored one day after the remineralization treatments were performed. The improved mineral matrix ratio corroborates the findings of an attenuated total reflection Fourier transform infrared spectroscopy study that confirmed the BG remineralization effect on a partially demineralized dentin surface during a seven-day treatment.[22] This long period of time required for evidence of mineral deposition to emerge may be explained by the use of a 0.5-mM ethylenediamine tetra-acetic acid solution rather than a phosphoric acid gel during the demineralization step. Additionally, the ability of BS to induce hydroxycarbonate apatite precipitation on the dentin surface was also evaluated by a Fourier transform infrared spectroscopy study, which was found to occur one day after remineralization treatment.[17]

The application of bleaching agents to dentin tissue may promote changes in the dentin surface morphology and structure.[32] Modifications of the dentin structure not only change the ratio between its organic and inorganic components[33] but also increase dentin collagen degradation by activation of MMPs,[4] which then decrease dentin bonding efficacy.[5,32] Although remineralization treatment of BD with bioactive agents has not been tested previously, different studies[34,35] have evaluated the use of BG and BS as desensitizing agents after enamel bleaching and concluded that remineralization treatment reduced enamel mineral loss and preserved enamel surface integrity.

Dentin bleaching treatment resulted in a decrease in the mineral matrix ratio that was accentuated by the acid conditioning step. Application of both bioactive agents generated the remineralization effect one day after the treatment was completed, restoring the dentin structural components that were lost due to acid etching. Nevertheless, this mineral formation was not sufficient to reestablish the components present in dentin before the bleach-

ing treatment. When non-remineralized BD was stored in artificial saliva, the mineral matrix ratio did not change and remained constant during the 15 days of bioactive analysis. The remineralization reaction is known to occur only when bioactive agents are in contact with body fluids.[24] Several liquids have been used to induce this reaction, such as water, simulated body fluid, or artificial saliva.[36] Considering that saliva compounds are readily available to remineralize dental tissue, the use of artificial saliva can be listed as a limitation in a remineralization study. Although fluoride participates in conventional tooth remineralization through a top-down approach, its action on biomineralization has not been proven.[11] This fact corroborates these research results since the bioactive analysis showed that the remineralization effect occurred only in remineralized specimens.

The second null hypothesis of this study was rejected because the dentin bond strength was reduced after dentin bleaching and improved with remineralization treatment. These data are consistent with the findings of other studies reporting that dentin bleaching significantly decreases the dentin bond strength.[37,38] This reduction in the dentin μTBS has been related to adhesive polymerization inhibition caused by oxygen and free radicals resulting from the bleaching reaction. Therefore, some studies have reported that μTBS values were restored when such components were eliminated, which was achieved by postponing the restorative procedures to 7-14 days after bleaching treatment.[39] Nevertheless, the reduced adhesive bonding with BD has also been associated with the oxidizing effect of peroxide,[40] which promotes the dissolution of dentin mineral compounds and dentin collagen denaturation and activates organic enzymatic degradation of dentin by MMPs.[4] The bioactive test results revealed that the decreases in the dentin mineral matrix were not reversible even after 14 days of specimen immersion in artificial saliva, corroborating the μTBS findings that only remineralization treatments were able to improve the BD bond strength values.

Dentin mechanical properties are directly affected by the degree and quality of the dentin mineral content. Mineral deposition resulting from remineralization treatment protects the resin-dentin interfacial integrity from adhesive hydrolysis through its dehydration mechanism and protects denuded collagen from MPP degradation.[14] Although treatment with both bioactive agents increased the μTBS values of CD and BD, the difference was not significant when BS was applied to CD. Microtensile studies have revealed that dentin treatment with an experimental primer or adhesives containing BG did not change the μTBS values over 24 hours but provided durable resin-dentin bonds when long-term analyses were conducted.[20,28] In the present study, significantly improved μTBS values were obtained seven days after remineralization treatment, which differed from the results when BG was introduced into the adhesive compounds. This fact may indicate that the bioactive components are more reactive when available in a separate solution and are not associated with other chemical molecules. To date, the use of BS to improve resin-dentin bonds has been tested in only one study,[19] which found higher μTBS values after six months when BS was used as a dentin remineralization solution after the acid treatment approach of self-etching and etch-and-rinse adhesives.

Dentin remineralization not only changed the mineral composition (961 cm^{-1}/1650 cm^{-1}) of the fractured dentin interface but also induced new physicochemical interactions of the dentin tissue with adhesive monomers (1295 cm^{-1}/1650 cm^{-1}), thus leading to rejection of the third hypothesis of this study. Physicochemical analysis of the fractured dentin beam confirmed the findings of the bioactive test as both analyses demonstrated the same mineral matrix ratio patterns in the CD and BD before and after remineralization treatment. Micromechanical retention of the etch-and-rinse adhesives is improved when methacrylate monomers and/or carboxylic esters chemically interact with the etched inorganic dentin compounds.[41] Considering that the MRS bands are fingerprints of specific specimen molecules, they provide chemical information expressed by changes in or the appearance of new peaks.[42] Therefore, the new peaks observed in the remineralized groups in the present study (CD-BG, BD-BG, and BD-BS) demonstrated that the adhesive methacrylate monomers are more susceptible to interacting with dentin when its mineral compounds are present in larger quantities. Additionally, the presence of these new peaks was more evident on the dentin beams of the groups with higher μTBS values, proving their association with an improved dentin-adhesive bond.

CONCLUSION

Both bioactive materials tested in this study (the calcium sodium phosphosilicate glass and the fully crystalline glass-ceramic) present a high remineralization ability on bleached dentin surfaces. Remineralization treatment of BD promoted mineral

deposition on the dentin surface, improved dentin's ability to chemically interact with adhesive monomers, and consequently increased the resin-dentin bond strength.

Acknowledgement

The study was supported by the Brazilian funding agency CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior).

Regulatory Statement

This study was conducted in accordance with all the provisions of the local human subjects oversight committee guidelines and policies of State University of Maringa Ethics Committee. The approval code for this study is 50615715.1.0000.0104.

Conflict of Interest

The authors of this manuscript certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

(Accepted 25 March 2019)

REFERENCES

1. Dietschi D, Duc O, Krejci I, & Sadan A (2008) Biomechanical considerations for the restoration of endodontically treated teeth: A systematic review of the literature, Part II (Evaluation of fatigue behavior, interfaces, and in vivo studies) *Quintessence International* **39(2)** 117-129.
2. Samran A, Al-Afandi M, Kadour JA, & Kern M (2015) Effect of ferrule location on the fracture resistance of crowned mandibular premolars: An in vitro study *Journal of Prosthetic Dentistry* **114(1)** 86-91.
3. Azevedo RA, Silva-Sousa YT, Souza-Gabriel AE, Messias DC, Alfredo E, & Silva RG (2011) Fracture resistance of teeth subjected to internal bleaching and restored with different procedures *Brazilian Dental Journal* **22(2)** 117-121.
4. Toledano M, Yamauti M, Osorio E, & Osorio R (2011) Bleaching agents increase metalloproteinases-mediated collagen degradation in dentin. *Journal of Endodontics* **37(12)** 1668-1672.
5. Jiang T, Ma X, Wang Y, Zhu Z, Tong H, & Hu J (2007) Effects of hydrogen peroxide on human dentin structure *Journal of Dental Research* **86(12)** 1040-1045.
6. Swift EJ Jr (2008) Effects of bleaching on tooth structure and restorations, part III: Effects on dentin *Journal of Esthetic and Restorative Dentistry* **20(2**) 1-7.
7. Nakabayashi N, Kojima K, & Masuhara E (1982) The promotion of adhesion by the infiltration of monomers into tooth substrates *Journal of Biomedical Materials Research* **16(3)** 265-273.
8. Spencer P & Swafford JR (1999) Unprotected protein at the dentin-adhesive interface *Quintessence International* **30(7)** 501-507.
9. Hashimoto M (2010) A review-micromorphological evidence of degradation in resin-dentin bonds and potential preventional solutions *Journal of Biomedical Materials Research Part B Applied Biomaterials* **92(1)** 268-280.
10. Wang Y & Spencer P (2003) Hybridization efficiency of the adhesive/dentin interface with wet bonding *Journal of Dental Research* **82(2)** 141-145.
11. Liu Y, Tjaderhane L, Breschi L, Mazzoni A, Li N, Mao J, Pashley DH, & Tay FR (2011) Limitations in bonding to dentin and experimental strategies to prevent bond degradation *Journal of Dental Research* **90(8)** 953-968.
12. Pashley DH, Tay FR, Breschi L, Tjaderhane L, Carvalho RM, Carrilho M, & Tezvergil-Mutluay A (2011) State of the art etch-and-rinse adhesives *Dental Materials* **27(1)** 1-16.
13. Hench LL, Splinter RJ, Allen WC. & Greenlee TK (1971) Bonding mechanisms at the interface of ceramic prosthetic materials *Journal of Biomedical Materials Research* **5(6)** 117-141.
14. Zanotto ED, Ravagnani C, Peitl O, Panzeri H, & Lara EH (2004) Process and compositions for preparing particulate, bioactive or resorbable Biosilicate for use in the treatment of oral ailments *Geneve: World Intellectual Property Organization* **September 2** Patent WO2004074199A1.
15. Kim J, Gu L, Breschi L, Tjäderhane L, Choi KK, Pashley DH, & Tay FR (2010) Implication of ethanol wet-bonding in hybrid layer remineralization *Journal of Dental Research* **89(6)** 575-580.
16. Ryou H, Niu LN, Dai L, Pucci CR, Arola DD, Pashley DH, & Tay FR (2011) Effect of biomimetic remineralization on the dynamic nanomechanical properties of dentin hybrid layers *Journal of Dental Research* **90(9)** 1122-1128.
17. Tirapelli C, Panzeri H, Soares RG, Peitl O, & Zanotto ED (2010) A novel bioactive glass-ceramic for treating dentin hypersensitivity *Brazilian Oral Research* **24(4)** 381-387.
18. Tirapelli C, Panzeri H, Lara EHG, Soares RG, Peitl Filho O, & Zanotto ED (2011) The effect of a novel crystallised bioactive glass-ceramic powder on dentine hypersensitivity: a long-term clinical study *Journal of Oral Rehabilitation* **38(4)** 253-262.
19. de Morais RC, Silveira RE, Chinelatti M, Geraldeli S, & de Carvalho Panzeri Pires-de-Souza F (2017) Bond strength of adhesive systems to sound and demineralized dentin treated with bioactive glass ceramic suspension *Clinical Oral Investigations* **22(5)** 1923-1931.
20. Profeta AC, Mannocci F, Foxton R, Watson TF, Feitosa VP, De Carlo B, Mongiorgi R, Valdré G, & Sauro S (2013) Experimental etch-and-rinse adhesives doped with bioactive calcium silicate-based micro-fillers to generate therapeutic resin-dentin interfaces *Dental Materials* **29(7)** 729-741.
21. Sauro S, Thompson I, & Watson TF (2011) Effects of common dental materials used in preventive or operative dentistry on dentin permeability and remineralization *Operative Dentistry* **36(2)** 222-230.
22. Wang Z, Jiang T, Sauro S, Wang Y, Thompson I, Watson TF, Sa Y, Xing W, Shen Y, & Haapasalo M (2011) Dentine remineralization induced by two bioactive glasses developed for air abrasion purposes *Journal of Dentistry* **39(11)** 746-756.

23. Khoroushi M, Mousavinasab SM, Keshani F, & Hashemi S (2012) Effect of resin-modified glass ionomer containing bioactive glass on the flexural strength and morphology of demineralized dentin *Operative Dentistry* **38(2)** E1-E10.

24. Crovace MC, Souza MT, Chinaglia CR, Peitl O, & Zanotto ED (2015) Biosilicate® — A multipurpose, highly bioactive glass-ceramic. In vitro, in vivo and clinical trials *Journal of Non-Crystalline Solids* **432(A)** 90-110.

25. Sauro S, Watson TF, Thompson I, & Banerjee A (2012) One-bottle self-etching adhesives applied to dentine air-abraded using bioactive glasses containing polyacrylic acid: an in vitro microtensile bond strength and confocal microscopy study *Journal of Dentistry* **40(11)** 896-905.

26. Colthup NB, Daly LH, & Wiberley SE (1990) *Introduction to Infrared and Raman Spectroscopy* 3rd edition Cambridge, Massachusetts/EUA.

27. Xu J, Stangel I, Butler IS, & Gilson DFR (1997) An FT-Raman spectroscopic investigation of dentin and collagen surfaces modified by 2-hydroxyethylmethacrylate *Journal of Dental Research* **76(1)** 596-601.

28. Sauro S, Osorio R, Watson TF, & Toledano M (2012) Therapeutic effects of novel resin bonding systems containing bioactive glasses on mineral-depleted areas within the bonded-dentine interface *Journal of Materials Science. Materials in Medicine* **23(6)** 1521-1532.

29. Nanci A & Ten Cate AR (2013) *Ten Cate's Oral Histology: Development, Structure, and Function* **8th edition** Elsevier, Amsterdam, Netherlands.

30. Bertassoni LE, Habelitz S, Kinney JH, Marshall SJ, & Marshall GW (2009) Biomechanical perspective on the remineralization of dentin *Caries Research* **43(1)** 70-77.

31. Tay FR & Pashley DH (2009) Biomimetic remineralization of resin-bonded acid-etched dentin *Journal of Dental Research* **88(8)** 719-724.

32. Uysal T, Er O, Sagsen B, Ustdal A, & Akdogan G (2009) Can intracoronally bleached teeth be bonded safely? *American Journal of Orthodontics and Dentofacial Orthopedics* **136(5)** 689-694.

33. Plotino G, Buono L, Grande NM, Pameijer CH, & Somma F (2008) Nonvital tooth bleaching: A review of the literature and clinical procedures *Journal of Endodontics* **34(4)** 394-407.

34. Deng M, Wen HL, Dong XL, Li F, Xu X, Li H, Li JY, & Zhou XD (2013) Effects of 45S5 bioglass on surface properties of dental enamel subjected to 35% hydrogen peroxide International *Journal of Oral Science* **5(2)** 103-110.

35. Rastelli ANS, Nicolodelli G, Romano RA, Milori DMBP, Perazzoli ILO, Ferreira EJ, Pedroso ACB, Souza MT, Peitl O, & Zanotto ED (2016) After bleaching enamel remineralization using a bioactive glass-ceramic (BioSilicate®) *Biomedical Glasses* **2(1)** 2299-3932.

36. Kokubo T & Takadama H (2006) How useful is SBF in predicting in vivo bone bioactivity? *Biomaterials* **27(15)** 2907-2915.

37. Demarco FF, Turbino M L, Jorge AG, & Matson E (1998) Influence of bleaching on dentin bond strength *American Journal of Dentistry* **11(2)** 78-82.

38. Elkhatib H, Nakajima M, Hiraishi N, Kitasako Y, Tagami J, & Nomura S (2003) Surface pH and bond strength of a self-etching primer/adhesive system to intracoronal dentin after application of hydrogen peroxide bleach with sodium perborate *Operative Dentistry* **28(5)** 591-597.

39. Cavalli V, Sebold M, Shinohara MS, Pereira PNR, & Giannini M (2018) Dentin bond strength and nanoleakage of the adhesive interface after intracoronal bleaching *Microscopy Research and Technique* **81(4)** 428-436.

40. Tam LE & Noroozi A (2007) Effects of direct and indirect bleach on dentin fracture toughness *Journal of Dental Research* **86(12)** 1193-1197.

41. Van Meerbeek B, Peumans M, Poitevin A, Mine A, Van Ende A, Neves A, & De Munck J (2010) Relationship between bond-strength tests and clinical outcomes *Dental Materials* **26(2**) e100-e121.

42. Zhang Y & Wang Y (2013) Effect of application mode on interfacial morphology and chemistry between dentine and self-etch adhesives *Journal of Dentistry* **41(3)** 231-240.

©Operative Dentistry, 2020, **45-3,** 297-305

Influence of Light-curing Distances on Microflexural Strength of Two Resin-based Composites

AO Al-Zain • HY Marghalani

Clinical Relevance

Clinicians may light cure thin layers of the resin-based composites explored at 2-mm and 8-mm distances without significantly affecting the microflexural strength.

SUMMARY

Objective: Our objective was to investigate the influence of different curing distances on microflexural strength and the microflexural modulus of two resin-based composites.

Methods: Two nanohybrid composites were used; Filtek Z250 (Z250) and Tetric EvoCeram (TEC). Rectangular specimens were prepared (2-mm wide × 1-mm deep × 6-mm long) light cured according to the manufacturer's instructions at 0-mm, 2-mm, and 8-mm distances (n=10) and were stored wet at 37°C for 24 hours. A microflexural strength test was performed using a universal testing machine at a crosshead speed of 1 mm/min. The microflexural strength and microflexural modulus data were analyzed using a two-way analysis of variance followed by a Tukey multiple comparison post hoc test (α=0.05).

Results: The TEC composite had a significantly higher microflexural strength at an 8-mm distance compared with the 0-mm distance. The Z250 composite expressed significantly higher microflexural strength, at 2-mm and 8-mm compared with the 0-mm distance. TEC showed a significantly higher microflexural modulus at an 8-mm distance compared with the 0-mm and 2-mm distances. Z250 also exhibited a significantly higher microflexural modulus at the 2-mm distance, compared with the 8-mm distance. In total, Z250 presented a significantly higher microflexural strength and modulus compared with TEC.

Conclusion: Curing the explored composites at 2-mm or 8-mm distances from the specimen surface did not have a significant influence on microflexural strength but did significantly affect the microflexural modulus.

*Afnan O Al-Zain, BDS, MSD, PhD, Diploma of Professional Development in Teaching and Learning, Operative and Esthetic Dentistry Division, Restorative Dentistry Department, Faculty of Dentistry, King Abdulaziz University, Jeddah, Saudi Arabia

Hanadi Y Marghalani, BDS, MSc, PhD, DRBBA-Research Group, Operative and Esthetic Dentistry Division, Restorative Dentistry Department, Faculty of Dentistry, King Abdulaziz University, Jeddah, Saudi Arabia

*Corresponding author: PO Box 80209, 21589, Jeddah, Saudi Arabia; e-mail: alzain@kau.edu.sa

https://doi.org/10.2341/19-001-L

INTRODUCTION

Light activated resin-based composite (RBC) is considered to be the material of choice as a direct restorative material due to its high esthetic demand.[1] Various external and internal factors affect

polymerization effectiveness, which may affect the longevity of the final restoration.[2] External factors are related to the operator's technique and light-curing unit (LCU) characteristics, including the distance between the light-guide tip and the restoration surface.[2-4] Internal factors that affect polymerization effectiveness are related to the composite properties and composition, including the monomer, photoinitiator system, and concentration levels, filler type and size, as well as the shade and pigments.[2] Investigating the influence of curing distances and different resin composites associated with single and dual photoinitiator systems on the restoration's strength may contribute to understanding the material's performance and longevity from a clinical perspective.

A light-activated composite restoration must receive the required energy at the correct wavelength to effectively activate the photoinitiators for sufficient polymerization and for the material to perform functionally as intended by the manufacturer.[4,5] The manufacturer's curing time is typically based on laboratory studies when curing was performed at a 0-mm distance from the restoration.[4] Testing at 0-mm is not usually attainable clinically, as the distance between the guide tip and the gingival floor of a deep proximal box in a Class II cavity may reach up to 8-mm in distance.[4] Therefore, testing at a 0-mm distance is not clinically relevant.[6] Increasing the curing distance may result in a restoration receiving less than required irradiance and radiant exposure.[2,3] This may result in an insufficient composite polymerization, which could cause leaching of the unreacted monomer into the oral environment, thus negatively affecting the integrity of the final restoration and its overall properties.[2,3]

Composites contain different resin monomers, fillers, and photoinitiator systems. Camphorquinone (CQ) is the most commonly used photoinitiator and has an absorbance wavelength that peaks near 470 nm.[7] CQ is yellowish in color, which may affect esthetics; therefore, alternative photoinitiators have been developed, such as diphenyl (2,4,6-trimethylbenzoyl) phosphine oxide (TPO), which is typically found in bleaching shades and has an absorbance wavelength that peaks near 380 nm.[7]

Composite restorations are subjected clinically to different stresses, such as flexure, tension, compression, and shear.[8] A flexural strength test is typically used to evaluate material behavior because it simulates complex forces generated at stress concentration areas.[9,10] This test produces compressive and tension stresses at the area of loading in opposite directions.[10] Microflexural strength tests (microflexural strength, σ_{μ}) are performed on specimens using smaller dimensions than those described in the International Organization for Standardization (ISO) 4049 specifications, which better simulate the clinical setting. Specimen dimensions for the σ_{μ} test are smaller than the active diameter of the light-guide tip, which allows a single shot curing.[9,11]

Most studies have investigated flexural strength at a 0-mm distance and have used the manufacturer's recommended curing time.[9,12,13] A study reported that specimen dimension and curing distance significantly affected flexural strength values, however, the specimen dimensions in the mentioned study were larger than the guide tip and required multiple shots for curing.[14] It was reported that flexural strength values varied among composites that had different filler content.[8,13,15] On the other hand, a study found no significant differences in flexural strength and modulus for some composites.[12] Therefore, exploring the influence of multiple curing distances on a composite's microflexural strength and modulus was worth investigating.

The aim of the study was to investigate the influence of curing distances on microflexural strength and microflexural modulus of two nanohybrid resin composites. The working hypothesis was that increasing the curing distance would significantly decrease the microflexural strength and microflexural modulus compared with a 0-mm distance.

METHODS AND MATERIALS

Two nanohybrid RBCs were investigated: Tetric EvoCeram (TEC) (Ivoclar Vivadent, Amherst, NY, USA) and Filtek Z250 (Z250) (3M ESPE Dental Products, St Paul, MN, USA). Both composites explored were shade A2, and their compositions are presented in Table 1.

Sample Preparation

A total of 60 rectangular specimens were prepared using a custom-made mold (6-mm long × 2-mm wide × 1-mm deep). Composite material was sandwiched between Mylar strips and glass slides to remove excess material. Samples were light cured, according to the manufacturer's instruction for each composite: Z250 (20 seconds) and TEC (10 seconds) by a multiple-emission peak light-emitting diode (LED)

Table 1: *Manufacturers' Composition of the Resin Composites*

Resin-based Composite	Organic Monomers	Photoinitiator System	Filler Type	Filler (%)	Manufacturer	Lot No.
Tetric EvoCeram (TEC)	UDMA Bis-GMA Bis-EMA	CQ and TPO	Barium glass Ytterbium trifluoride Mixed oxides Prepolymer Inorganic filler particle size (40-3,000 nm) Mean particle size (550 nm)	75-76 (wt), 53-55 (vol)	Ivoclar Vivadent, Amherst, NY, USA	W98455
Feltik Z250 (Z250)	UDMA Bis-GMA Bis-EMA	CQ	Zirconia/silica Particle size (0.01-3.5 μm)	82 (wt), 60 (vol)	3M ESPE Dental Products, St Paul, MN, USA	N915750

Abbreviations: Bis-EMA, ethoxylated bisphenol A dimethacrylate; Bis-GMA, bisphenol A dimethacrylate, CQ, camphorquinone; TPO, diphenyl (2,4,6-trimethylbenzoyl) phosphine oxide; UDMA, urethane dimethacrylate; vol, volume; wt, weight.

curing unit (Bluephase N, Ivoclar Vivadent) at three different curing distances (0-mm, 2-mm, and 8-mm) from the top surface of the sample (n=10). The light guide tip optical diameter was 9-mm, and the LCU included a violet and blue spectral range (360-540 nm). The LCU irradiance and radiant exposure were measured for both curing times at the three distances using a laboratory-based spectrometer (Managing Accurate Resin Calibrator-Light Corrector, BlueLight Analytics, Halifax, Canada). The LCU position was standardized and centered over the uncured sample using a mechanical arm. After sample preparation, all the samples were finished using 800-grit to 2500-grit SiC abrasive papers. Samples were then stored in deionized water for 24 hours at 37°C.

Mechanical Testing

Specimen dimensions were measured using a digital caliper. After 24 hours of specimen fabrication and storage, the σ_μ test was performed using a universal testing machine (Instron model 5944, Norwood, MA, USA). The load cell was 2.5 kilonewtons. A mini three-point bending fixture (Instron, RO.25 6543) at a crosshead speed of 1 mm/min, and a 4-mm support span (Instron, CAT no. S4843A) was used. The σ_μ in MPa was calculated according to the following equation:

$$\sigma_\mu = \frac{3Fl}{2bh^2}$$

F is the maximum load exerted on the sample in newtons; l is the distance between the supports in millimeters; b is the width of the sample in millimeters; and h is the height of the sample in millimeters.

The microflexural modulus (E_μ) in GPa was calculated according to the following equation:

$$E_\mu = \frac{Fl^3}{4bh^3d}$$

F was the maximum load exerted on the sample in newtons; l is the distance between the supports in millimeters; b is the width of the sample in millimeters; h is the height of the sample in millimeters; and d is the deflection in millimeters.

Statistical Analysis

The effect of the curing distance and composite on σ_μ and E_μ was determined using a two-way analysis of variance followed by a Tukey multiple comparison test (α=0.05). Log transformation was performed for the σ_μ data. Statistical analysis was performed using SigmaPlot (Version 12.0, San Jose, CA, USA).

RESULTS

The LCU irradiance values measured for the 9-mm optical diameter were 1342.7±3.21, 1324.0±4.36, and 1226.7±1.53 mW/cm^2 at 0-mm, 2-mm, and 8-mm distances, respectively. The radiant exposure values measured at 10 seconds were 13.6±0.12, 13.4±0.02, and 12.3±0.01 J/cm^2 for 0-mm, 2-mm, and 8-mm distances, respectively. Moreover, the radiant exposure values measured at 20 seconds were 27.0 ± 0.06, 26.7 ± 0.10, and 24.7 ± 0.04 J/cm^2 for 0-mm, 2-mm, and 8-mm distances, respectively.

The σ_μ and E_μ mean and standard deviation values of the two composite materials examined at three different curing distances are presented in Figures 1 through 4. The highest mean σ_μ value was demonstrated by Z250 at a 2-mm curing distance (217.1±15.5 MPa) followed by the same material at

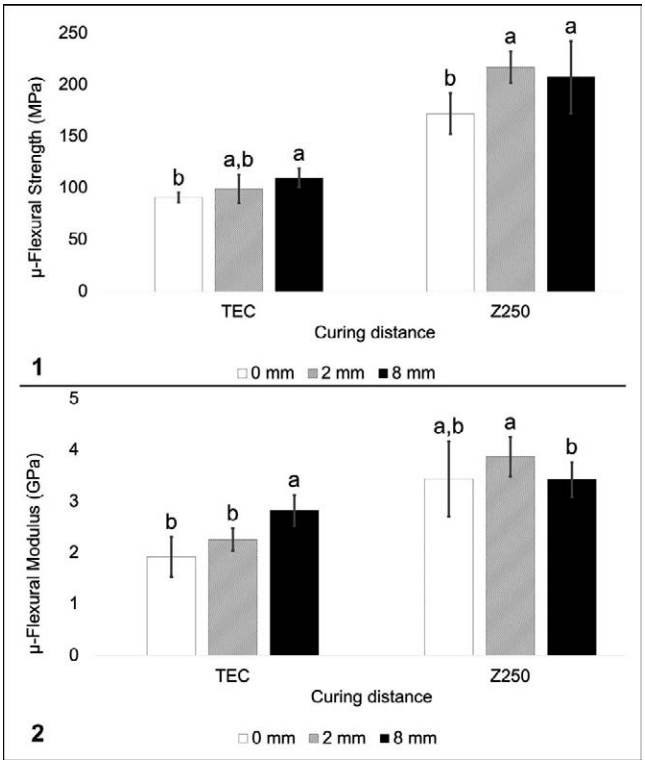


Figure 1. *Microflexural strength (MPa) means (SD) and significant differences among the curing distances for Z250 and TEC composites. Different letters represent significant differences among distances for each composite.*

Figure 2. *Microflexural modulus (GPa) means (SD) and significant differences among the curing distances for Z250 and TEC composites. Different letters represent significant differences among distances for each composite.*

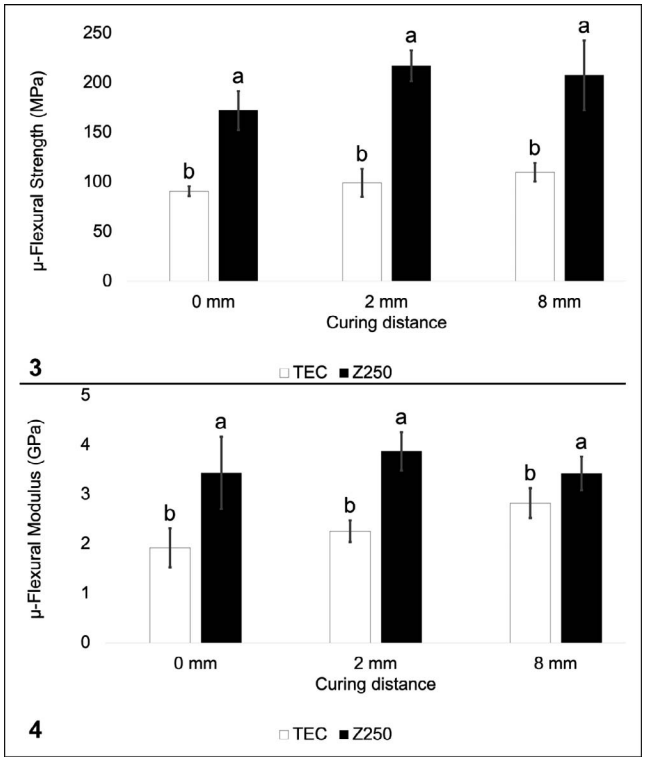


Figure 3. *Microflexural strength (MPa) means (SD) and significant differences between Z250 and TEC composites at each curing distance. Different letters represent significant differences between composites at each distance.*

Figure 4. *Microflexural modulus (GPa) means (SD) and significant differences between Z250 and TEC composites at each curing distance. Different letters represent significant differences between composites at each distance.*

an 8-mm distance (207.4±34.9 MPa) and at a 0-mm distance (172±19.6 MPa). The lowest mean σ_μ value was presented by TEC at a 0-mm curing distance (90.8±4.8 MPa), followed by a 2-mm distance (99.2±14.1 MPa) and an 8-mm distance (109.9±9.3 MPa). A similar trend followed for the E_μ values. The highest modulus value was for Z250 at the 2-mm curing distance (3.9±0.4 GPa) followed by 0-mm and 8-mm distances (3.4±0.7 and 3.4±0.3 GPa, respectively). The lowest E_μ was for TEC at a 0-mm curing distance (1.9±0.4 GPa) followed by 2-mm (2.3±0.2 GPa) and 8-mm (2.8±0.3 GPa) distances.

Significant differences were found between the σ_μ values among the curing distances for both materials ($p<0.05$). In general, the curing distance had a significant influence on σ_μ, where 2-mm and 8-mm distances showed significantly higher σ_μ compared with a 0-mm distance. The significant difference trend among curing distances was not the same for each composite. For TEC, comparisons among the curing distances showed significantly higher σ_μ values at an 8-mm compared with a 0-mm distance. For Z250, significantly higher σ_μ values were shown at 2-mm and 8-mm distances compared with a 0-mm distance (Figure 1).

Significant differences between the E_μ values among the curing distances for both materials were examined ($p<0.05$). In general, curing distance had a significant influence on E_μ, where the 8-mm distance showed a significantly higher E_μ compared with the 0-mm distance. The significant difference trend among curing distances for each material was not the same. In addition, the significant trend was not the same as for the σ_μ values. TEC showed significantly higher E_μ at the 8-mm distance compared with the 2-mm and 0-mm distances. Z250 showed significantly higher E_μ at the 2-mm distance compared with the 8-mm distance (Figure 2).

The E_μ significant comparisons between the composites at each curing distance were performed ($p<0.05$). Z250 had significantly higher σ_μ (Figure 3)

Table 2: *Microflexural Strength (MPa) and Microflexural Modulus (GPa) Means (Standard Deviations) for the Resin Composites Cured at Different Distances*[a]

Curing Distance (mm)	Microflexural Strength (MPa)		Microflexural Modulus (GPa)	
	TEC	Z250	TEC	Z250
0	90.8 (4.8)^{z,Z}	172.0 (19.6)^{z,Y}	1.9 (0.4)^{z,Z}	3.4 (0.7)^{y,z,Y}
2	99.2 (14.1)^{y,z,Z}	217.1 (15.5)^{y,Y}	2.3 (0.2)^{z,Z}	3.9 (0.4)^{y,Y}
8	109.9 (9.3)^{y,Z}	207.4 (34.9)^{y,Y}	2.8 (0.3)^{y,Z}	3.4 (0.3)^{y,Z}

Abbreviations: TEC, Tetric EvoCeram; Z250, Feltik Z250.
[a] *Different superscript lowercase letters represent significant differences among the curing distances for each composite and property (each column). Different superscript uppercase letters represent significant differences between Z250 and TEC composites at each distance for each property (row of each property).*

and E_μ values (Figure 4) compared with TEC. The σ_μ, E_μ values and significant differences among the curing distances for each composite and property, as well as the significant differences between the composites at each distance for each property are presented in Table 2.

DISCUSSION

One of the factors that affects the longevity of a composite restoration is its ability to withstand complex clinical stresses.[16] Exploring the effect of different light curing distances (0-, 2-, and 8-mm) on σ_μ and E_μ would provide beneficial information regarding material clinical performance. The 2-mm and 8-mm curing distances were selected to represent the best and worst clinical case scenarios, respectively.[4] Investigating the effect of curing composites at different distances would aid in the understanding of material clinical performance.

Characterizing polymerization effectiveness using the σ_μ test can better simulate the clinical setting compared with the ISO 4049 flexural strength test.[8,17,18] The flexural strength test according to ISO 4049 for polymer-based restorative materials uses a rectangular specimen with a dimensions of 2 $\times$ 2 $\times$ 25 mm.[19] These dimensions are not clinically relevant because they do not represent the tooth's dimensions.[8,18] Also, the active light guide tip of the different LCUs ranges from 7 to12 mm in diameter, which results in the flexural strength specimens being light cured in multiple irradiation cycles.[8,17] This results in certain areas on the specimens, receiving a higher radiant exposure, which can affect specimen polymerization uniformity.[8,17,20] Therefore, the reliability of the flexural strength test data may be affected.[14,20] The literature has reported that different sample dimensions have been used for the σ_μ test.[9,14,21] In our study, the specimen dimensions selected were smaller than the active diameter of the light guide tip in order to ensure a single-shot curing.[9,11,14] Smaller specimens result in higher flexural strength values and represent the combined effect of compressive, tension and shear deformation stresses.[8]

Generally, comparisons among the curing distances showed a significantly higher σ_μ at 2-mm and 8-mm compared with 0-mm and a significantly higher E_μ at 8-mm compared with 0-mm. The trend was similar between σ_μ and E_μ for each composite and differed to some extent in the significant differences among distances for each composite (Figures 1 and 2). TEC showed significantly higher σ_μ at the 8-mm distance compared with the 0-mm distance, and Z250 showed a significantly higher strength at 2-mm and 8-mm distances compared with 0-mm. The modulus for TEC significantly increased at the 8-mm distance compared with the 0-mm and 2-mm distances, which suggested that the TEC specimens were stronger and stiffer as the distance increased. On the other hand, the modulus for Z250 significantly decreased at the 8-mm distance compared with the 2-mm distance, which may denote that the Z250 specimens were strong but more flexible as the distance increased. Therefore, the working hypothesis was partially accepted. On the top surface of a restoration, light is reflected, scattered, and absorbed by the RBC components and structures surrounding the restoration, such as the Mylar strip, matrix band, and tooth structure.[22-24] The close proximity of the tip at the 0-mm distance to the Mylar strip may have affected the strength values because the light emitted from the curing unit could have reflected or scattered off the Mylar strip surface to a greater extent at a closer distance. As the distance between the guide tip and specimen increases, the light beam spreads over a larger surface area.[4,25] The increased distance may have allowed for less scattering and reflection off the Mylar strip surface permitting better light penetration through the specimens. Our results agreed to some extent with other work where no significant differences were observed when a clear Mylar strip was placed over a 2-mm specimen and cured at 0-mm or 2-mm distances.[26]

In our study, the differences between 2-mm and 8-mm distances were not significant regardless of the composite used. This might indicate that the 1-mm-thick specimens may have allowed light to reach the bottom of the specimen resulting in sufficient strength, which could also indirectly indicate satisfactory polymerization. This is supported with other work where 1-mm-thick microflexural strength specimens exhibited a satisfactory degree of conversion values on the top and bottom surfaces.[9] Other studies reported that hardness decreased on the bottom surfaces of increments more than 1-mm thick.[27,28] In our study, specimens were 1-mm thick, so we would expect specimens to exhibit sufficient hardness and degree of conversion. The nonsignificant differences between 2-mm and 8-mm distances, regardless of the composite, may also suggest that the amount of photoinitiator activated was sufficient to effectively generate enough free radicals that resulted in satisfactory composite strength. Our results were supported with a study that light cured 2-mm-thick specimens at 0-mm, 2-mm, 4-mm, and 8-mm distances and reported no significant change between 2-mm and 8-mm distances. However, there were some differences between 0-mm and 8-mm distances with which we agree.[14] The differences in the specimen dimensions in our study and the aforementioned study may have contributed to the differences in the results.

An association was suggested between material strength and other properties, such as hardness and degree of conversion.[29-31] Another study reported that the σ_μ and the degree of conversion was not compromised at a 0-mm distance.[9] It was also reported that the degree of conversion is not necessarily correlated to material strength.[32] A study stated that the increased distance resulted in a decreased degree of conversion.[33] In our study, specimens at increments of 1-mm thick were light cured using irradiance values that ranged from 1226.7-1342.7 mW/cm^2 at the different distances. These values were greater than 400 mW/cm^2, which is the minimum irradiance suggested to achieve sufficient polymerization according to the ISO 10650-2 specifications.[34] In addition, the mold used in our study was a light gray in color, which may have facilitated light transmission. It was previously reported that molds fabricated from lighter-colored material facilitated light transmission more than dark metal molds.[35] Our specimens were cured according to the manufacturer's instructions, which were different for unique to each composite. The radiant exposure values at 20 seconds ranged from 24.7 to 27.0 J/cm^2 and at 10 seconds ranged from 12.3 to 13.6 J/cm^2 at the different distances. Since the curing time affects the amount of radiant exposure received by the restoration, this may have contributed to the significantly higher σ_μ and E_μ values shown for Z250 compared with TEC. The literature has reported that a 2-mm-thick increment needs 12-24 J/cm^2 radiant exposure to achieve effective polymerization.[36,37] Recent work reported that 10-11 J/cm^2 resulted in a satisfactory degree of conversion for 2-mm-thick increments.[38] The aforementioned factors can indicate that the specimens received sufficient irradiance and radiant exposure to adequately polymerize the RBC. Nevertheless, further investigation about the influence of curing distance on other properties is needed.

Comparisons among composites showed that σ_μ and E_μ values were significantly higher for Z250 compared with TEC regardless of the curing distance. This may be explained by composite properties and how they are affected by various factors, including the polymer matrix, filler content, coupling agents, and light transmission through the composite.[2,32] It was reported that flexural strength and modulus values were influenced by monomer composition and the nature of the polymer matrix.[32] In this study, as shown in Table 1, Z250 and TEC had similar monomer combinations. In addition, both composites had similar filler particle size and some variations in the filler loading weight and volume percentage, filler type, and additives. Therefore, the differences observed in our results could be related to the photoinitiator system type and filler content. The higher filler loading, pigments, and additives can lead to scattering and attenuation of the light and decrease in light transmission.[2,39] In addition, filler particles can hinder light transmission by scattering, or refraction at the resin-filler interface, due to the refractive index mismatch.[2,40-42] Photoinitiators and pigments may absorb light, resulting in a lower depth of cure in darker shades.[43-45] In our study, one shade was investigated.

Photoinitiator concentration is a key factor that affects polymerization efficiency.[2,46] Composites in this study had different photoinitiator systems; therefore, specimens were light cured using a multiple emission peak LED unit that included the blue and violet LED chips needed to activate most photoinitiators. Interestingly, Z250, which contained only CQ, showed significantly higher strength and modulus values compared with TEC, which contained CQ and TPO photoinitiator sys-

tems. The differences in photoinitiator systems type and concentration may partially explain the significant differences between both composites. CQ is activated upon exposure to longer blue light wavelengths.[47-49] TPO is highly reactive with high molar absorptivity and is activated upon exposure to shorter violet light wavelengths.[47-49] When TPO is activated, free-radical growth centers are generated and form a polymer network at a faster rate compared with CQ.[47,50,51] However, due to the high reactivity of TPO, more entrapment of free radicals within the polymer network may occur, compared with CQ, thereby affecting the quality of polymerization.[2] This may partially explain the significant differences in strength and modulus values between composites. The results in our study suggest that polymerization kinetics has an important role in specimen strength. A strong correlation was shown between autoacceleration of the polymerization and entrapment of free radicals.[52] This suggested that a larger number of free radicals might have been entrapped in the TEC composite, resulting in a significantly lower strength and modulus value regardless of the distance.

Various fillers are incorporated in TEC (Table 1). Barium glass and ytterbium trifluoride are radiopaque agents.[53,54] It was reported that ytterbium trifluoride decreased flexural strength at higher concentrations.[53] Since the ytterbium trifluoride concentration was not disclosed by the manufacturer, this could have partially contributed to the lower strength and modulus for TEC in our study. The presence of prepolymer in TEC may have contributed to the significantly lower flexural strength and modulus compared with Z250. Our findings were supported by findings of other studies.[55,56] Additionally, the presence of zirconia and silica particles can improve the material mechanical properties.[57,58] This may partially explain the significantly increased flexural strength and modulus values for Z250 compared with TEC. The mentioned factors and the possible undisclosed components of the composites, including monomer ratios and weight percentages, may also contribute to the explanation of the significantly higher σ_μ and E_μ values for Z250 compared with TEC regardless of the distance. It is important to note that the results may differ to a certain extent using different composites and shades, thicker specimens, or curing with different LCU types. Further investigation is needed to explore the influence of curing distance on different composite properties using different LCUs.

CONCLUSION

Light curing of the RBCs explored, at 2-mm or 8-mm distances between the light guide tip and the composite surface, did not significantly affect microflexural strength values for the composites investigated but did significantly affect microflexural modulus values.

Acknowledgements

This project was funded by the Deanship of Scientific Research (DSR) at King Abdulaziz University, Jeddah, under grant no. G: 250-165-1439. The authors, therefore, acknowledge with thanks DSR for technical and financial support. The authors, also acknowledge DarTec Engineering for the 3D mold fabrication and Miss Layan Fakhry, Miss Renad Tallab, Mr Fahd Alsadi, and Dr Eliseu Münchow for their technical support.

Conflict of Interest

The authors of this manuscript certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

(Accepted 25 May 2019)

REFERENCES

1. Rasines Alcaraz MG, Veitz-Keenan A, Sahrmann P, Schmidlin PR, Davis D, & Iheozor-Ejiofor Z (2014) Direct composite resin fillings versus amalgam fillings for permanent or adult posterior teeth *Cochrane Database Systemic Review* **3** CD005620. doi: 10.1002/14651858.CD005620.pub2
2. Leprince JG, Palin WM, Hadis MA, Devaux J, & Leloup G (2013) Progress in dimethacrylate-based dental composite technology and curing efficiency *Dental Materials* **29(2)** 139-156. doi: 10.1016/j.dental.2012.11.005
3. Shortall AC, Price RB, MacKenzie L, & Burke FJ (2016) Guidelines for the selection, use, and maintenance of LED light-curing units—Part 1 *Brazilian Dental Journal* **221(8)** 453-460. doi: 10.1038/sj.bdj.2016.772
4. Price RB, Labrie D, Whalen JM, & Felix CM (2011) Effect of distance on irradiance and beam homogeneity from 4 light-emitting diode curing units *Journal of the Canadian Dental Association* **77** b9.
5. Price RB, Labrie D, Rueggeberg FA, Sullivan B, Kostylev I, & Fahey J (2014) Correlation between the beam profile from a curing light and the microhardness of four resins *Dental Materials* **30(12)** 1345-1357, doi: 10.1016/j.dental.2014.10.001
6. Price RB, Fahey J, & Felix CM (2010) Knoop microhardness mapping used to compare the efficacy of LED, QTH and PAC curing lights *Operative Dentistry* **35(1)** 58-68. doi: 10.2341/09-055-L
7. Jandt KD & Mills RW (2013) A brief history of LED photopolymerization *Dental Materials* **29(6)** 605-617. doi: 10.1016/j.dental.2013.02.003
8. Yap AUJ & Teoh SH. (2003) Comparison of flexural properties of composite restoratives using the ISO and

mini-flexural tests *Journal of Oral Rehabilitation* **30(2)** 171-177. doi: 10.1046/j.1365-2842.2003.01004.x

9. Eshmawi YT, Al-Zain AO, Eckert GJ, & Platt JA (2018) Variation in composite degree of conversion and micro-flexural strength for different curing lights and surface locations *Journal of the American Dental Association*. doi: 10.1016/j.adaj.2018.06.004
10. Reinhardt JW, Boyer DB, & Stephens NH (1994) Effects of secondary curing on indirect posterior composite resins *Operative Dentistry* **19(6)** 217-220.
11. Calheiros FC, Pfeifer CS, Brandao LL, Agra CM, & Ballester RY (2013) Flexural properties of resin composites: Influence of specimen dimensions and storage conditions *Dental Materials Journal* **32(2)** 228-232.
12. Stahl F, Ashworth SH, Jandt KD, & Mills RW (2000) Light-emitting diode (LED) polymerisation of dental composites: Flexural properties and polymerisation potential *Biomaterials* **21(13)** 1379-1385.
13. Chung SM, Yap AU, Chandra SP, & Lim CT (2004) Flexural strength of dental composite restoratives: Comparison of biaxial and three-point bending test *Journal of Biomedical Material Research Part B Applied Biomaterials* **71(2)** 278-283. doi: 10.1002/jbm.b.30103
14. El-Askary FS, Botros SA, Nassif MSA, & Ozcan M (2017) Flexural strength of nano-hybrid resin composite as a function of light attenuation distance and specimen dimension *Journal of Adhesion Science and Technology* **31(5)** 520-529. doi: 10.1080/01694243.2016.1221251
15. Peutzfeldt A & Asmussen E (1991) Mechanical properties of three composite resins for the inlay/onlay technique *Journal of Prosthetic Dentistry* **66(3)** 322-324.
16. Douglas W (1996) Considerations for modeling *Dental Materials* **12(3)** 203-207. doi:10.1016/S0109-5641(96)80023-6
17. Palin WM, Fleming GJ, & Marquis PM (2005) The reliability of standardized flexure strength testing procedures for a light-activated resin-based composite *Dental Materials* **21(10)** 911-919. doi: 10.1016/j.dental.2005.01.005
18. Yap AU, Eweis AH, & Yahya NA (2018) Dynamic and static flexural appraisal of resin-based composites: Comparison of the ISO and mini-flexural tests *Operative Dentistry* **43(5)** E223-E231. doi: 10.2341/17-224-L
19. ISO (2009) *4049. Dentistry - Polymer-based Filling, Restorative and Luting Materials* International Standards Organization, Geneva, Switzerland.
20. Ferracane JL, Ferracane LL, & Musanje L (2003) Effect of light activation method on flexural properties of dental composites *Americal Journal of Dentistry* **16(5)** 318-322.
21. Munchow EA, Zanchi CH, Ogliari FA, Silva MG, de Oliveira IR, & Piva E (2014) Replacing HEMA with alternative dimethacrylates in dental adhesive systems: Evaluation of polymerization kinetics and physicochemical properties *Journal of Adhesive Dentistry* **16(3)** 221-228. doi: 10.3290/j.jad.a31811
22. Palin WM, Leprince JG, & Hadis MA (2018) Shining a light on high volume photocurable materials *Dental Materials* **34(5)** 695-710. doi: 10.1016/j.dental.2018.02.009
23. Shortall AC, Wilson HJ, & Harrington E (1995) Depth of cure of radiation-activated composite restoratives—Influence of shade and opacity *Journal of Oral Rehabilitation* **22(5)** 337-342.
24. Watts DC & Cash AJ (1994) Analysis of optical transmission by 400-500 nm visible light into aesthetic dental biomaterials *Journal of Dentistry* **22(2)** 112-117.
25. Andre CB, Nima G, Sebold M, Giannini M, & Price RB (2018) Stability of the light output, oral cavity tip accessibility in posterior region and emission spectrum of light-curing units *Operative Dentistry* **43(4)** 398-407. doi: 10.2341/17-033-L
26. Mousavinasab SM, Barekatain M, Sadeghi E, Nourbakhshian F, & Davoudi A (2014) Evaluation of light curing distance and mylar strips color on surface hardness of two different dental composite resins *Open Dentistry Journal* **8** 144-147. doi: 10.2174/1874210601408010144
27. Price RB, Murphy DG, & Derand T (2000) Light energy transmission through cured resin composite and human dentin *Quintessence International* **31(9)** 659-667.
28. Baharav H, Abraham D, Cardash HS, & Helft M (1988) Effect of exposure time on the depth of polymerization of a visible light-cured composite resin *Journal of Oral Rehabilitation* **15(2)** 167-172.
29. Dewaele M, Asmussen E, Peutzfeldt A, Munksgaard EC, Benetti AR, Finne G, Leloup G, & Devaux J (2009) Influence of curing protocol on selected properties of light-curing polymers: Degree of conversion, volume contraction, elastic modulus, and glass transition temperature *Dental Materials* **25(12)** 1576-1584. doi: 10.1016/j.dental.2009.08.001
30. Vankerckhoven H, Lambrechts P, van Beylen M, Davidson CL, & Vanherle G (1982) Unreacted methacrylate groups on the surfaces of composite resins *Journal of Dental Research* **61(6)** 791-795. doi: 10.1177/00220345820610062801
31. Ferracane JL & Greener EH (1986) The effect of resin formulation on the degree of conversion and mechanical properties of dental restorative resins *Journal of Biomedical Material Research* **20(1)** 121-131. doi: 10.1002/jbm.820200111
32. Asmussen E & Peutzfeldt A (1998) Influence of UEDMA BisGMA and TEGDMA on selected mechanical properties of experimental resin composites *Dental Materials* **14(1)** 51-56.
33. Froes-Salgado NR, Pfeifer CS, Francci CE, & Kawano Y (2009) Influence of photoactivation protocol and light guide distance on conversion and microleakage of composite restorations *Operative Dentistry* **34(4)** 408-414. doi: 10.2341/08-104
34. ISO (2007) *10650-2:2007 Dentistry-powered Polymerizationactivators: Part 2: Light-emitting Diode (LED) Lamps* International Standards Organization, Geneva, Switzerland 7.
35. Harrington E & Wilson HJ (1993) Depth of cure of radiation-activated materials—Effect of mould material and cavity size *Journal of Dentistry* **21(5)** 305-311.

36. Calheiros FC, Kawano Y, Stansbury JW, & Braga RR (2006) Influence of radiant exposure on contraction stress, degree of conversion and mechanical properties of resin composites *Dental Materials* **22(9)** 799-803. doi: 10.1016/j.dental.2005.11.008

37. Fan PL, Schumacher RM, Azzolin K, Geary R, & Eichmiller FC (2002) Curing-light intensity and depth of cure of resin-based composites tested according to international standards *Journal of the American Dental Association* **133(4)** 429-434; quiz 491-423.

38. Al-Zain AO, Eckert GJ, & Platt JA (2019) The influence of distance on radiant exposure and degree of conversion using different light-emitting-diode curing units *Operative Dentistry* **44(3)** E133-E144. doi: 10.2341/18-004-L.

39. Fujita K, Ikemi T, & Nishiyama N (2011) Effects of particle size of silica filler on polymerization conversion in a light-curing resin composite *Dental Materials* **27(11)** 1079-1085. doi: 10.1016/j.dental.2011.07.010

40. Emami N, Sjodahl M, & Soderholm KJ (2005) How filler properties, filler fraction, sample thickness and light source affect light attenuation in particulate filled resin composites *Dental Materials* **21(8)** 721-730. doi: 10.1016/j.dental.2005.01.002

41. Shortall AC, Palin WM, & Burtscher P (2008) Refractive index mismatch and monomer reactivity influence composite curing depth *Journal of Dental Research* **87(1)** 84-88.

42. Howard B, Wilson ND, Newman SM, Pfeifer CS, & Stansbury JW (2010) Relationships between conversion, temperature and optical properties during composite photopolymerization *Acta Biomaterials* **6(6)** 2053-2059. doi: 10.1016/j.actbio.2009.11.006

43. Musanje L & Darvell BW (2006) Curing-light attenuation in filled-resin restorative materials *Dental Materials* **22(9)** 804-817. doi: 10.1016/j.dental.2005.11.009

44. Shortall AC (2005) How light source and product shade influence cure depth for a contemporary composite *Journal of Oral Rehabilitation* **32(12)** 906-911. doi: 10.1111/j.1365-2842.2005.01523.x

45. Ogunyinka A, Palin WM, Shortall AC, & Marquis PM (2007) Photoinitiation chemistry affects light transmission and degree of conversion of curing experimental dental resin composites *Dental Materials* **23(7)** 807-813. doi: 10.1016/j.dental.2006.06.016

46. de Oliveira DC, Rocha MG, Gatti A, Correr AB, Ferracane JL, & Sinhoret MA (2015) Effect of different photoinitiators and reducing agents on cure efficiency and color stability of resin-based composites using different LED wavelengths *Journal of Dentistry* **43(12)** 1565-1572. doi: 10.1016/j.jdent.2015.08.015

47. Leprince JG, Hadis M, Shortall AC, Ferracane JL, Devaux J, Leloup G, & Palin WM (2011) Photoinitiator type and applicability of exposure reciprocity law in filled and unfilled photoactive resins *Dental Materials* **27(2)** 157-164. doi: 10.1016/j.dental.2010.09.011

48. Neumann MG, Miranda WG Jr, Schmitt CC, Rueggeberg FA, & Correa IC (2005) Molar extinction coefficients and the photon absorption efficiency of dental photoinitiators and light curing units *Journal of Dentistry* **33(6)** 525-532. doi: 10.1016/j.jdent.2004.11.013

49. Santini A, Miletic V, Swift MD, & Bradley M (2012) Degree of conversion and microhardness of TPO-containing resin-based composites cured by polywave and monowave LED units *Journal of Dentistry* **40(7)** 577-584. doi: 10.1016/j.jdent.2012.03.007

50. Ikemura K & Endo T (2010) A review of the development of radical photopolymerization initiators used for designing light-curing dental adhesives and resin composites *Dental Materials Journal* **29(5)** 481-501.

51. Vaidyanathan TK, Vaidyanathan J, Lizymol PP, Ariya S, & Krishnan KV (2017) Study of visible light activated polymerization in BisGMA-TEGDMA monomers with type 1 and type 2 photoinitiators using Raman spectroscopy *Dental Materials* **33(1)** 1-11. doi: 10.1016/j.dental.2016.09.002

52. Zhu S, Tian Y, Hamielec AE, & Eaton DR (1990) Radical concentrations in free radical copolymerization of MMA/EGDMA *Polymer* **31(1)** 154-159. doi: 10.1016/0032-3861(90)90368-9

53. Collares FM, Ogliari FA, Lima GS, Fontanella VR, Piva E, & Samuel SM (2010) Ytterbium trifluoride as a radiopaque agent for dental cements *International Endodontics Journal* **43(9)** 792-797. doi: 10.1111/j.1365-2591.2010.01746.x

54. Watts DC (1987) Radiopacity vs. composition of some barium and strontium glass composites *Journal of Dentistry* **15(1)** 38-43.

55. Fronza BM, Ayres A, Pacheco RR, Rueggeberg FA, Dias C, & Giannini M (2017) Characterization of inorganic filler content, mechanical properties, and light transmission of bulk-fill resin composites *Operative Dentistry* **42(4)** 445-455. doi: 10.2341/16-024-L

56. Beun S, Glorieux T, Devaux J, Vreven J, & Leloup G (2007) Characterization of nanofilled compared to universal and microfilled composites *Dental Materials* **23(1)** 51-59. doi: 10.1016/j.dental.2005.12.003

57. Guo G, Fan Y, Zhang JF, Hagan JL. & Xu X (2012) Novel dental composites reinforced with zirconia-silica ceramic nanofibers *Dental Materials* **28(4)** 360-368. doi: 10.1016/j.dental.2011.11.006

58. Wille S, Holken I, Haidarschin G, Adelung R, & Kern M (2016) Biaxial flexural strength of new Bis-GMA/TEGDMA based composites with different fillers for dental applications *Dental Materials* **32(9)** 1073-1078. doi: 10.1016/j.dental.2016.06.009

©Operative Dentistry, 2020, **45-3,** 306-317

How Do the Etching Mode and Thermomechanical Loading Influence the Marginal Integrity of Universal Adhesives?

K Kaczor • M Krasowski • S Lipa • J Sokołowski • A Nowicka

Clinical Relevance

Adhese Universal exhibited better marginal integrity than Peak Universal, and for both adhesives, thermomechanical loading degraded the bonding durability, particularly for nonetched enamel and pre-etched dentin.

SUMMARY

Objective: This study evaluated the effect of etching mode and thermomechanical loading on universal adhesives.

Methods and Materials: Two universal adhesives, Peak Universal and Adhese Universal, were used in two etching modes as the experimental groups: Peak Universal etch-and-rinse (PER), Peak Universal self-etch (PSE), Adhese Universal etch-and-rinse (AER), and Adhese Universal self-etch (ASE). Two adhesives considered gold standards were used as control groups: OptiBond FL (OER) was used as a control group for the etch-and-rinse (ER) mode, and Clearfil SE Bond (CSE) was used as a control group for the self-etch (SE) mode. Standardized class V cavities were created on the buccal and lingual surface in 30 extracted caries-free human third molars. Each adhesive and resin composite was applied according to the manufacturer's instructions. The specimens were subjected to thermomechanical loading (TML) immediately after the fillings were placed. Before and after TML, replicas and photographs of the fillings were performed and evaluated quantitatively and qualitatively. The Mann-Whitney U-test or Kruskal-Wallis test was used for quantitative analyses, and Fisher exact test was used for qualitative analysis.

Results: Adhese Universal achieved a significantly higher percentage of continuous margin in the enamel than Peak Universal for the two types of etching both before and after TML

Kinga Kaczor, DDS, Doctoral Studies of the Faculty of Dentistry, Pomeranian Medical University of Szczecin, Szczecin, Poland

Michał Krasowski, PhD, University Laboratory of Materials Research, Medical University of Lodz, Lodz, Poland

Sebastian Lipa, PhD, Institute of Materials Science and Engineering, Lodz University of Technology, Lodz, Poland

Jerzy Sokołowski, DDS, PhD, Department of General Dentistry, Medical University of Lodz, Lodz, Poland

*Alicja Nowicka, DDS, PhD, Department of Conservative Dentistry and Endodontics, Pomeranian Medical University of Szczecin, Szczecin, Poland

*Corresponding author: al Powstancow Wielkopolskich 72, 70-111 Szczecin, Poland; e-mail: nowicka6@gmail.com

https://doi.org/10.2341/19-002-L

(except for the SE group after TML). In dentin, the greatest percentage of continuous margin was achieved for Adhese Universal in the ER group (100%) before TML and for both universal adhesives in the SE groups (61%) after TML. For both etching modes and both time points, Adhese Universal had a greater percentage of continuous margin than Peak Universal for the whole margin. For the ER approach, significant differences were observed both before and after TML, and for the SE approach, significant differences were observed before TML. TML did not cause a significant decrease in the percentage of continuous margin in the enamel, but the results were the opposite in dentin. A qualitative assessment using World Dental Federation criteria did not show statistically significant differences between the groups.

Conclusions: Scanning electron microscope assessment of marginal integrity showed that the evaluated factors such as etching mode and TML significantly influenced the marginal integrity of the universal adhesives. The replica method shows that laboratory and clinical assessment methods complement each other and give a broader view of marginal integrity.

INTRODUCTION

The effectiveness of adhesive systems can be evaluated by analyzing different factors (eg, the bond strength and marginal integrity of the resin-tooth interface).[1] Good marginal integrity is achieved when there are no marginal microgaps around the filling, with sufficiently deep penetration of the adhesive into the tissue. The gaps occurring at that interface contribute to the penetration of bacteria and fluids, which may provoke hypersensitivity, pulpitis, marginal staining, and debonding with retention loss.[2,3] Marginal integrity might be greatly influenced by shrinkage stress on the restorative material, the size and type of the cavity, the insertion and polymerization technique, the composition and type of the adhesive system used, and the etching approach.[4-6]

Etching pretreatment of the tooth surface and bonding between the tooth tissue and adhesive can be achieved through an etch-and-rinse (ER) or self-etch (SE) approach.[7] Compared with the SE technique, the ER technique, which commonly employs a 30% to 40% phosphoric acid gel, results in more effective and stable bonding to the enamel.[7] Unfortunately, in dentin, this etching mode can ultimately result in the collapse of collagen fibrils demineralized by acid etching, which leads to weaker bond strengths and a low-quality hybrid layer.[8] Compared with the ER technique, the SE technique is simpler and more favorable for dentin. SE adhesives are designed to infiltrate the regions that they have demineralized and should produce a hybridized complex comprising the residual smear layer and a thin, partially demineralized dentin collagen matrix.[9] To combine the advantages of these two modes, new universal adhesives have been introduced. These adhesives can be used as ER or SE adhesives or can be applied using the selective enamel etching approach. The aim of universal adhesives is to accelerate and simplify the process, with the end result of making the procedure easier (ie, less technique sensitive) and improving the clinical effectiveness of adhesives, including marginal integrity, bond durability, and long-term esthetics.[10] In 2015, Loguercio and others[11] applied field-emission scanning electron microscopy (direct and replica techniques) to assess qualitatively the influence of enamel preparation on the application of five universal adhesives. The authors found that the ER approach resulted in a deeper and more pronounced etching pattern in the enamel than the SE method. For the SE technique, the etching pattern was poorer in passive application than active application of the adhesive to enamel. However, there is still a lack of laboratory studies on quantitative assessments of the marginal integrity of universal adhesives under different conditions.

Laboratory tests, especially those with thermomechanical loading (TML), allow researchers to predict the clinical performance of adhesive systems and filling materials under different use conditions and to evaluate their mechanical and structural characteristics during aging.[12] The clinical assessment of marginal integrity is one of the functional properties of the World Dental Federation (FDI) criteria, which were introduced in 2007; the criteria are more rigorous for identifying differences in composite resin restorations than previous criteria.[13] The greatest opportunity for connecting laboratory and clinical research is the replica technique, in which a model based on an impression taken *in vivo* or *in vitro* is analyzed. Therefore, the purpose of this study was to evaluate the external marginal integrity of universal adhesives for different etching modes before and after TML *in vitro* in noncarious cervical lesions (NCCLs) using the replica technique and FDI criteria and to compare the two assessment methods. The first null hypothesis was that there are

no differences in the extent of marginal integrity when using universal adhesives with the ER or SE strategy. The second null hypothesis was that the universal adhesives were characterized by similar marginal integrity to "gold standard" adhesives. The third null hypothesis was that the results for the two methods of assessment of marginal integrity are comparable.

METHODS AND MATERIALS

Tooth Preparation and Bonding Procedures

The experimental part of this study is presented in Figure 1. Thirty extracted caries-free human third molars were cleaned from concrements and soft-tissue remnants and used in this research. The teeth were stored in aqueous solution of 0.5% chloramine-T and used within six months after extraction. Standardized class V cavities were created on the buccal and lingual surface of each specimen with a round diamond drill (EDENTA-801.314.012), which was replaced after five preparations. The cavities were 4-mm wide, 4-mm tall (2 mm above and below the cement-enamel junction), and 2-mm deep (controlled by a caliper). Fine-grained diamond burs were used for finishing the preparations and placing the enamel bevel (EDENTA-862.204.012). Next, the teeth were randomly allocated into six groups of 10 specimens each, divided according to the adhesive and etching approach. Two universal adhesives, Peak Universal and Adhese Universal, were applied with two etching modes as experimental groups: Peak Universal etch-and-rinse (PER), Peak Universal self-etch (PSE), Adhese Universal etch-and-rinse (AER), and Adhese Universal self-etch (ASE). Two adhesives considered gold standards were used as control groups: OptiBond FL (OER) was used as a control group for the ER group, and Clearfil SE Bond (CSE) was used as a control group for the SE group. The composition, manufacturer, batch number, and application technique of each adhesive system are shown in Table 1. After application of the adhesive systems, the cavities were filled with two increments of composite resin, which were polymerized (Demi Plus, Kerr, Orange, CA, USA) according to the manufacturer's instructions (Table 1). Immediately after the filling procedure, the restorations were finished with a flexible disc (Soflex, 3M ESPE, Maplewood, MN, USA).

Thermomechanical Loading

The specimens were subjected to combined thermal and mechanical loading immediately after the fillings were applied. Thermal cycling consisted of 3000 cycles in water at a temperature of 5°C and 55°C with a dwell time of 20 seconds in each temperature bath and a transfer time of 13 seconds (SD Mechatronik GmbH, Feldkirchen-Westerham, Germany). Mechanical loading was performed over 100,000 cycles with a load of 110 N at a frequency of 2 Hz using a rounded tip as an antagonist (Walter +Bai Dynamic Testing Systems LFV-50kN, Walter +Bai, Löhningen, Switzerland).

Assessment of External Marginal Integrity by Scanning Electron Microscopy

Before and after TML, impressions of each restoration were acquired with an A-polyvinylsiloxane material (Aquasil Ultra XLV, Densply Sirona, York, PA, USA). Next, to obtain positive replicas, the impressions were filled with epoxy resin (EpoFix, Struers, Torrance, CA, USA). The replicas were sputter coated with gold-palladium and subjected to margin analysis using scanning electron microscopy (SEM) at 15 kV and 35× or 200× magnification (SU-70, Hitachi, Tokyo, Japan). The obtained SEM images were analyzed using ImageJ software (National Institutes of Health, Bethesda, MD, USA) to estimate the length and percentage of the continuous margin in relation to the entire assessable margin before and after TML.

Assessment of Marginal Integrity by FDI Criteria

Before and after TML, photographs of the fillings were acquired using a surgical microscope with a camera (Karl Kaps SOM 62 No. 16810). The photographs of each filling were rated according to the following FDI criteria for marginal adaptation, as suggested by Hickel and others[13]:

1. VG: clinically very good, which means harmonious outline, no gaps, no white or discolored lines
2. GO: clinically good, which means a marginal gap <150 μm, white lines or small marginal fractures removable by polishing or slight ditching, slight steps/flashes, minor irregularities
3. SS: clinically sufficient/satisfactory, which means a gap <250 μm that is not removable, several small marginal fractures or major irregularities, ditching or flashes, steps
4. UN: clinically unsatisfactory, which means a gap >250 μm, dentin/base exposed or severe ditching, marginal fractures, large irregularities or steps (repair necessary)

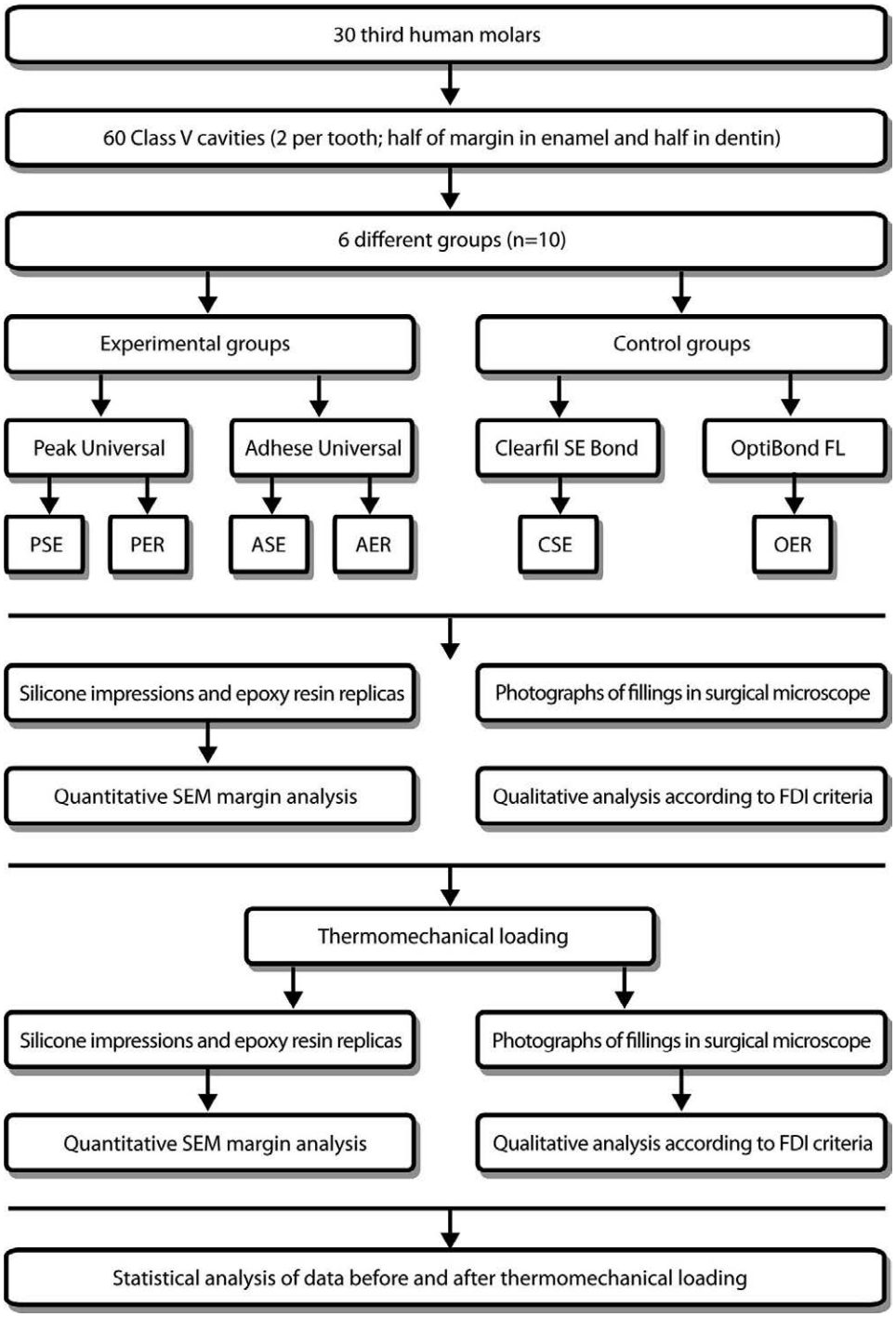


Figure 1. *Diagram of the current study.*

5. PO: clinically poor, which means a loose *in situ* restoration (complete or partial), major gaps or irregularities

Statistical Analysis

The Kolmogorov-Smirnov test revealed a nonnormal distribution of data in some groups; therefore, nonparametric tests (Mann-Whitney U test and Kruskal-Wallis test) were used for quantitative analyses. The Kruskal-Wallis test was used for testing whether samples originate from the same distribution (for testing more than two groups concurrently). The test determines whether the medians of the two or more groups are different, but it does not show the differences that exist between the groups. The Mann-Whitney test was

Table 1: *Adhesive and Composite, Application Mode, Composition, Manufacturer, and Batch Number for the Experimental and Control Groups*

Group	Adhesive (Manufacturer; Lot No.)	Application Mode	Composition	Application Method	Composite (Manufacturer; Lot No.)
Experimental					
PER	Peak Universal Bond (Ultradent, South Jordan, UT, USA; 5135 BBBXD)	Etch-and-Rinse	Ethyl alcohol, 2-hydroxyethyl methacrylate, methacrylic acid, 0.2% chlorhexidine di(acetate)	1. Acid etching for 20 s 2. Rinse for 5 s 3. Remove excess moisture 4. Apply adhesive 5. Air stream for 10 s 6. Light cure for 20 s	Amelogen Plus (Ultradent; 9031 BB5BJ)
PSE		Self-Etch		1. Apply Peak SE Primer for 20 s 2. Dry 3. Apply adhesive 4. Air stream for 10 s 5. Light cure for 20 s	
AER	Adhese Universal (Ivoclar Vivadent, Schaan, Lichtenstein; U23288)	Etch-and-Rinse	MDP, bis-GMA, HEMA, MCAP, D3MA, ethanol, water, initiator, stabilizers, silicon dioxide	1. Apply etchant for 15 s 2. Rinse for 5 s 3. Dry until chalky white 4. Apply adhesive 5. Gently air thin for 5 s 6. Light cure for 10 s at 1200 mW/cm^2	IPS Empress Direct (Ivoclar Vivadent; T39377)
ASE		Self-Etch		1. Scrub (ACTIVE[b]) or leave undisturbed (PASSIVE) one coat of adhesive for 20 s 2. Gently air thin for 5 s 3. Light cure for 10 s at 1200 mW/cm^2	
Control					
OER	OptiBond FL (Kerr, Orange, CA, USA; 5457273)	Etch-and-Rinse	Primer: HEMA, glycerol phosphate dimethacrylate, mono-2-methacryloyloxyethyl phthalate, water, ethanol Bond: Bis-GMA, HEMA, glycerol dimethacrylate, filler particles (fumed SiO_2, barium aluminoborosilicate, Na_2SiF_6)	1. Apply etchant for 15 s, rinse and blot dry 2. Apply primer with scrubbing for 15 s 3. Gentle air stream 4. Apply adhesive with brushing motion for 15 s 5. Light cure for 20 s	Herculite XRV Ultra (Kerr; 5136056)
CSE	Clearfil SE (Kuraray Noritake Dental, Tokyo, Japan; 000147)	Self-Etch	Primer: water, 10-MDP, HEMA, hydrophilic aliphatic dimethacrylate, accelerators, dl-camphorquinone Bond: 10-MDP, bis-GMA, HEMA, initiators, colloidal silica, dl-camphorquinone, accelerator	1. Apply primer with brushing motion for 20 s 2. Air dry for 5 s 3. Using the same applicator, apply adhesive with light brushing motion for 15 s 4. Air thin for 3 s 5. Light cure for 10 s at 1200 mW/cm^2	Clearfil Majesty (Kuraray Noritake Dental; 3J0009)

used to compare the two groups. Fisher's exact test was used to analyze the FDI criteria score. The level of significance was established as $p=0.05$ for all tests.

RESULTS

Enamel Marginal Integrity

Adhese Universal achieved a significantly higher percentage of continuous margin in the enamel than Peak Universal for the two types of etching both before and after TML (except for the SE group after TML). Both experimental Peak Universal groups achieved a significantly lower percentage of continuous margin than the control groups. For Adhese Universal, a significantly lower percentage of continuous margin was observed only for the ASE group after TML compared with Clearfil SE Bond. Both before and after TML, significantly better results were observed in the experimental ER groups than the experimental SE groups (Table 2). A significantly greater percentage of continuous margin in enamel than dentin was observed for the AER ($p=0.0001$), PER ($p=0.0004$), and CSE ($p=0.0233$) groups after TML (Table 2). The largest decrease in the percentage of continuous margin after TML was observed

Table 2: *Percentage (%) of Continuous Margin in Enamel, Dentin, and Enamel and Dentin Together Before and After Thermomechanical Loading (TML) for Different Etching Modes*[a]

Time	Tooth Tissue	Etch-and-Rinse			Self-Etch		
		PER	AER	OER	PSE	ASE	CSE
Before TML	Enamel	94 ± 6^{bde}	99 ± 1^{ad}	100 ± 1^{ce}	86 ± 11^{abc1}	96 ± 4^{ac1}	97 ± 5^{b1}
	Dentin	81 ± 16^{fgh2}	100 ± 1^{g2}	100 ± 0^{h2}	97 ± 5^{f12}	99 ± 3^{12}	100 ± 0^{f12}
	Enamel + dentin	88 ± 8^{kl2}	99 ± 1^{ik2}	100 ± 1^{l2}	90 ± 7^{ij2}	97 ± 2^{ik2}	98 ± 3^{j2}
After TML	Enamel	81 ± 15^{AC1}	99 ± 2^{AD1}	96 ± 7^{BC}	63 ± 19^{A}	72 ± 21^{BD}	92 ± 5^{AB1}
	Dentin	34 ± 20^{EF12}	49 ± 18^{G12}	89 ± 13^{FG2}	61 ± 29^{E2}	61 ± 23^{2}	78 ± 24^{12}
	Enamel + dentin	60 ± 11^{J2}	81 ± 9^{JK2}	93 ± 9^{HJ2}	62 ± 12^{I2}	67 ± 14^{HK2}	86 ± 10^{HI2}

[a] N=*10, mean ± SD. The same lowercase superscript indicates a difference at the 5% significance level between groups before TML in the same tooth tissue. The same uppercase superscript indicates a difference at the 5% significance level between groups after TML in the same tooth tissue. The superscript number "1" for the same group and time indicates a difference at the 5% significance level between tooth tissues. The superscript number "2" for the same group and tooth tissue indicates a difference at the 5% significance level between times.*

for both experimental SE groups; however, neither the experimental nor the control group showed a significant decrease in continuous margin (Figure 2).

Dentin Marginal Integrity

In the ER mode, Adhese Universal had a higher percentage of continuous margin than Peak Universal both before and after TML (before TML, the differences were significant). For the SE approach, Adhese Universal and Peak Universal had comparable percentages of continuous margin both before and after TML. Peak Universal exhibited a significantly lower percentage of continuous margin than the control group both before and after TML. Compared with the control group, the AER group had similar results before TML and significantly worse results after TML. Both universal adhesives in the SE approach before and after TML had a lower percentage of continuous margin than the control groups, and for the PSE group, this difference was significant. A significantly greater percentage of continuous margin in the dentin than the enamel was observed for the ASE (p=0.0255), PSE (p=0.0306), and CSE (p=0.0306) groups before TML. After TML, the experimental and control groups had a lower percentage of continuous margin in the dentin than in the enamel; this difference was significant for both universal adhesive ER groups. TML led to a significant decrease in the percentage of continuous margins for both the experimental and controls groups, and the largest decrease was observed for the two universal adhesives with the ER approach (Figure 2).

Enamel and Dentin Marginal Integrity

For both etching modes and both time points, Adhese Universal had a greater percentage of continuous margin than Peak Universal (Table 2). For the ER approach, the differences were significant both before and after TML, while for the SE approach, the differences were significant only before TML. Peak Universal exhibited a significantly lower percentage of continuous margin than the control groups for both etching approaches and both time points. Adhese Universal exhibited a lower percentage of continuous margin than the control groups for both etching approaches and both time points, but the differences were significant for the SE approach only.

Qualitative SEM Assessment of Marginal Integrity

Representative SEM micrographs of the PSE and PER, ASE and AER, and control groups are presented in Figures 3, 4, and 5, respectively. The influence of TML on the resin-enamel and resin-dentin interfaces of the same region is presented in these figures.

Qualitative Assessment According to FDI Criteria

Each filling received a "very good" or "good" rating based on the five-level scale. The best scores were obtained by the AER and OER groups both before and after TML, with 10 scores of "very good" in each group (Table 3). There were no significant differences for any single group before and after TML or between different groups at a single time point (p>0.05).

DISCUSSION

The outcomes of an adhesive procedure can differ widely depending on the adhesive and clinical situation. Therefore, the influence of application mode of universal adhesives on enamel and dentin bond efficacy was investigated. In this study, statis-

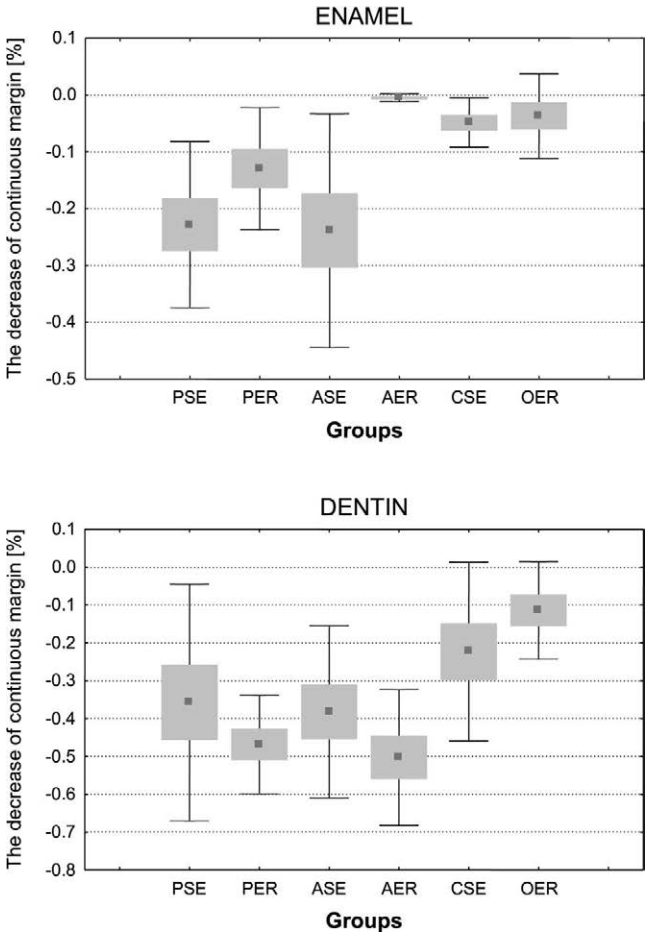


Figure 2. *The decrease in the continuous margin in enamel (upper graph) and dentin (lower graph) after TML as a percentage (%).*
Mean
±standard error
±standard deviation

tically better marginal integrity was observed for both universal adhesives with the ER method for enamel before and after TML and with the SE technique for dentin (except for Adhese Universal before TML); thus, the first null hypothesis was rejected.

This study is the first to evaluate the marginal integration of universal adhesives with the replica technique. This approach is a nondestructive technique for tooth specimens that enables the assessment and comparison marginal defects at different time points, as well as before and after applying different stresses to the tooth specimens, such as TML.[14] SEM is widely used to evaluate marginal integrity and allows marginal gaps to be distinguished from marginal irregularities or tooth fractures; moreover, areas of concern can be evaluated at a higher magnification.[15]

This study was performed using adhesive and resin composite from the same manufacturer, and the same operator performed all restorations to avoid variability.[14,16,17] Before the study, the teeth were stored in 0.5% chloramine-containing water to prevent bacterial growth, according to ISO Technical Specification 11405[18] and previous studies.[19,20] This study was based on class V cavities because they are easy to create with low researcher variability, and most studies evaluating the effectiveness of adhesives have used NCCLs.[12,16,21] NCCLs have no mechanical retention form and are located in enamel and dentin, facilitating a comparative assessment of the resin-dentin interface and the resin-enamel interface at the same time.[22,23] Moreover, cervical restorations are clinically challenging because of difficulties in moisture control, caries access, and proximity to the gingival margin.[24]

TML was performed to assess changes in the resin-tooth tissue interface under oral conditions. Thermocycling is commonly used as an artificial aging method because it creates repetitive expansion and contraction stresses along the resin-tooth tissue interface.[25,26] Hot water may also accelerate the hydrolysis of areas not covered by adhesive collagen and may extract poorly polymerized resin composite.[27] Similarly, mechanical loading imitates chewing on the sample, which causes tooth deformation and generates stress on the restoration margins.[28] These stresses are expected to increase the length of existing gaps or lead to the development of new gaps. Although there is a lack of standardized thermocycling protocols, the parameters used in this research are comparable with those used in other studies.[27] Mechanical loading is an additional factor that causes tension in the resin-tooth interface, leading to deformations such as microcracks or gaps.[29] In the literature, there is no standard protocol for mechanical loading; other studies have applied forces ranging from 50 N[30,31] to 100 N/250 N[21] at frequencies from 0.5 Hz[30] to 1.5 Hz[31] over 10,000[21] to 250,000 cycles.[31] Comparing the results before and after TML revealed that all groups, except the AER group for enamel, showed a significant decrease in the percentage of continuous margin (Table 2). Greater loss occurred in the experimental ER group at the composite-dentin interface than the composite-enamel interface. The opposite trend was observed for the experimental SE group. A decrease in the continuous margin after TML was also observed in other studies testing Clearfil SE Bond,[32] Silorane System Adhesive,[33] Syntac, XP Bond, Single Bond Plus, AdheSE, and Clearfil SE Bond.[30]

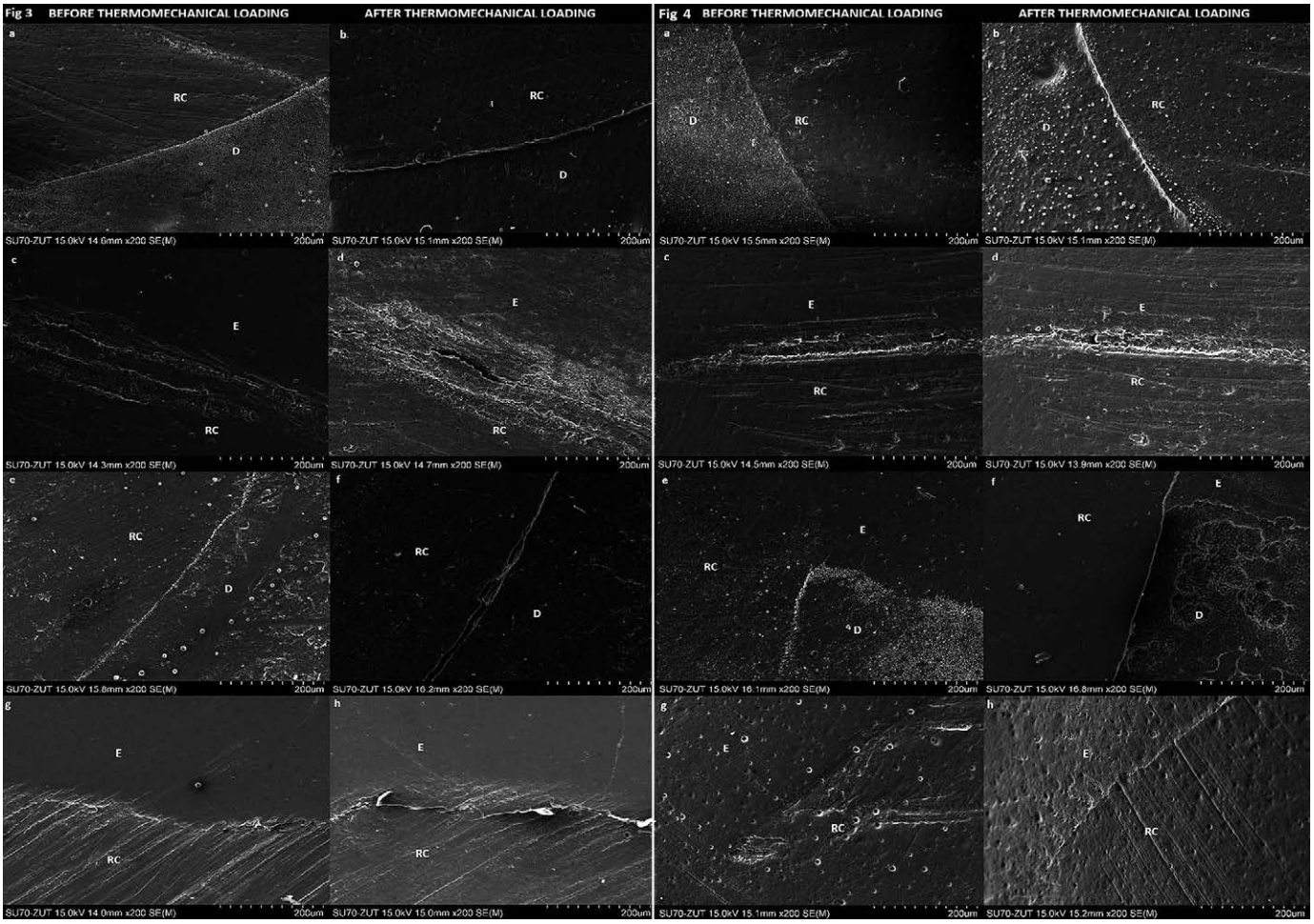


Figure 3. *Representative SEM micrographs from the same region of the PSE (a-d) and PER (e-h) groups before and after TML. The micrographs show the appearance of gaps in the resin-dentin interface (a, b and e, f) and an increase in current gaps at the resin-enamel interface (c, d and g, h) in the PSE and PER groups, respectively, after TML. E, enamel; D, dentin; RC, resin composite.*

Figure 4. *Representative SEM images from the same region of the ASE (a-d) and AER (e-h) groups before and after TML. (a-d): The micrographs show no visible changes in the resin-dentin interface (a, b) and increased irregularity in the resin-enamel interface (c, d) for the ASE group after TML. (e-h): The micrographs show a manifestation of gaps in the resin-dentin interface (e, f) and free gaps in the resin-enamel interface (g, h) for the AER group after TML. E, enamel; D, dentin; RC, resin composite.*

In this study, two universal adhesives were compared for different etching modes. It was found that the ER approach had higher percentages of continuous margins in enamel than in dentin and that the SE approach achieved better results in dentin than in enamel (except for the AER and ASE groups before TML), which was more prominent after TML. Similar conclusions were obtained by Bortolotto and others,[16] who tested 12 adhesives, and Gregor and others,[33] who investigated Silorane System Adhesive. Moreover, Casselli and others[17] demonstrated that the gap width also can vary depending on the etching approach and tooth tissue. Casselli and others[17] and Blunck and Zaslansky[19] demonstrated that the margins in enamel observed after using one-bottle one-step SE adhesives are much poorer than the margins of restorations in which phosphoric acid etching was used, which is consistent with the obtained results. This result occurs because in the ER technique, the adhesive fills the space surrounding the etched region in the enamel and envelops individual hydroxyapatite crystals, creating a stable bond with the enamel.[7] After TML, in dentin, poorer results were observed for the ER group than the SE group (the difference was significant in the Peak Universal group), which may be due to excessive etching in the ER approach. When etching dentin with phosphoric acid, the adhesive may not penetrate to a sufficient depth, and overdrying the cavity may cause the collagen network on the dentin surface to collapse, which reduces bond durability.[34] With regard to the whole

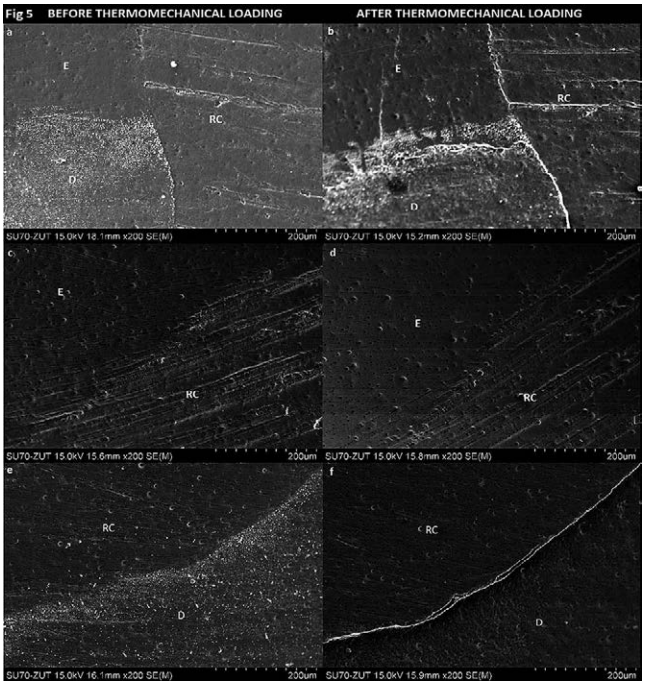


Figure 5. *Representative SEM micrographs from the same region of the CSE (a-b) and OER (c-f) groups before and after TML. (a, b): The micrographs show greater irregularity in the resin-dentin interface than the resin-enamel interface in the CSE group after TML. (c, d): The resin-enamel interface is barely detectable in the OER group both before and after TML. (e, f): The micrographs show the manifestation of gaps in the resin-dentin interface in the OER group after TML. E, enamel; D, dentin; RC, resin composite.*

margin in enamel and dentin, the AER group had a smaller decrease than the PER group, but the decrease was still larger than that observed for Scotchbond Universal applied with the ER technique, as reported by Bortolotto and others,[35] who found that the continuous margin decreased from 98.5% before TML to 97.8% after TML. However, there is still a lack of laboratory studies assessing universal adhesives under different conditions.

This study compared the marginal integrity of universal adhesives with two gold standard adhesives: OptiBond FL and Clearfil SE Bond. Peak Universal Bond had statistically worse marginal integrity than the control groups in both etching techniques and time points (except the PSE group in dentin after TML) in contrast to Adhese Universal. When comparing this system to the control group, a significant difference was observed only in the ER technique in dentin after TML, so the second null hypothesis is partially rejected. OptiBond FL presented a relatively equal marginal adaptation on enamel and dentin, both before and after TML, which is comparable with results from other studies[16,35]; this adhesive and Clearfil SE Bond are considered the gold standard of ER and SE adhesives, respectively.[36-39] Compared with other studies, this study obtained both similar[40] and contrasting[30] results for Clearfil SE Bond, confirming that adhesion to dentin is unpredictable and may be worse if the dentin is etched before the application of SE adhesive. This study also emphasized that preetching of enamel by phosphoric acid remains the most reliable, durable, and fatigue-resistant mode of enamel bonding,[10,40,41] as reported by Körner and others[42] and Bortolotto and others.[43]

The composition of an adhesive also influences its bond stability. Peak Universal had the smallest continuous margin before and after TML (not significant in all cases; Table 2), despite containing chlorhexidine (Table 1), which is widely used as an antimicrobial agent. Chlorhexidine may inhibit matrix metalloproteinases and, consequently, prevent the degradation of collagen fibrils at the resin-dentin interface[44,45] and partially conserve the integrity of the hybrid layer to improve bond durability.[46] However, the small continuous margin observed for Peak Universal in both etching modes may be due to the lack of 10-methacryloyloxydecyl dihydrogen phosphate (10-MDP) monomer, which is present in the composition of Adhese Universal and Clearfil SE (Table 1). 10-MDP is primarily used as an etching monomer due to its dihydrogen phosphate group, which dissociates in water to form two

Table 3: *Number of Evaluated Restorations Classified According to the World Dental Federation (FDI) Criteria*[13]

FDI Criteria	Time											
	Before TML						After TML					
	PER	PSE	AER	ASE	OER	CSE	PER	PSE	AER	ASE	OER	CSE
VG	9	7	10	8	10	9	9	6	10	6	10	9
GO	1	3	—	2	—	1	1	4	—	4	—	1
SS	—	—	—	—	—		—	—	—	—	—	—
UN	—	—	—	—	—	—	—	—	—	—	—	—
PO	—	—	—	—	—	—	—	—	—	—	—	—
N	10	10	10	10	10	10	10	10	10	10	10	10

protons. 10-MDP is hydrophobic (its long carbonyl chain favors ethanol and acetone as solvents) and hydrolytically stable.[47,48] 10-MDP monomers can form an ionic bond with the calcium in hydroxyapatite and can hydrolytically nucleate stable 10-MDP-calcium salts.[39] To improve bonding stability, it could be useful to connect MDP-10 monomer and chlorhexidine in a single adhesive to combine their advantages.

This study compared clinical and laboratory methods for assessing marginal integrity. The AER and OER groups received the best scores in FDI assessment both before and after TML; however, there were no significant differences between any of the groups or time points in the FDI assessment. Thus, the third null hypothesis was rejected. Similar conclusions were reported by Lopes and others,[49] who assessed the universal adhesive Xeno Select in clinical studies. However, Loguercio and others,[50] who evaluated Scotchbond Universal Adhesive, noted a significantly worse rating of marginal integrity after a three-year trial, although the application method did not influence this parameter at the baseline or at later time points. Laboratory (SEM) and clinical (FDI criteria) assessment methods are crucial because gaps seen in the laboratory that are imperceptible clinically may cause postoperative sensitivity, marginal staining, or retention loss.[2] Moreover, this short-term study is the first stage of research and did not include water degradation of adhesives; thus, there is a need to perform long-term research using the replica method in a laboratory and clinical study.

CONCLUSION

Within the limitations of this laboratory study, the evaluated factors such as etching mode and TML influenced the marginal integrity of universal adhesives. For both etching modes and both time points, Adhese Universal offered better results in both enamel and dentin than Peak Universal, and its marginal integrity is comparable to the gold standard adhesives. For the ER approach, the differences in the percentage of continuous margin were significant both before and after TML, while for the SE approach, the differences were significant only before TML. Unfortunately, the new universal adhesives do not resolve the problem of dentin adhesion, because in each group, a significant decrease in the percentage of continuous margin was observed for dentin and thus for the whole margin. Moreover, the replica method shows that clinical and laboratory tests complement each other and give a broader view of marginal integrity.

Acknowledgements

All experimental protocols were approved by the Local Ethics Committee of Pomeranian Medical University in Szczecin, Poland (approval No. KB-0012/82/11/2014). This study was funded by the Polish Ministry of Science and Higher Education, program for years 2016-2018 for The Faculty of Medicine & Dentistry, Pomeranian Medical University, Szczecin Poland (grant No. MB-262-186/16).

Regulatory Statement

This study was conducted in accordance with all the provisions of the local human subjects oversight committee guidelines and policies of the Local Ethics Committee of Pomeranian Medical University in Szczecin, Poland. The approval code for this study is KB-0012/82/11/2014.

Conflict of Interest

The authors of this article certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

(Accepted 11 April 2019)

REFERENCES

1. Heintze SD (2007) Systematic reviews: I. The correlation between laboratory tests on marginal quality and bond strength. II: the correlation between marginal quality and clinical outcome *Journal of Adhesive Dentistry* **9(Supplement 1)** 77-106.
2. Heintze SD (2013) Clinical relevance of tests on bond strength, microleakage and marginal adaptation *Dental Materials* **29(1)** 59-84.
3. Sano H, Shono T, Takatsu T, & Hosoda H (1994) Microporous dentin zone beneath resin-impregnated layer *Operative Dentistry* **19(2)** 59-64.
4. Feilzer AJ, De Gee AJ, & Davidson CL (1987) Setting stress in composite resin in relation to configuration of the restoratives *Journal of Dental Research* **66(11)** 1636-1639.
5. Peutzfeldt A & Asmussen E (2004) Determinants of *in vitro* gap formation of resin composites *Journal of Dentistry* **32(2)** 109-115
6. Breschi L, Mazzoni A, Ruggeri A, Cadenaro M, Di Lenarda R, & De Stefano Dorigo E (2008) Dental adhesion review: aging and stability of the bonded interface *Dental Materials* **24(1)** 90-101.
7. Van Meerbeek B, De Munck J, Yoshida Y, Inoue S, Vargas M, Vijay P, Van Landuyt K, Lambrechts P, & Vanherle G (2003) Buonocore memorial lecture adhesion to enamel and dentin: current status and future challenges *Operative Dentistry* **28(3)** 215-235.
8. Pashley DH, Tay FR, Breschi L, Tjäderhane L, Carvalho RM, Carrilho M, & Tezvergil-Mutluay A (2011) State of the art etch-and-rinse adhesives *Dental Materials* **27(1)** 1-16.

9. Van Landuyt KL, De Munck J, Mine A, Cardoso MV, Peumans M, & Van Meerbeek B (2010) Filler debonding & subhybrid-layer failures in self-etch adhesives *Journal of Dental Research* **89(10)** 1045-1050.
10. Perdigão J & Swift EJ Jr (2015) Universal adhesives *Journal of Esthetic and Restorative Dentistry* **27(6)** 331-334.
11. Loguercio AD, Muñoz MA, Luque-Martinez I, Hass V, Reis A, & Perdigão J (2015) Does active application of universal adhesives to enamel in self-etch mode improve their performance? *Journal of Dentistry* **43(9)** 1060-1070.
12. Heintze SD, Blunck U, Göhring TN, & Rousson V (2009) Marginal adaptation *in vitro* and clinical outcome of Class V restorations *Dental Materials* **25(5)** 605-620.
13. Hickel R, Peschke A, Tyas M, Mjör I, Bayne S, Peters M, Hiller KA, Randall R, Vanherle G, & Heintze SD (2010) FDI World Dental Federation: clinical criteria for the evaluation of direct and indirect restorations-update and clinical examples *Journal of Adhesive Dentistry* **12(4)** 259-272.
14. Blunck U & Zaslansky P (2007) Effectiveness of all-in-one adhesive systems tested by thermocycling following short and long-term water storage *Journal of Adhesive Dentistry* **9(Supplement 2)** 231-240.
15. Lindberg A, van Dijken JW, & Hörstedt P (2005) *In vivo* interfacial adaptation of class II resin composite restorations with and without a flowable resin composite liner *Clinical Oral Investigations* **9(2)** 77-83.
16. Bortolotto T, Doudou W, Kunzelmann KH, & Krejci I (2012) The competition between enamel and dentin adhesion within a cavity: an *in vitro* evaluation of class V restoration *Clinical Oral Investigations* **16(4)** 1125-1135.
17. Casselli DS, Faria-e-Silva AL, Casselli H, & Martins LR (2013) Marginal adaptation of class V composite restorations submitted to thermal and mechanical cycling *Journal of Applied Oral Science* **21(1)** 68-73.
18. ISO-Standards (2003) ISO/TS 11405 Dental materials—testing of adhesion to tooth structure *Geneva: International Organization for Standardization*.
19. Blunck U & Zaslansky P (2011) Enamel margin integrity of Class I one-bottle all-in-one adhesives-based restorations *Journal of Adhesive Dentistry* **13(1)** 23-29.
20. Saikaew P, Matsumoto M, Chowdhury A, Carvalho RM, & Sano H Does shortened application time affect long-term bond strength of universal adhesives to dentin? *Operative Dentistry* **43(5)** 549-558.
21. Arisu HD, Uçtasli MB, Eligüzeloglu E, Ozcan S, & Omürlü H (2008) The effect of occlusal loading on the microleakage of Class V restorations *Operative Dentistry* **33(2)** 135-141.
22. Van Meerbeek B, Perdigao J, Lambrechts P, & Vanherle G (1998) The clinical performance of adhesives *Journal of Dentistry* **26(1)** 1-20.
23. Chee B, Rickman LJ, & Satterthwaite JD (2002) Adhesives for the restoration of non-carious cervical lesions: a systematic review *Journal of Dentistry* **40(6)** 443-452.
24. Pecie R, Krejci I, García-Godoy F, & Bortolotto T (2011) Noncarious cervical lesions (NCCL)—a clinical concept based on the literature review. Part 2: restoration *American Journal of Dentistry* **24(3)** 183-192.
25. Amaral FLB, Colucci V, Palma-Dibb RG, & Corona SAM (2007) Assessment of *in vitro* methods used to promote adhesive interface degradation: a critical review *Journal of Esthetic and Restorative Dentistry* **19(6)** 340-353.
26. De Munck J, Van Landuyt K, Peumans M, Poitevin A, Lambrechts P, Braem M, & Van Meerbeek B (2005) A critical review of the durability of adhesion to tooth tissue: methods and results *Journal of Dental Research* **84(2)** 118-132.
27. Morresi AL, D'Amario M, Capogreco M, Gatto R, Marzo G, D'Arcangelo C, & Monaco A (2014) Thermal cycling for restorative materials: does a standardized protocol exist in laboratory testing? A literature review *Journal of the Mechanical Behavior of Biomedical Materials* **29(1)** 295-308.
28. Wang Y, Liao Z, Liu D, Liu Z, McIntyre GT, Jian F, Lv W, Yang J, Zhao Z, & Lai W (2011) 3D-FEA of stress levels and distributions for different bases under a Class I composite restoration *American Journal of Dentistry* **24(1)** 3-7.
29. Davidson CL & Davidson-Kaban SS (1998) Handling of mechanical stresses in composite restorations *Dental Update* **25(7)** 274-279.
30. Frankenberger R, Lohbauer U, Roggendorf MJ, Naumann M, & Taschner M (2008) Selective enamel etching reconsidered: better than etch-and-rinse and self-etch? *Journal of Adhesive Dentistry* **10(5)** 339-344.
31. Senawongse P, Pongprueksa P, & Tagami J (2010) The effect of the elastic modulus of low-viscosity resins on the microleakage of Class V resin composite restorations under occlusal loading *Dental Materials Journal* **29(3)** 324-329.
32. Borges AF, Santos JS, Ramos CM, Ishikiriama SK, & Shinohara MS (2012) Effect of thermo-mechanical load cycling on silorane-based composite restorations *Dental Materials Journal* **31(6)** 1054-1559.
33. Gregor L, Bortolotto T, Feilzer AJ, & Krejci I (2013) Effect of different bonding strategies on the marginal adaptation of class 1 silorane restorations *American Journal of Dentistry* **26(3)** 127-131.
34. Yesilyurt C & Bulueu B (2006) Bond strength of total-etch dentin adhesive systems on peripheral and central dentinal tissue: a microtensile bond strength test *Journal of Contemporary Dental Practice* **7(2)** 26-36.
35. Bortolotto T, Mast P, & Krejci I (2017) Laser-prepared and bonding-filled fissure sealing: SEM and OCT analysis of marginal and internal adaptation *Dental Materials Journal* **36(5)** 622-629.
36. Peumans M, De Munck J, Van Landuyt KL, Poitevin A, Lambrechts P, & Van Meerbeek B (2012) A 13-year clinical evaluation of two three-step etch-and-rinse adhesives in non-carious class-V lesions *Clinical Oral Investigations* **16(1)** 129-137.
37. Perdigão J, Gomes G, Gondo R, & Fundingsland JW (2006) *In vitro* bonding performance of all-in-one adhesives. Part I—microtensile bond strengths *Journal of Adhesive Dentistry* **8(6)** 367-373.

38. Peumans M, De Munck J, Van Landuyt KL, Poitevin A, Lambrechts P, & Van Meerbeek B (2010) Eight-year clinical evaluation of a 2-step self-etch adhesive with and without selective enamel etching *Dental Materials* **26(12)** 1176-1184.

39. Van Meerbeek B, Yoshihara K, Yoshida Y, Mine A, Demunck J, & Van Landuyt K (2011) State of the art of self-etch adhesives *Dental Materials* **27(1)** 17-28.

40. Frankenberger R & Tay FR (2005) Self-etch vs etch-and-rinse adhesives: effect of thermo-mechanical fatigue loading on marginal quality of bonded resin composite restorations *Dental Materials* **21(5)** 397-412.

41. Shimada Y & Tagami J (2003) Effects of regional enamel and prism orientation on resin bonding *Operative Dentistry* **28(1)** 20-27.

42. Körner P, El Gedaily M, Attin R, Wiedemeier DB, Attin T, & Tauböck TT (2017) Margin integrity of conservative composite restorations after resin infiltration of demineralized enamel *Journal of Adhesive Dentistry* **19(6)** 483-489.

43. Bortolotto T, Bahillo J, Richoz O, Hafezi F, & Krejci I (2015) Failure analysis of adhesive restorations with SEM and OCT: from marginal gaps to restoration loss *Clinical Oral Investigations* **19(8)** 1881-1890.

44. Pashley DH, Tay FR, Yiu C, Hashimoto M, Breschi L, Carvalho RM, & Ito S (2004) Collagen degradation by host-derived enzymes during aging *Journal of Dental Research* **83(3)** 216-221.

45. Carrilho MR, Tay FR, Donnelly AM, Agee KA, Tjäderhane L, Mazzoni A, Breschi L, Foulger S, & Pashley DH (2009) Host derived loss of dentin matrix stiffness associated with solubilization of collagen *Journal of Biomedical Materials Research Part B Applied Biomaterials* **90(1)** 373-380.

46. Hebling J, Pashley DH, Tjäderhane L, & Tay FR (2005) Chlorhexidine arrests subclinical degradation of dentin hybrid layers *in vivo Journal of Dental Research* **84(8)** 741-746.

47. Hayakawa T, Kikutake K, & Nemoto K (1998) Influence of self-etching primer treatment on the adhesion of resin composite to polished dentin and enamel *Dental Materials* **14(2)** 99-105.

48. Van Landuyt KL, Snauwaert J, De Munck J, Peumans M, Yoshida Y, Poitevin A, Coutinho E, Suzuki K, Lambrechts P, & Van Meerbeek B (2007) Systematic review of the chemical composition of contemporary dental adhesives *Biomaterials* **28(26)** 3757-3785.

49. Lopes LS, Calazans FS, Hidalgo R, Buitrago LL, Gutierrez F, Reis A, Loguercio AD, & Barceleiro MO (2016) Six-month follow-up of cervical composite restorations placed with a new universal adhesive system: a randomized clinical trial *Operative Dentistry* **41(5)** 465-480.

50. Loguercio AD, de Paula EA, Hass V, Luque-Martinez I, Reis A, & Perdigão J (2015) A new universal simplified adhesive: 36-month randomized double-blind clinical trial *Journal of Dentistry* **43(9)** 1083-1092.

©Operative Dentistry, 2020, **45-3,** 318-326

Does Diamond Stone Grinding Change the Surface Characteristics and Flexural Strength of Monolithic Zirconia?

R Aliaga • LN Miotto • LM Candido • LMG Fais • LAP Pinelli

Clinical Relevance

Dentists commonly need to perform grinding procedures to gain space when adapting a prosthesis; however, this grinding may induce damage to the surface. Thus, it is important to perform grinding that does not impair the properties, and the best way is without irrigation for conventional and monolithic zirconias.

SUMMARY

Purpose: The present study evaluated the effect of grinding on the surface morphology, mean roughness, crystalline phase, flexural strength, and Weibull modulus of monolithic (MZ) and conventional (CZ) zirconias.

Methods and Materials: CZ and MZ bars and square-shaped specimens were distributed into three subgroups, combining grinding (G) and irrigation (W) with distilled water: Ctrl (Control: no grinding, 20 × 4 × 1.2 mm and 12 × 1.2 mm), DG (dry grinding, 20 × 4 × 1.5 mm and 12 × 1.5 mm), and WG (grinding with irrigation, 20 × 4 × 1.5 mm and 12 × 1.5 mm). The grinding (0.3 mm) was performed on a standardized device using a low-rotation wheel-shaped diamond stone. The four-point flexural strength test was performed on the EMIC 2000 machine (5 KN, 0.5 mm/min). Scanning electron microscopy (SEM) was used to evaluate the surface morphology. An X-ray diffractometer (XRD) was used to obtain the crystalline structures that were analyzed by the Rietveld method. Flexural strength (FS) values were subjected to the Shapiro-Wilk test and two-way analysis of variance followed by the Tukey's test (for all tests, α=0.05).

Raquel Aliaga, DDS, Department of Dental Materials and Prosthodontics, São Paulo State University (Unesp), School of Dentistry, Araraquara, São Paulo, Brazil

Larissa Natiele Miotto, DDS, MSD, PhD student, Department of Dental Materials and Prosthodontics, São Paulo State University (Unesp), School of Dentistry, Araraquara, São Paulo, Brazil

Lucas Miguel Candido, DDS, MSD, PhD student, Department of Dental Materials and Prosthodontics, São Paulo State University (Unesp), School of Dentistry, Araraquara, São Paulo, Brazil

Laiza Maria Grassi Fais, DDS, MSD, PhD, postdoctoral research, Department of Dental Materials and Prosthodontics, São Paulo State University (Unesp), School of Dentistry, Araraquara, São Paulo, Brazil

*Lígia Antunes Pereira Pinelli, DDS, MSD, PhD, associate professor, Department of Dental Materials and Prosthodontics, São Paulo State University (Unesp), School of Dentistry, Araraquara, São Paulo, Brazil

*Corresponding author: Rua Humaitá, 1680, Araraquara-SP, CEP 14801-903, Brazil; e-mail: ligia.pinelli@unesp.br

https://doi.org/10.2341/19-023-L

Results: Grinding, either with or without irrigation, did not change the FS of the MZ but increased the FS of the CZ. Both MZ and CZ showed similar morphologic patterns after grinding, and in the WG groups, the grinding was more aggressive. The MZ had greater monoclinic content in all groups; grinding without irrigation caused the smallest t→m transformation.

Conclusion: The grinding, when necessary, should be carried out without irrigation for conventional and monolithic zirconias.

INTRODUCTION

Since the 1960s, when Helmer and Driskell[1] published the first work on different biomedical applications of zirconia,[2] researchers and manufacturers have made admirable efforts to promote its clinical indications. Zirconia is a polymorphic material primarily with three phases, monoclinic (m), tetragonal (t), and cubic (c),[3,4] which changes according to thermo-mechanical factors that can impact the properties of the zirconia.

Initially, studies concentrated on the addition of oxides, such as yttria[5–8] to stabilize the material in the tetragonal phase at room temperature. Then, in the 1990s, the yttrium oxide–stabilized tetragonal zirconia polycrystal (Y-TZP) was indicated for dental use due to its high flexural fracture strength and its toughening process. Y-TZP also features biocompatibility, low radioactivity, interesting optical properties, high hardness, grinding resistance, good frictional behavior, an absence of magnetism, high corrosion resistance in acids and alkali, elasticity modulus similar to steel, and thermal expansion coefficient similar to iron.[2]

Among dental ceramics, Y-TZP has shown the best mechanical properties due to transformation toughening.[2–4,9] This property relates to zirconia's ability in the tetragonal phase to prevent the spread of small cracks. Compared with the dental tissues, this ability would be similar to the blockage provided by the interface of the dentino-enamel junction and the crystalline microstructure of the enamel.[10]

Due to these advantageous properties, Y-TZP was used for infrastructures of all-ceramic fixed crowns and prostheses, implants, abutments, and orthodontic brackets.[2,4,11] It is considered the most appropriate material to resist the high tension that affects multiple all-ceramic frameworks up to five elements.[11] However, there are contraindications such as those related to patients with poor oral hygiene, high caries activity, active periodontal disease and parafunction,[12,13] and failures related to marginal adaptation, delamination, and chipping.[14,15]

To solve delamination and chipping, improvements in the zirconia/veneer interface have been made,[16–20] such as the development of a zirconia without esthetic coating, named monolithic zirconia (MZ).[21,22] MZ was developed by adding different dopants and coloring liquids, changing the sintering temperatures, eliminating porosities, and changes in grain size,[21,23–25] resulting in greater transmittance and translucency.[24,25] In addition, MZ has good fracture resistance,[26] and its acceptable esthetics allows for use as veneers in posterior teeth[27] and requires less tooth removal because a smaller material thickness is sufficient.[28]

However, even with computer-aided design/computer-aided manufacturing technology, clinical adjustments through grinding are indispensable for obtaining adequate occlusal contacts in total monolithic zirconia crowns,[21,22] and such procedures increase surface roughness, as well as induce transformation t→m. Although these transformations make the zirconia surface more tenacious, over time it may have negative effects on mechanical stability depending on the total or partial loss of the materials' ability to prevent or delay the spread of cracks and could become critically unreliable.[12]

The available evidence on the influence of grinding/finishing on the flexural strength of zirconia is still contradictory.[29–38] Regardless of the grinding method used, changes in the material surface may favor or damage the mechanical properties depending on the quantity of t→m transformation, and zirconia with higher monoclinic content will be more subject to the impact of long-term degradation.[39]

The aim of the present study was to evaluate the effect of grinding on surface morphology, mean roughness, crystalline phase, flexural strength, and Weibull modulus in MZ and conventional zirconia (CZ). The first null hypothesis was that both zirconias have the same surface characteristics and the second was that both zirconias have the same mechanical properties.

METHODS AND MATERIALS

Specimen Preparation

After a pilot study, the sample size (n) for each test was calculated using $\alpha=0.05$ and $\beta=0.80$. Two types of zirconia were used, one CZ (group CZ, control, ICE Zirkon, Zirkonzahn GmbH, Gais, Bolzano, Italy) and

Table 1: *Distribution and Nomenclature Adopted for the Experimental Groups*

Groups	Treatments
CZ	Conventional zirconia without grinding
CZDG	Conventional zirconia with dry grinding
CZWG	Conventional zirconia with wet grinding
MZ	Monolithic zirconia without grinding
MZDG	Monolithic zirconia with dry grinding
MZWG	Monolithic zirconia with wet grinding

the other MZ (group MZ, Prettau Zirkon, Zirkonzahn GmbH). As previously described, bars and square-shaped specimens were obtained[24,32] with the following dimensions: $25 \times 5 \times 1.5$ mm and 15×1.5 mm for specimens that would not be ground (CZ and MZ groups) and $25 \times 5 \times 1.9$ mm and 15×1.9 mm for specimens that would be ground.

Surface irregularities were removed with silicone tips (Exacerapol, Edenta, Labordental, Hauptstrasse, Switzerland), and a final polishing was performed with #1200, #1500, and #2000 silicon carbide abrasive papers (401Q, 3M ESPE, Tidal, SP, Brazil). Bar-shaped specimens had their edges beveled at 45°.

Sintering was performed according to the manufacturer's recommendations in a Zirkonofen furnace (600/V2, Zirkonzahn GmbH) with a heat treatment program of eight hours at a maximum temperature of 1500°C for the CZ and 8.2 hours at a maximum temperature at 1600°C for the MZ. The dimensions after the sintering (volumetric contraction ~20%) were $20 \times 4 \times 1.2$ mm and 12×1.2 mm for the CZ and MZ groups and $20 \times 4 \times 1.5$ mm and 12×1.5 mm for the groups that were ground. The final dimensions were measured using digital calipers (500-144B, Mitutoyo Sul Americana, Suzano, SP, Brazil).

The specimens that would be ground were further subdivided into two subgroups: grinding without irrigation (dry grinding [DG]) and grinding with irrigation (wet grinding [WG]). The experimental groups' distribution and nomenclature adopted are shown in Table 1.

Grinding Procedure

A standardized grinding apparatus capable of controlling the amount of grinding and rotation speed was used.[24,32] The surface grinding (0.3 mm) was performed with a diamond stone of medium grit (MasterCeram, 133-104-SDN, Polierwerk, Straubenhardt, Baden-Württemberg, Germany) in a low-speed electric handpiece (Micro Electric Motor Bench for Prosthetics LB 100, Beltec, Araraquara, SP, Brazil) at 20,000 rpm; specimens from WG were ground under distilled water flowing from a triple syringe. After grinding, all specimens possessed 1.2-mm thicknesses. Before the tests, all specimens were cleaned in an ultrasonic bath using distilled water (five minutes) and isopropyl alcohol (five minutes).

Surface Morphology

Two specimens of each group were sputter-coated with gold. Overall surface morphology was characterized by scanning electron microscopy (SEM, JEOL JSM-6610LV, Akishima, Tokyo, Japan) with secondary electrons.

Mean Surface Roughness

Mean surface roughness values (Ra, μm) were determined in square-shaped specimens (n=13) using a profilometer (Mitutoyo SJ 400, Mitutoyo Corp, Yokohama, Japan) with an accuracy of 0.01 μm, active tip radius of 5 μm, and speed of 0.5 mm/s at three equidistant different locations on one side of the specimens. To respect the cutoff, an λC of 2.5 mm was adopted for the WG groups and 0.8 mm for the other groups; the limited Ra for the cutoff was 2 μm. The measurement locations were the same for all specimens: one in the center and the others equidistant (5 mm). The measurements were performed in the opposite direction of the grinding lines for the groups submitted to this procedure.

Crystallography

To identify the crystalline structure, one specimen from each group was analyzed in a X-ray diffractometer (DRX-6000, Shimadzu do Brazil) using Cu-Kα radiation, 2θ scan between 10° and 80°, an angular step of 0.05°, and a step time of three seconds. The crystalline phases were identified by comparison with standard microfiche of the International Centre for Diffraction Data JCPDS files.

Flexural Strength and Weibull Modulus

Flexural strength (FS, n=13) was carried out by a four-point device attached to the EMIC 2000 testing machine (Equipamentos e Sistemas de Ensaio Ltda, São José dos Pinhais, Paraná, Brazil) with a 5-kN load cell and speed of 1 mm/min (ISO 6872:2008). The FS values were calculated according to the following formula: $\sigma = 3PL/4wb^2$, where σ = flexural strength, in MPa; P = force at the moment of the

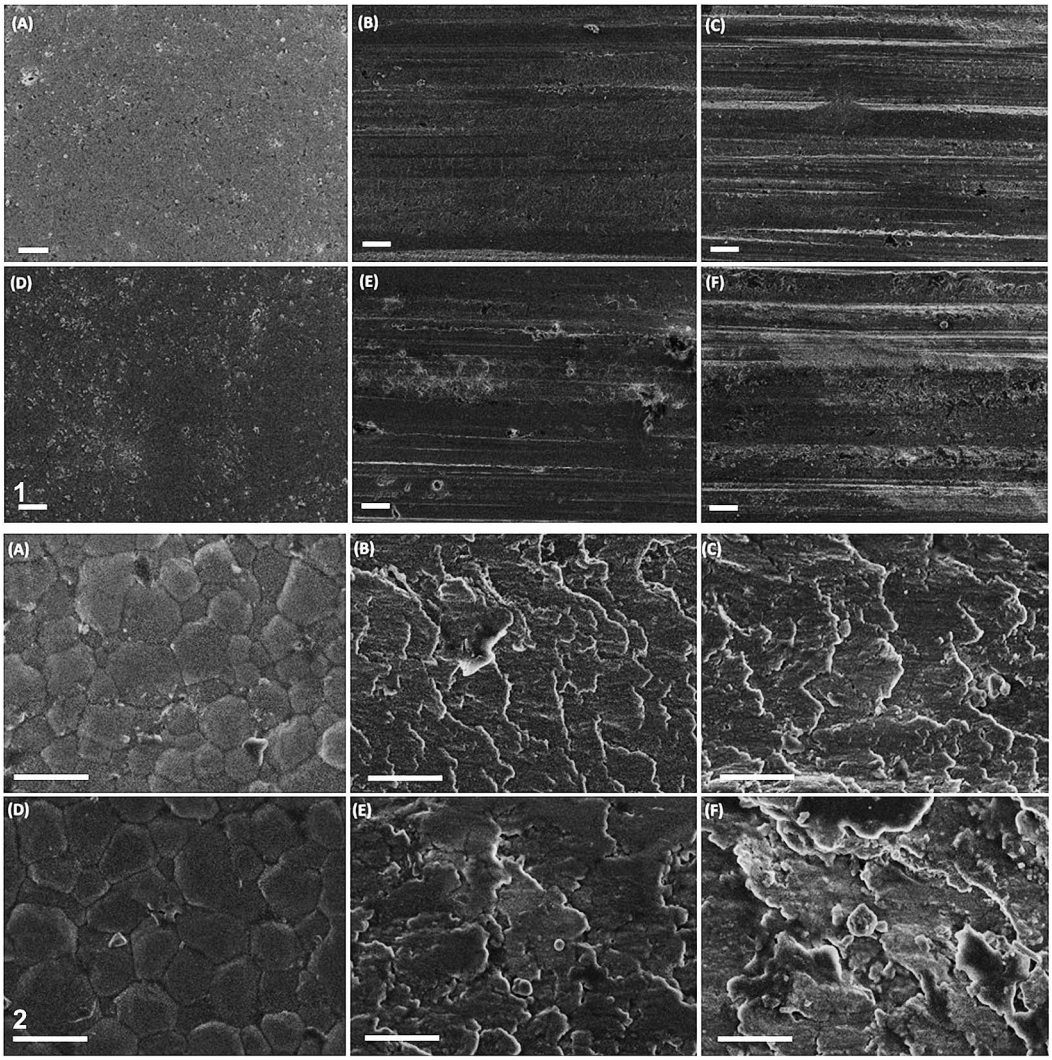


Figure 1. *Surface morphology of the groups at 1000× magnification: (A) CZ, (B) CZDG, (C) CZWG, (D) MZ, (E) MZDG, and (F) MZWG. In A and D, the morphology reveals a flat surface without scratches. In B, C, E, and F, the presence of grooves could be seen that follows the grinding direction and plastic deformation.*

Figure 2. *Surface morphology of the groups at 25,000× magnification: (A) CZ, (B) CZDG, (C) CZWG, (D) MZ, (E) MZDG, and (F) MZWG. In A and D, the morphology reveals similarity in grain conformation with slightly larger grains in MZ. In B, C, E, and F, the presence of scales, loss of grain disclosure, and plastic deformation could be seen, being more evident in C and F. E and F shows bigger scales.*

fracture in newtons; L = the distance between the outer supports in millimeters; w = the width of the specimen in millimeters; and b = the thickness of the specimen in millimeters.

The reliability of the materials was calculated by the determination of the Weibull modulus (m). The equation $P(\sigma) = 1 - \exp(-\sigma/\sigma_0)^m$ was applied to calculate the Weibull modulus, where $P(\sigma)$ is the fracture probability, σ is the fracture strength at a given $P(\sigma)$, σ_0 is the characteristic strength, and m is the Weibull modulus, which is the slope of the $1n$ ($1n$ $1/1 - P$) versus σ plots.[30,40–42]

Statistical Analysis

The SEM images were submitted to descriptive analysis, and XRD data were analyzed by the Rietveld method. Ra and FS were submitted to normality and homoscedasticity tests and subsequently to the analysis of variance (ANOVA) two-way test (α=0.05) followed by the Tukey's *post hoc* (α=0.05) in the BioEstat 5.0 software.

RESULTS

The micrographs are depicted in Figures 1 and 2. In the smallest magnification (1000×), the surface

Table 2: *Means and SDs of Mean Roughness (Ra, in μm)*[a]

Treatments	Groups	
	CZ	MZ
—	0.14 ± 0.02 Ca	0.15 ± 0.03 Ca
DG	1.49 ± 0.46 Ba	1.53 ± 0.36 Ba
WG	2.79 ± 0.59 Ab	3.26 ± 0.43 Aa

[a] *Different lowercase letters indicate statistical difference between columns and uppercase between lines (p<0.05).*

Table 3: *Volume Fraction (%) of the Monoclinic (M), Tetragonal (T), and Cubic (C) Phases in Y-TZP*

Treatments	Groups					
	CZ			MZ		
	T	M	C	T	M	C
—	76.23	7.20	16.57	69.12	10.76	20.12
DG	94.26	5.74	0.00	92.44	7.56	0.00
WG	89.64	10.36	0.00	85.71	14.29	0.00

morphology of the CZ and MZ revealed similarity (Figure 1A,D), but when analyzed in the highest magnification (25,000×), it was possible to visualize slightly larger grains. Grinding caused grooves that followed the grinding direction (Figure 1B,C,E,F), as well as loss of grain disclosure and the presence of scales and plastic deformation (Figure 2B,C,E,F). These changes were more evident when irrigation was done: with a surface with aggressive cuts, deeper and irregular valleys (Figure 1C,F), and larger scars (Figure 2C,F). In addition, when comparing the types of zirconia, it is possible to visualize that the changes in the monolithic zirconia were more evident (Figures 1E,F and 2E,F).

The means and standard deviations of Ra, in micrometers, are shown in Table 2. Statistically significant differences were observed among the treatments ($p<0.05$), indicating the lowest value of Ra for the no grinding groups and the highest value for the groups with wet grinding. Between zirconias, the statistical difference was observed just in the WG group ($p<0.05$).

The quantification of the crystalline phases of the samples is provided in Table 3. The CZ and MZ showed all three phases: tetragonal (T), monoclinic (M), and cubic (C). In both zirconias, grinding (with or without irrigation) transformed the entire cubic phase in the tetragonal phase of the specimens' surface. WG in both zirconias presented a more monoclinic phase than the other groups.

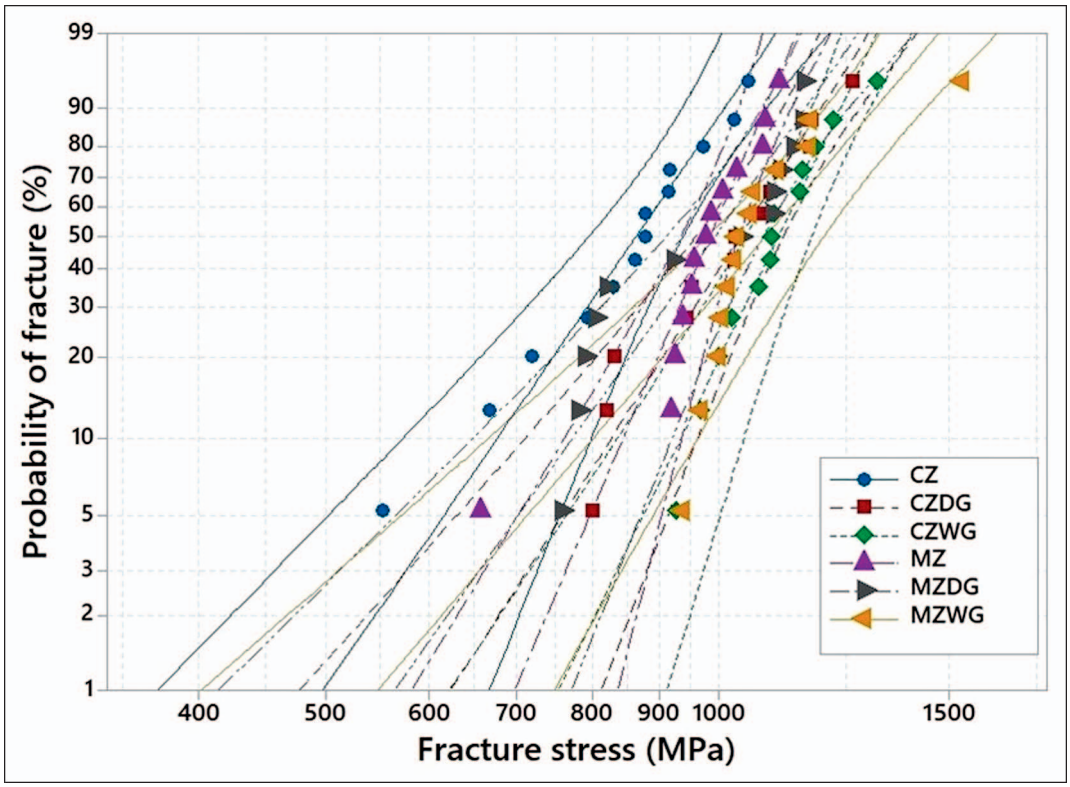


Figure 3. *Weibull plot for fracture data of the groups.*

Table 4: *Mean FS (in MPa), Weibull Modulus (m), and Respective 95% CI*[a]

Treatments	Groups							
	CZ				MZ			
	FS	95% CI (FS)	m	95% CI (m)	FS	95% CI (FS)	m	95% CI (m)
—	851.2 Ba	783.1-925.3	7.7 Aa	5.0-11.9	971.7 Aa	921.6-1024.5	12.3Aa	8.0-19.1
DG	1021.99 Aa	945.53-1104.64	8.3 Aa	5.4-12.8	977.99 Aa	897.25-1066.0	7.5Aa	4.8-11.8
WG	1096.07 Aa	1032.27-1163.81	10.9 Aa	7.3-16.3	1069.75 Aa	965.94-1184.71	6.2Aa	4.3-8.9

[a] *Different lowercase letters indicate statistical difference between columns and uppercase between lines ($p<0.05$).*

Table 4 shows the mean FS (in MPa), the Weibull Modulus (m), and the respective confidence intervals (95% CI). Figure 3 shows the Weibull plot. Statistically, there was no interaction between groups ($p=0.08$) for the FS and no difference between the two types of zirconias ($p=0.56$). Grinding did not change the FS of the MZ ($p=0.10$) but increased the FS of the CZ ($p<0.05$). There was no difference between dry or wet grinding ($p>0.05$). No significant statistical difference was found for the Weibull modulus comparisons.

DISCUSSION

MZ has recently been introduced into the market to eliminate the delamination and chipping, which are the main problems related to CZ. The indication of MZ significantly increased in situations where the interdental space is insufficient causing fractures in the crown.[43] Nevertheless, it is common that dentists need to perform grinding procedures to gain space when adapting a prosthesis,[44,45] and this grinding may induce damage to the surface.[46] It is fundamental to understand if grinding procedures could damage the MZ and how. Thus, the present study evaluated the effect of grinding on flexural strength, surface morphology, and the crystalline phases of an MZ compared with a CZ. For the surface characteristics, the null hypothesis was rejected because all the properties changed after the experimental treatments. For the mechanical properties, the null hypothesis was partially accepted because the Weibull modulus of both zirconias and the monolithic flexural strength did not change after the treatments.

When zirconia is ground, the introduced surface defects can become microfissures, ie, grooves that follow the main direction, some with lateral projections and even cracks depending on the rotary cutting tool type, grit-size, load, and applied speed).[33] In the present study, both CZ and MZ showed similar morphologic patterns after grinding, with more pronounced changes in MZ (Figures 1 and 2). This difference could be attributed to the microstructural differences between the types of zirconia.[21,23–25] In both types of zirconia, more changes could be observed in the WG subgroup (Figures 1C,F and 2C,F). According to Candido and others,[32] this result could be attributed to a higher cutting performance because water could remove dust that impregnates on the rotary cutting tool. These surfaces also showed superficial plastic deformation that hides grain boundaries, as reported by Preis and others.[22] Previous studies[31,34,47] have shown the same images patterns.

The present study also evaluated zirconia-grinding effects on the FS. The results (Table 4) indicate that grinding did not significantly change the MZ values of the FS, both in wet (MZWG 974.43±164.62 MPa) and in dry (MZDG 1082.31±152.40 MPa) conditions. On the other hand, there were significant changes in the FS values of the CZ after grinding: an increase of approximately 20% in the CZDG and 29% in the CZWG. These differences could probably be explained due to the larger cubic content present in the MZ surfaces (MZ=20.12% and CZ=16.57%). Surfaces with more cubic phases would be expected to have less residual stress than those fully tetragonal with equal grain sizes; therefore, the direct result of this minor residual stress is a reduction in the force to dissipate the t→m transformation, resulting in a stabilization of the tetragonal grains.[48] This phenomenon was not observed in the CZ group where the FS increased after grinding. The Weibull modulus (Table 4; Figure 3) did not have a statistical difference for all zirconias and between the treatments, which means that the reliability[30,40–42] of the materials and treatment were equal.

Different results were reported in the literature. Pereira and others[35] obtained higher values of FS for the MZ after grinding with a coarse diamond bur (181 μm); also, Guilard and others[33] obtained these when the MZ was ground with an extra fine diamond bur (30 μm) compared with coarse diamond bur (150 μm) grinding. Regarding the CZ, although dry and wet grinding increased the FS in the present study,

corroborating studies of other authors,[32,34] a large number of papers reported contradictory results.[29–31]

In general, it can be assumed that for both CZ and MZ, changes in FS depend on several factors, such as the rotary cutting tool type and its grit size, the size of zirconia grains, changes in crystalline structure, and surface roughness.[49,50] According to Kosmac and others,[29] for the CZ, there is a decrease in FS after grinding with diamond burs and a negative correlation between the FS and the size of zirconia grains. Pereira and others[31] also evaluated the effect of grinding with a diamond disc and bur, verifying that FS increased after grinding for high and low grit size burs, but decreased when larger grit size discs were used. For Polli and others[51] and Hatanaka and others,[52] the grinding with a diamond bur (151 μm) was also responsible for the increased FS.

Another source of influence on the FS would be the surface roughness. The roughness data (Table 1) corroborate the morphologic differences observed in the micrographs (Figures 1 and 2). It can be observed that surfaces with more pronounced grooves and plastic deformation showed higher Ra values. When ground without irrigation, the zirconias did not show differences, but with irrigation, the MZ showed higher roughness. This alteration may be due to the association of severe grinding with the microstructural differences. Moreover, the literature shows that ceramic roughness had a negative correlation with FS[53]; however, in the present study, grinding surfaces with higher Ra (Table 2) did not show any changes (MZ) or even exhibited higher flexural strength (CZ). The Ra-FS relation should be interpreted with caution because the phase transformation toughening mechanism and the depth of the introduced cracks may have a counter-balance effect, excluding the effects of roughening.[54]

It is important to evaluate whether grinding changes the zirconia crystalline structure, because grinding can induce a phase transformation, whereas it can have a negative or a positive impact on the mechanical properties, and it depends on the volume percentage of the t→m transformation and on the conversion's metastability.[49,50] Regarding the quantification of the crystalline structure (Table 3), it is observed that wet grinding was responsible for higher t→m transformation, indicating a rougher procedure. These findings were similar to the results of Subaşı and others,[47] Pereira and others,[31] Preis and others,[22] and Mohammadi-Bassir and others[34] but differ from those found by Polli and others[51] who carried out the grinding in high rotation with a diamond bur, and this difference could be attributed to the grinding severity that was directly related to the amount of t→m transformation.[2,50] In addition, Guilard and others[33] observed that the higher the grit size of the diamond bur, the greater the t→m transformation. Candido and others[32] assumed that this transformation occurs after the surface was ground, because the energy generated by this procedure modifies the structure of the tetragonal grain, causing it to increase in size and become monoclinic. The transformation to a monoclinic phase toughens the zirconia surface.[49,50] The MZ showed more balanced phase stability, because during dry grinding, there was a decrease in the order of 30% in relation to the initial monoclinic content against 21% that occurred when the conventional zirconia was dry ground. When irrigation was used, there was an increase of 32% of monoclinic content for the ZM and 43% for the ZC.

The present study has some limitations such as the static loading for the FS and the specimen geometries that do not reproduce intraoral conditions. Further clinical investigations with dynamic loadings and a specimen with crown design are indicated to better understand the effects of grinding for the mechanical properties of Y-TZP. Chairside adjustments of the monolithic zirconia will still be necessary to optimize the emergence profile, improving adaptation and occlusion.[33] The formation of the monoclinic phase decreases the mechanical properties and its stability in a humid medium.[3] Thus, and based on the results of the present work, the dentist should guide the adjustment procedures to be carried out in low-speed rotation without irrigation to reduce the monoclinic and cubic content.

CONCLUSION

The grinding procedure with a diamond stone, either dry or wet, did not change the monolithic zirconia flexural strength; however, it was able to increase the flexural strength for the conventional zirconia. Grinding with irrigation was rougher, principally for monolithic zirconia. It was concluded that when a diamond stone was used, grinding without irrigation (dry) should be carried out for both zirconias.

Conflict of Interest

The authors of this manuscript certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

(Accepted 27 May 2019)

References

1. Helmer JO, & Driskell TD (1969) Research on bioceramics *Symposium on Use of Ceramics as Surgical Implants* Clemson University, Clemson, SC.
2. Vagkopoulou T, Koutayas SO, Koidis P, & Strub JR (2009) Zirconia in dentistry: Part 1 Discovering the nature of an upcoming bioceramic *European Journal of Esthetic Dentistry* **4(2)** 130-151.
3. Piconi C & Maccauro G (1999) Zirconia as a ceramic biomaterial *Biomaterials* **20(1)** 1-25.
4. Denry I & Kelly JR (2008) State of the art of zirconia for dental applications *Dental Materials* **24(3)** 299-307.
5. Garvie RC, & Nicholson PS (1972) Structure and thermomechanical properties of partially stabilized zirconia in Cao-ZrO2 system *Journal of the American Ceramic Society* **55(3)** 152-157.
6. Christel P, Meunier A, Heller M, Torre JP, & Peille CN (1989) Mechanical properties and short-term in-vivo evaluation of yttrium-oxide-partially-stabilized zirconia *Journal of Biomedical Materials Research* **23(1)** 5-61.
7. Taira M, Nomura Y, Wakasa K, Yamaki M, & Matsui A (1990) Studies on fracture-toughness of dental ceramics *Journal of Oral Rehabilitation* **17(6)** 551-563.
8. Hayashi K, Matsuguchi N, Uenoyama K, & Sugioka Y (1992) Reevaluation of the biocompatibility of bioinert ceramics in vivo *Biomaterials* **13(4)** 195-200.
9. Chevalier J (2006) What future for zirconia as a biomaterial? *Biomaterials* **27(4)** 535-546.
10. Giordano R (2002) CAD/CAM: an overview of machines and materials *Journal of the Massachusetts Dental Society* **51(1)** 12-15.
11. Studart AR, Filser F, Kocher P, Luthy H, & Gauckler LJ (2007) Cyclic fatigue in water of veneer-framework composites for all-ceramic dental bridges *Dental Materials* **23(2)** 177-185.
12. Suarez MJ, Lozano JFL, Salido MP, & Martinez F (2004) Three-year clinical evaluation of In-Ceram zirconia posterior FPDs *International Journal Prosthodontics* **17(1)** 35-38.
13. Raigrodski AJ, Chiche GJ, Potiket N, Hochstedler JL, Mohamed SE, Billiot S, & Mercante DE (2006) The efficacy of posterior three-unit zirconium-oxide-based ceramic fixed partial dental prostheses: a prospective clinical pilot study *Journal of Prosthetic Dentistry* **96(4)** 237-244.
14. Ortop A, Kihl ML, & Carlsson GE (2009) A 3-year retrospective and clinical follow-up study of zirconia single crowns performed in a private practice *Journal of Dentistry* **37(9)** 731-736.
15. Belo YD, Sonza QN, Borba M, & Bona AD (2013) Zircônia tetragonal estabilizada por ítria: comportamento mecânico, adesão e longevidade clínica *Cerâmica* **59(352)** 633-639.
16. Ohlmann B, Rammelsberg P, Schmitter M, Schwarz S, & Gabbert O (2008) All-ceramic inlay-retained fixed partial dentures: preliminary results from a clinical study *Journal of Dentistry* **36(9)** 692-696.
17. Mosharraf R, Rismanchian M, Savabi O, & Ashtiani AH (2011) Influence of surface modification techniques on shear bond strength between different zirconia cores and veneering ceramics *Journal of Advanced Prosthodontics* **3(4)** 221-228.
18. Göstemeyer G, Jendras M, Borchers L, Bach FW, Stiesch, & Kohorst P (2012) Effect of thermal expansion mismatch on the Y-TZP/veneer interfacial adhesion determined by strain energy release rate *Journal of Prosthodontics Research* **56(2)** 93-101.
19. Harding AB, Norling BK, & Teixeira EC (2012) The effect of surface treatment of the interfacial surface on fatigue-related microtensile bond strength of milled zirconia to veneering porcelain *Journal of Prosthodontics* **21(5)** 346-352.
20. Wang G, Zhang S, Bian C, & Kong H (2014) Effect of zirconia surface treatment on zirconia/veneer interfacial toughness evaluated by fracture mechanics method *Journal of Dentistry* **42(7)** 808-815.
21. Preis V, Behr M, Hahnel S, Handel G, & Rosentritt M (2012) In vitro failure and fracture resistance of veneered and full-contour zirconia restorations *Journal of Dentistry* **40(11)** 921-928.
22. Preis V, Schmalzbauer M, Bougeard D, Schneider-Feyrer S, & Rosentritt M (2015) Surface properties of monolithic zirconia after dental adjustment treatments and in vitro wear simulation *Journal of Dentistry* **43(1)** 133-139.
23. Jiang L, Liao Y, Wan Q, & Li W (2011) Effects of sintering temperature and particle size on the translucency of zirconium dioxide dental ceramic *Journal of Materials Science: Materials in Medicine* **22(11)** 2429-2435.
24. Candido LM, Miotto LN, Fais L, Cesar PF, & Pinelli L (2018) Mechanical and Surface Properties of Monolithic Zirconia *Operative Dentistry* **43(3)** E119-E128.
25. Zhang Y & Lawn BR (2019) Evaluating dental zirconia *Dental Materials* **35(1)** 15-23.
26. Flinn B, Raigrodski AJ, Mancl LA, Toivola R, & Kuykendall T (2017) Influence of aging on flexural strength of translucent zirconia for monolithic restorations *Journal of Prosthetic Dentistry* **117(2)** 303-309.
27. Kim HK & Kim SH (2014) Effect of the number of coloring liquid applications on the optical properties of monolithic zirconia *Dental Materials* **30(9)** 229-237.
28. Sari F, Secilmis A, Simsek I, & Ozsevik S (2016) Shear bond strength of indirect composite material to monolithic zirconia *Journal of Advanced Prosthodontics* **8(4)** 267-274.
29. Kosmac T, Oblak C, Jevnikar P, Funduk N, & Marion L (2000) Strength and reliability of surface treated Y-TZP dental ceramics *Journal of Biomedical Materials Research* **53(4)** 304-13.
30. Karakoca S & Yilmaz H (2009) Influence of surface treatments on surface roughness, phase transformation, and biaxial flexural strength of Y-TZP ceramics *Journal of Biomedical Materials Research Part B Applied Biomaterials* **91(2)** 930-937.
31. Pereira GK, Amaral M, Simoneti R, Rocha GC, Cesar PF, & Valandro LF (2014) Effect of grinding with diamond-

disc and bur on the mechanical behavior of a Y-TZP ceramic *Journal of the Mechanical Behavior of Biomedical Materials* **37** 133-140.

32. Candido LM, Fais LMG, Ferreira EB, Antonio SG, & Pinelli LAP (2017) Characterization of a diamond ground Y-TZP and reversion of the tetragonal to monoclinic transformation *Operative Dentistry* **42(4)** 407-417.
33. Guilard LF, Pereira GK, Gündel A, Rippe MP, & Valandro LF (2017) Surface micro-morphology, phase transformation, and mechanical reliability of ground and aged monolithic zirconia ceramic *Journal of the Mechanical Behavior of Biomedical Materials* **65(Jan)** 849-856.
34. Mohammadi-Bassir M, Jamshidian M, Rezvani MB, & Babasafari M (2017) Effect of coarse grinding, overglazing, and 2 polishing systems on the flexural strength, surface roughness, and phase transformation of yttrium-stabilized tetragonal zirconia *Journal of Prosthetic Dentistry* **118(5)** 658-665.
35. Pereira GK, Silvestri T, Amaral M, Rippe MP, Kleverlaan CJ, & Valandro LF (2016) Fatigue limit of polycrystalline zirconium oxide ceramics: Effect of grinding and low-temperature aging *Journal of the Mechanical Behavior of Biomedical Materials* **61(Aug)** 45-54.
36. Dapieve KS, Guilardi LSF, Silvestri T, Rippe MP, Pereira GKR, & Valandro LF (2018) Mechanical performance of Y-TZP monolithic ceramic after grinding and aging: survival estimates and fatigue strength *Journal of the Mechanical Behavior of Biomedical Materials* **87(Nov)** 288-295.
37. Polli GS, Hatanaka GR, Abi-Rached FO, Góes MS, & Reis JMDSN (2018) Fatigue behavior and surface characterization of a Y-TZP after laboratory grinding and regeneration firing *Journal of the Mechanical Behavior of Biomedical Materials* **88(Dec)** 305-312.
38. Zucuni CP, Guilardi LF, Rippe MP, Pereira GKR, & Valandro LF (2018) Polishing of ground Y-TZP ceramic is mandatory for improving the mechanical behavior *Brazilian Dental Journal* **29(5)** 483-491.
39. Júnior LR, Miranda ME, & Zanetti AL (2003) All-ceram crowns with the procera system *Revista Gaúcha de Odontologia* **51** 297-300.
40. Quinn JB & Quinn GD (2010) A practical and systematic review of Weibull statistics for reporting strengths of dental materials *Dental Materials* **26(2)** 135-147.
41. ASTM C1239-13 (2013) Standard practice for reporting uniaxial strength data and estimating Weibull distribution parameters for advanced ceramics ASTM International, West Conshohocken, PA.
42. Ramos GF, Pereira GK, Amaral M, Valandro LF, & Bottino MA (2016) Effect of grinding and heat treatment on the mechanical behavior of zirconia ceramic *Brazilian Oral Research* **30(1)** 1-8.
43. Lan TH, Liu PH, Chou MM, & Lee HE (2016) Fracture resistance of monolithic zirconia crowns with different occlusal thicknesses in implant prostheses *Journal of Prosthetic Dentistry* **115(1)** 76-83.
44. Fleming GJ, El-Lakwah SF, Harris JJ, & Marquis PM (2004) The influence of interfacial surface roughness on bilayered ceramic specimen performance *Dental Materials* **20(2)** 142-149.
45. Fleming GJ, Nolan L, & Harris JJ (2005) The in-vitro clinical failure of all-ceramic crowns and the connector area of fixed partial dentures: the influence of interfacial surface roughness *Journal of Dentistry* **33(5)** 405-412.
46. Chang CW, Waddell JN, Lyons KM, & Swain MV (2011) Cracking of porcelain surfaces arising from abrasive grinding with a dental air turbine *Journal of Prosthodontics* **20(8)** 613-620.
47. Subaşı MG, Demir N, Kara O, Ozturk AN, & Özel F (2014) Mechanical properties of zirconia after different surface treatments and repeated firings *Journal of Advanced Prosthodontics* **6(6)** 462-467.
48. Casellas D, Sánchez-Bajo F, Forsling W, Llane L, & Anglada M (2001) On the transformation toughening of Y–ZrO2 ceramics with mixed Y–TZP/PSZ microstructures *Journal of the European Ceramic Society* **21(6)** 765-767.
49. Kosmac T, Oblak C, Jevnikar P, Funduk N, & Marion L (1999) The effect of surface grinding and sandblasting on flexural strength and reliability of Y-TZP zirconia ceramic *Dental Materials* **15(6)** 426-433.
50. Guazzato M, Albakry M, Quach L, & Swain MV (2005) Influence of surface and heat treatments on the flexural strength of a glass-infiltrated alumina/zirconia-reinforced dental ceramic *Dental Materials* **21(5)** 454-463.
51. Polli GS, Hatanaka GR, Abi-Rached FO, Pinelli LAP, de Sousa Goes M, Cesar PF, & Reis JM (2016) Effect of grinding and resintering on the fatigue limit and surface characterization of a Y-TZP ceramic *Brazilian Dental Journal* **27(4)** 468-475.
52. Hatanaka GR, Polli GS, Fais LMG, Reis JMDSN, & Pinelli LAP (2017) Zirconia changes after grinding and regeneration firing *Journal of Prosthetic Dentistry* **118(1)** 61-68.
53. Flury S, Peutzfeldt A, & Lussi A (2012) Influence of surface roughness on mechanical properties of two computer-aided design/computer-aided manufacturing (CAD/CAM) ceramic materials *Operative Dentistry* **37(6)** 617-624.
54. Quinn GD (2006) *NIST Recommended Practice Guide Special Publication: Fractography of Ceramics and Glasses* Nacional Institute of Standards and Technology, Washington.

©Operative Dentistry, 2020, **45-3,** 327-338

Influence of Multiple Peak Light-emitting-diode Curing Unit Beam Homogenization Tips on Microhardness of Resin Composites

J Soto-Montero • G Nima • FA Rueggeberg • CTS Dias • M Giannini

Clinical Relevance

Lack of beam homogeneity in multiwave light-curing units might produce inadequate polymerization in composite restorations, causing a decreased microhardness that lessens clinical longevity of a restoration. Light curing units producing homogeneous beams are recommended.

SUMMARY

This study evaluated the effect of light curing unit (LCU) guide type (regular or homogenizing) on top and bottom microhardness of conventional and bulk-fill resin-based composites (RBCs). A polywave light-emitting-diode (LED) LCU (Bluephase Style, Ivoclar Vivadent AG) was used with two different light guides: a regular tip (RT, 935 mW/cm^2 emittance) and a homogenizer tip (HT, 851 mW/cm^2 emittance). Two conventional RBCs (Herculite Ultra [HER], Kerr Corp; Tetric EvoCeram [TEC], Ivoclar Vivadent AG) and two bulk-fill RBCs (SonicFill [SOF], Kerr Corp; Tetric EvoCeram Bulk Fill [TBF], Ivoclar Vivadent AG) were tested. Disc-shaped samples (10 mm Ø), 2-mm thick for conventional composites and 4-mm thick for bulk-fill composites were prepared. Samples were light cured according to manufacturer-recommended times. Knoop microhardness values (KHN) were obtained on the top and bottom surfaces of each specimen at locations correlated with the output of the three LED chips emitting blue (456 nm) or violet light (409 nm). Beam profile analysis using both light guides was also performed. Microhardness of each composite was analyzed using three-way analysis of variance and Tukey honestly significant difference *post*

*Jorge Soto-Montero, DDS, MS, MS, PhD student, Operative Dentistry, Piracicaba Dental School, University of Campinas, Piracicaba, Brazil and professor, Department of Restorative Dentistry, University of Costa Rica - School of Dentistry, San José, Costa Rica

Gabriel Nima, DDS, MSc, PhD student, Dental Materials, Piracicaba Dental School, University of Campinas, Piracicaba, Brazil

Frederick A Rueggeberg, DDS, MSc, professor, Dental Materials, Dental College of Georgia, Augusta University, Augusta, GA, USA

Carlos TS Dias, DDS, MS, PhD, titular professor, Department of Statistical Mathematics, Luiz de Queiroz Higher School of Agriculture, University of São Paulo, Piracicaba, Brazil

Marcelo Giannini, DDS, MS, PhD, associate professor, Department of Restorative Dentistry, Piracicaba Dental School, University of Campinas, Piracicaba, Brazil

*Corresponding author: Montes de Oca, San Jose 115012060 Costa Rica; e-mail: jorgerodrigo.soto@ucr.ac.cr

https://doi.org/10.2341/19-027-L

***hoc* test (α=0.05). Beam profile images showed better light distribution across the surface of the HT light guide. Use of the HT decreased KHN of HER at the locations of the blue LED chips at bottom of the sample but had no effect on the top surface. For TEC, use of HT increased KHN of all three LED locations at the top surface. Use of the HT increased KHN of SOF at locations corresponding to one of the blue and the violet LED chips at the bottom surface. For TBF, HT increased KHN at all top surface locations. All RBCs showed higher mean KHN at the top compared with the bottom surfaces. In general, all composites presented a higher KHN at the blue LED areas regardless of the surface or the tip used. Results suggest that the homogenizer light guide resulted in significantly increased microhardness at the top, in composite resins containing alternative photoinitiators; however, that effect was not observed at the bottom surfaces.**

INTRODUCTION

In most light-curing units (LCUs), radiation is transmitted from the source to the target surface using a nonflexible, removable, optic fiber light guide.[1–3] These guides, maintain the emitted light spectrum, such as used in some light-emitting-diode (LED) units preserving or enhancing the emittance.[2–5] The capability of the light guide to deliver the generated light spectrum and emittance has become important because use of the LED LCU has overtaken use of quartz-tungsten-halogen lights in most dental practices.[6–8]

LED LCUs contain one to four LED chips depending on the unit's design.[2] Some LCUs are capable of emitting blue and violet light within specific wavelength ranges, constituting what is known as "polywave," "multiple peak," or "multiwave" lights.[3,4,7] However, each chip produces light within a narrow spectral range, and some authors express concern regarding an uneven irradiance when using those LCUs.[5,6,9,10] Also, because each LED is placed at a specific location within the light-generating array, and little to no blending of the emitted beams occurs, a heterogeneous light distribution is produced at the emitting end of the guide.[5,6,9,11–16] This lack of uniformity within the emitted beam then exposes the target surface unevenly, producing a heterogeneous polymerization.[6,17] Thus, the target, light-curable restorative material may not receive light at all the emitted wavelengths and irradiance levels.[5–7,9,10,12]

The problem with a heterogeneous wavelength distribution of light becomes relevant with respect to the wide variety of photoinitiators used in resin-based materials: camphorquinone (CQ), 2,4,6-trimethylbenzoyldiphenyl phosphine oxide (TPO), bisacylphosphine oxide (BAPO), phenyl propanodione (PPD), and Ivocerin (Ivoclar Vivadent AG, Schaan, Liechtenstein).[2–4,18,19] Each of these photoinitiators responds preferably to light at specific wavelengths,[4,9,10,18,20] and a nonuniform wavelength distribution at the light emitting end might result in an incomplete or inconsistent polymerization of the target material due to lack of or partial activation of some photoinitiators.[6,9,10,12,21] Thus, a heterogeneous light distribution may result in localized areas of enhanced or reduced polymerization, which might be associated with clinical longevity of a restoration.[5,7,11,12,22] However, there is literature stating that a nonuniform light beam does not reduce the extent of polymerization in a 2-mm thick increment of CQ-based RBC and in composites containing up to 50% TPO in association with CQ.[14] In addition, it has been shown that increasing the polymerization time reduces the effect of the nonhomogeneity of the light beam on the degree of conversion of bulk-fill composites.[23] The lack of an effect has been attributed to special polymerization modifiers in bulk-fill composites, use of more efficient photoinitiator systems,[24,25] and overall enhanced light transmission in depth[24] by better matching of refractive indexes between filler particles and the resin components, which increase depth of cure.[25]

Clinically, an insufficient degree of monomer conversion in resin-based composites (RBCs) has been associated with decreased surface hardness,[5,12,26,27] discoloration,[9] reduced wear resistance,[5,28] lower bond strength,[9] cytotoxicity,[9] and a greater susceptibility to marginal gap defects.[9,29]

Relative comparison of the microhardness of the top and bottom surfaces of composite specimens has been proposed as an appropriate method to establish the effectiveness of light curing and as a way to study the polymerization of a specific material and its depth of cure using a particular curing condition.[27,30,31] This technique is valid because it has been reported that surface microhardness increases as the degree of conversion increases.[10,20,26,32] An international standards organization method uses measurement of the length of remaining, nonscrapable, perceptibly hardened composite as an

indicator to assess adequacy of composite curing.[33] However, it is claimed that those methods overestimate composite depth of cure values because they only measure the deepest polymerized region of the RBC without considering the effects of differences in LED chip positions and differences in wavelengths reaching the restoration surface.[20,21,31,34]

In response to concerns about possible inadequate RBC polymerization, an LCU manufacturer developed a light guide to better homogenize the irradiance and emitted spectral distribution across the emitting tip end:[12] the homogenizer light guide, designed for use with a Polywave LCU.[35,36] This item is designed to reduce the light beam heterogeneity while maintaining the delivered power from the LCU. However, no scientific study has been performed to directly address these claims.

The purpose of this study was to analyze the effects of photopolymerizing different conventional and bulk-fill commercial composites with the same LCU body using a homogenizer light guide compared with a conventional (regular) guide tip. The effect of differences in the light guides was measured using microhardness of the top or bottom restoration surfaces. The working hypotheses were that (1) the use of the homogenizer light guide type would significantly influence microhardness of conventional and bulk-fill composites; (2) for the same light guide, lower wavelength light would produce reduced microhardness on conventional and bulk-fill composites, and (3) the microhardness at the top of the conventional and bulk-fill composite discs using either type of light guide would be significantly higher than at the bottom.

METHODS AND MATERIALS

LCU Characterization

A Polywave LCU (Bluephase Style, Ivoclar Vivadent AG, Schaan, Liechtenstein) with two blue LED chips (456 nm; B1 and B2) and one violet chip (409 nm, V) was used. One regular tip (RT) and one homogenizer tip (HT) light guide, each with a circular, 10-mm Ø (9.3 mm of active internal diameter), were commercially available for use in the same LCU. The spectral irradiance of the LCU between 350 and 550 nm was measured with each light guide five times using a 6″ National Institute of Standards and Technology–traceable, calibrated integrating sphere (CTSM-LSM-60-SF, Labsphere Inc, North Sutton, NH, USA), connected to a fiber optic spectrometer (USB 2000, Ocean Optics, Dunedin, FL, USA). Spectra were recorded using software (SpectraSuite version 1.4.2, Ocean Optics), and data were entered into a spreadsheet program (Excel 2016, Microsoft Corporation, Redmond, WA, USA). The RT light guide was considered the control.

The beam profile of the LCU when using both light guides was measured using a laser beam profiler with a 10-mm-diameter internal aperture. No imaging target was used; the light distribution across the emitting tip end was directly visualized. The LCU light guide was aligned using a profile camera with a 50-mm focal length lens (USB-L070, Ophir-Spiricon, Logan, UT, USA). Three measurements were performed using each light guide: one of the unfiltered beam profile, another one with a custom-made violet filter (International Light Technologies, Peabody, MA, USA) that only allows the passage of blue light in a 430-550 nm wavelength range, and a third with a custom-made blue filter (International Light Technologies) that only allows the passage of violet light in a 350-430 nm wavelength range. The resulting images of the unfiltered, violet-filtered and blue-filtered beam profiles were collected using software (Beamgage version 6.6, Ophir-Spiricon, North Logan).

RBC Sample Preparation

Four commercial RBCs were tested. Two products were classified as conventional composites (indicated for increments 2-mm thick or less): Herculite Ultra (HER; Kerr Corporation, Orange, CA, USA) and Tetric EvoCeram (TEC; Ivoclar Vivadent AG). Two other materials were classified as high viscosity, bulk-fill materials intended for use in increments ranging from 4-mm to 5-mm thick: SonicFill (SOF; Kerr Corporation) and Tetric EvoCeram Bulk Fill (TBF; Ivoclar Vivadent AG). Product specifications are presented in Table 1.

Ten disc specimens (10-mm Ø, 2-mm thick) of each composite were fabricated using a polyvinyl siloxane impression material mold (Putty Soft, 3M Oral Care, St Paul, MN, USA) for the conventional composites (HER and TEC). For the bulk-fill products (SOF and TBF), the mold was 4-mm thick. All fabricated molds had three 0.5-mm notched extrusions on their inner walls, separated 120° from each other, which matched the locations of the LED chips at the proximal surface of the light guide: B1, B2, and V. Composites were placed in the matrix using a single increment, and a transparent polyester film was placed on the bottom and top surfaces of the composite-filled mold.[33] The assembly was lightly pressed between two microscope glass slides to remove excess composite. The specimen was placed

Table 1: *Classifications, Brand Names, Compositions, Exposure Time, Shades and Lot Numbers of Tested Materials*

Classification	Composite (Abbreviations)	Composition	Photoinitiators	Exposure Time, s	Shade	Lot Number
Conventional RBC (increment of 2 mm or less)	Herculite Ultra (HER)	Bis-GMA, TEGDMA, Bis-EMA, silica and barium glass, prepolymer filler, titanium oxide, 4-methoxyphenol, BPO, trimethylolpropane triacrylate	CQ	20	A2 Dentin	5444587
	Tetric EvoCeram (TEC)	Bis-GMA, UDMA, barium glass, ytterbium trifluoride, prepolymer filler, mixed oxide	CQ, TPO	10	A2 Dentin	T22777
Bulk-fill RBC (increments of 4 to 5 mm)	Sonic Fill (SOF)	Bis-GMA, TEGDMA, Bis-EMA, TMSPMA, barium glass, alumino-borosilicate glass	CQ	20	A2	5376244
	Tetric EvoCeram Bulk Fill (TBF)	Bis-GMA, Bis-EMA, UDMA, alumino-borosilicate glass, prepolymer filler (ytterbium trifluoride), mixed oxides	CQ, TPO, Ivocerin	10	IVA	S51408

Abbreviations: RBC, resin-based composite; Bis-EMA, bisphenolglycidyl ethyl-methacrylate; Bis-GMA, bisphenolglycidyl methacrylate; BPO, benzoyl peroxide; CQ, camphorquinone; TEGDMA, triethylene glycol dimethacrylate; TMSPMA, 3-trimethoxysilylpropyl methacrylate; TPO, Diphenyl (2,4,6-trimethylbenzoyl) phosphine oxide; UDMA, urethane dimethacrylate.

over a white filter paper (Grade 1, Whatman, Little Chalfont, UK) background and slides were removed.[33] The LCU was fixed in a clamp and the distal end of the light guide was positioned perpendicular to the specimen at 1-mm distance from the upper polyester film surface to simulate a clinical scenario during posterior restoration. The light guide completely covered the specimen.

Light-activation for each composite followed the manufacturer's recommendations (Table 1). After light exposure, the specimens were removed from the molds, and locations on composite surfaces corresponding to the LED chip positions on the top and bottom surfaces were marked using a graphite pencil on the lateral wall of each specimen. The specimens were then stored in a dark oven (Fanen, Guarulhos, Brazil) for one hour at 36°C ± 1°C and then machine-polished (Aropol, Arotec Indústria e Comércio Ltda, Cotia, Brazil) using 1000-grit and 1200-grit abrasive paper (Wetordry, 3M, Sorocaba, Brazil) for 1 minute each, under water cooling. After polishing, specimens were again stored in the same dark oven for 24 hours before microhardness testing.

Microhardness Test

A microhardness tester (Future-Tech FM Corp, Tokyo, Japan) coupled to software (FM-ARS 9000, Future-Tech FM Corp) was used to obtain Knoop hardness (KHN) values after applying a static load of 50 g (0.49 N) for five seconds to each composite surface. The average of three indentations, spaced at 100-μm distances from each other, at the central irradiant spot of each LED (Figure 1) were used to represent a single hardness value of that specific location for a given composite specimen. The location of the measurement area was determined using the notches made at the peripheral locations as reference, and from those locations, a displacement of 2.6 mm toward the center of the disc was defined as the starting point for Knoop indenter loading. The same protocol was followed for the top and bottom surfaces.

Statistical Analysis

Spectral outputs and radiant emittances of the LCU with each light guide at different wavelength ranges were compared using the Student t-test ($p>0.05$). Due to the different compositions of the tested RBCs, statistical analysis of KHN was performed separately for each material using three-way analysis of variance (ANOVA) factors: surface (top or bottom), light guide (HT or RT), and LED wavelength (456 nm or 409 nm) using software (SAS 9.3 for Windows, SAS Institute, Cary, NC, USA). Microhardness values were averaged among the three measurements at each location. An exponential transformation of 1.5 was applied to obtain normality in the hardness data. The Tukey honestly significant difference *post hoc* multiple comparison test ($\alpha=0.05$) was applied to compare pairwise group means and interactions among factors within each RBC.

RESULTS

Spectral Irradiance and Beam Profiles

Measurements of wavelength ranges and means of the total power output and radiant exitances of the LED LCU using the RT and HT are presented in Table 2. Figure 2 shows the emission spectra of the two wavelengths of LEDs using the RT and HT light guides. Visual inspection of the beam profiles shows great differences in light output distribution and

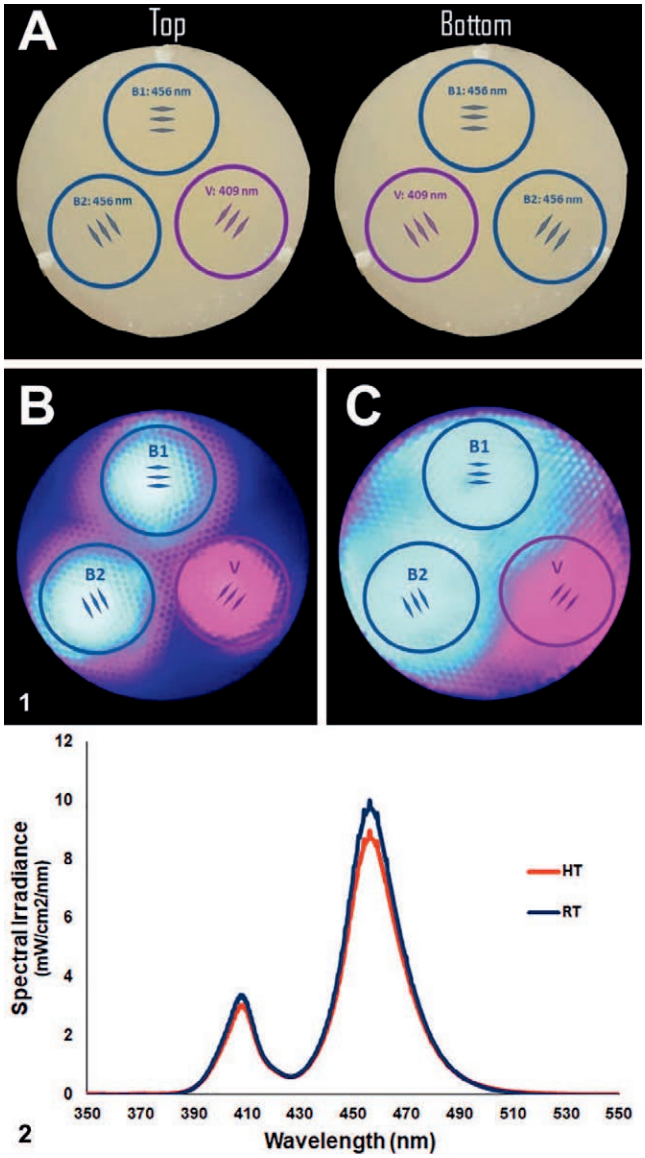


Figure 1. *Schematic representation for locations of microhardness measurements with respect to the specific LED chip that is emitting toward the proximal light guide end and from which light is emitted at the distal tip end (A): over the composite specimen, (B): at the output of the regular tip, and (C): al the output of the homogenizer tip.*

Figure 2. *Spectral irradiance profiles (mW/cm^2/nm) of the Bluephase Style LCU using the two different types of light guide tips. RT, regular tip; HT, homogenizer tip.*

emittance between both light guides (Figures 3 and 4). Figure 3 shows that the individual LED chips using the RT are visible and separated from one another through the length of the light guide. The separation among LED chips, visible at the distal end with the light off, remains when the LCU is turned on, demonstrating the nonuniformity of the light output. The beam profile using the RT is characterized by the presence of two strong areas of emission corresponding to B1 and B2 LED chips and a weaker emission area corresponding to V in the unfiltered beam profile. Those areas of higher emittance corresponded directly with the central spot of each individual LED chip. The power concentrations at these locations contrasts with that of the large surrounding areas, where the presence of emitted light was practically undetectable, even when using filters.

When using the HT, the location of the individual emitting LED chips is barely visible at the end of the light guide (Figure 4). The separation between LED chips becomes visible when the LCU is turned on, also demonstrating an incomplete uniformity of light output. Nevertheless, as not seen when using the RT, the emitted blue and violet light is distributed across most of the light-emitting distal end of the HT. The beam profile using the HT is characterized by the presence of two locations of strong power emission, with a peak output of 2260 mW, corresponding to B1 and B2, and a weaker emission in the area corresponding to V. Although the high-power locations showed a greater concentration of light in the central spot of each 456-nm LED chip, the power output remained relatively homogeneous across the whole cross section of the light-emitting end of the guide. Filtered beam profile images showed the diffusion of energy emitted by each LED across a wide area. The area of low power output was practically nonexistent when using the HT.

Surface Microhardness

Table 3 presents KHN results for the conventional composites HER and TEC. The three-way ANOVA for HER indicated that surface ($p<0.0001$), light guide type ($p<0.0001$), and wavelength ($p<0.0001$) significantly influenced the results, as well as the double interaction between light guide type and surface ($p<0.0001$) and light guide type and wavelength ($p= 0.0002$). For TEC, statistical analysis showed that surface ($p<0.0001$) and wavelength ($p<0.0001$), as well as the double interaction between light guide type and surface ($p<0.0001$), significantly influenced KHN results. However, the type of light guide did not significantly influence the results.

Table 4 presents KHN results for the bulk-fill composites SOF and TBF. For SOF, the three-way ANOVA results indicated that surface ($p<0.0001$), light guide type ($p<0.0001$), and wavelength ($p<0.0001$) all significantly influenced the results, as well as the double interaction between surface and wavelength ($p=0.026$). Regarding TBF, surface

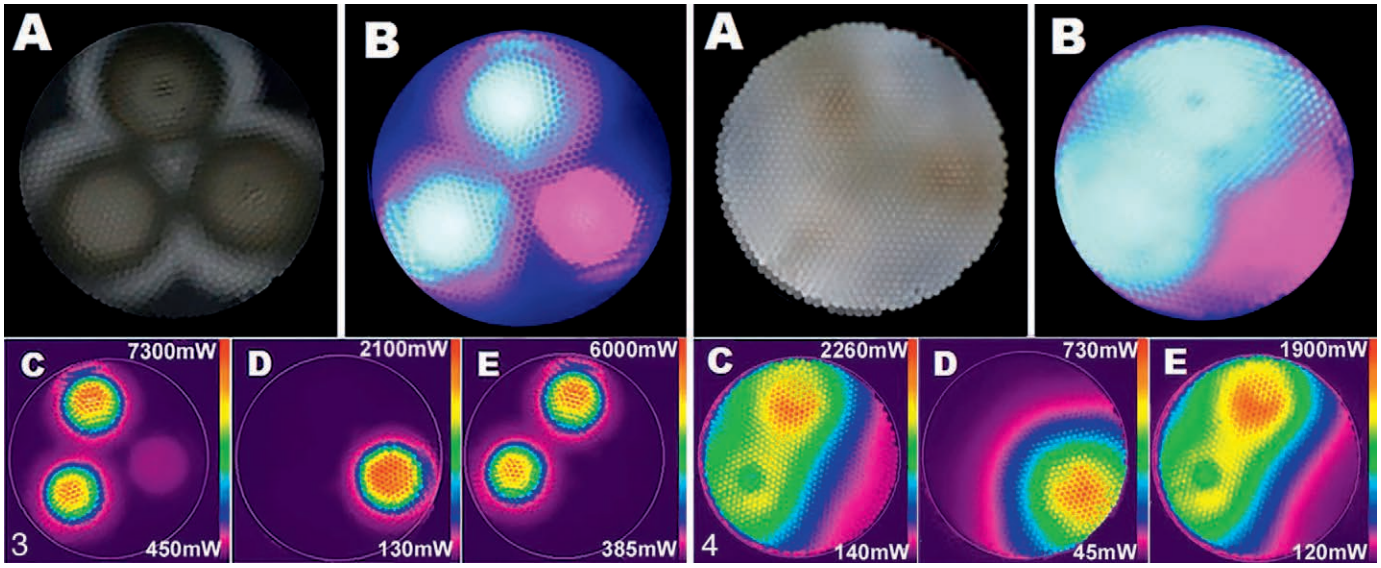


Figure 3. *Images of the distal end of the regular tip when inserted into the body of the Bluephase Style LCU. (A): LED with chips off. The location of the three LED chips can be seen through the light guide. (B): Light distribution from the LED chips across the regular tip when the LCU is on. Areas of blue and violet light emission can be distinguished, as well as areas of lower light levels. (C): Color-coded, scaled beam power profiles of the light emitted without using any bandpass filter. (D):Power distribution of only the violet chip using a 430-550 nm filter, and (E): Power distribution of only the blue light, using a 350-430 nm violet spectral filter placed in front of the camera lens of the beam profiler.*

Figure 4. *Images of the distal end of the homogenizer tip when inserted into the body of the Bluephase Style LCU (A): LED with chips off. The location of the three LED chips cannot be easily seen through the light guide. (B): Light distribution from the LED chips across the regular tip when the LCU is on. Areas of blue and violet light emission can be distinguished. (C): Color-coded, scaled beam power profiles of the light emitted without using any bandpass filter. (D): Power distribution of only the violet chip using a 430-550 nm filter, and (E): Power distribution of only the blue light, using a 350-430 nm filter placed in front of the camera lens of the beam profiler.*

($p<0.0001$), light guide type ($p<0.0001$), and wavelength ($p<0.0001$) significantly influenced KHN.

The bottom to top (B/T) hardness ratio of all the tested composites with the RT and the HT are presented in Figure 5. In general, for all the composites, KHN was higher at the top surface (0 mm) than those obtained at the bottom (2 or 4 mm thicknesses, according to composite type). Also, for both types of light guides, within the same surface (top and bottom), higher KHN was observed in areas irradiated by B1 and B2 than in locations of the V LED.

DISCUSSION

The first working hypothesis stating that using the homogenizer light guide would produce differences in the KHN of composites was partially accepted. Except for TEC, KHN of all tested composites was significantly affected by the homogenizer light guide. The second working hypothesis, stating that for the same light guide, lower wavelength light would reduce the microhardness of composites, was also accepted. For all the tested RBCs and type of light guide, statistical analysis showed significant differences in KHN between locations irradiated mainly

Table 2: *Wavelength Range, Power Output, and Radiant Emittance of the Light-curing Unit Measured When Using the Different Types of Light Guide*[a]

Wavelength Range, nm	Light Guide	Power Output, mW	Radiant Emittance, mW/cm^2
350-550	RT	635.8±1.3 A	935.0±2.1 A
	HT	578.0±1.0 B	850.6±1.9 B
350-430	RT	112.4±1.1 A	165.8±1.8 A
	HT	101.4±1.3 B	148.8±1.1 B
430-550	RT	523.0±1.0 A	750.2±0.4 A
	HT	476.4±0.5 B	683.8±1.1 B

Abbreviations: RT, regular tip; HT, homogenizer tip.
[a] *Different characters indicate significant difference among light guides for the same wavelength range within the same column by Student t-test (p>0.05).*

Table 3: *Microhardness of Conventional Composites HER and TEC According to LED Wavelength, Surface (Top and Bottom), and Tip Type*[a]

Composite	LED Wavelength, nm	Tip Type	Surface	
			Top[b]	Bottom
HER	B1 (456)	RT	59.1±3.3 Aa	33.9±9.6 Aa
		HT	58.5±1.3 Aa	20.4±3.3 Ba
	V (409)	RT	47.0±4.4 Ab	16.9±4.8 Ab
		HT	50.4±2.4 Ab	14.2±2.9 Ab
	B2 (456)	RT	59.4±5.1 Aa	32.5±6.3 Aa
		HT	57.9±2.1 Aa	19.7±2.7 Bab
TEC	B1 (456)	RT	51.5±4.0 Ba	46.6±4.2 Aa
		HT	55.5±3.4 Aa	43.1±2.9 Aa
	V (409)	RT	43.5±5.5 Bb	36.0±5.7 Ab
		HT	49.8±3.2 Ab	37.3±2.5 Ab
	B2 (456)	RT	51.7±5.0 Ba	46.3±5.9 Aa
		HT	55.4±3.3 Aa	42.3±3.6 Ba

Abbreviations: LED, light-emitting diode; HER, Herculite; TEC, Tetric EvoCeram; B1, blue LED 1; V, violet LED; B2, blue LED 2; RT, regular tip; HT, homogenizer tip.
[a] Statistical analysis was performed individually for each composite. Means followed by similar characters indicate no significant difference. Uppercase letters compare microhardness within the same composite, LED, and surface, using different light guides. Lowercase letters compare LED chips within the same composite, light guide, and surface.
[b] *KHN was significantly higher on the top surface of all composites within the same LED and tip.*

by the 409-nm violet LED and locations receiving blue light at 456 nm LED. The third hypothesis, stating that microhardness of composites would be higher at the top than at the bottom, was accepted because all tested composites exhibited significantly higher KHN at the top surface.

Four different composites were explored based on the different photoinitiator composition of the materials because HER and SOF are CQ-based composites, while TEC contains CQ and TPO, and TBF contains CQ, TPO, and Ivocerin. Given that beam profile analysis confirmed that the off-axis arrangement of the LED chips in the Polywave LCU results in a nonuniform beam, this study intended to test if the use of an HT would compensate for the beam heterogeneity, or if ,despite using the HT, differences in the KHN at the measurement locations of the top

Table 4: *Microhardness of Bulk-fill Composites SOF and TBF According to LED Wavelength, Surface (Top and Bottom), and Tip Type*[a]

Composite	LED Wavelength, nm	Tip Type	Surface	
			Top[b]	Bottom
SOF	B1 (456)	RT	63.2±1.4 Aa	53.2±4.4 Aa
		HT	65.8±4.8 Aa	54.6±2.2 Aa
	V (409)	RT	58.9±2.3 Ab	41.1±5.2 Bb
		HT	61.1±2.4 Ab	47.6±3.0 Ab
	B2 (456)	RT	63.4±2.6 Aa	50.6±4.5 Ba
		HT	66.0±3.0 Aa	53.8±1.6 Aa
TBF	B1 (456)	RT	57.5±3.5 Ba	50.8±4.1 Aa
		HT	62.8±4.7 Aa	52.5±4.4 Aa
	V (409)	RT	52.9±4.0 Bb	45.1±2.5 Ab
		HT	57.2±4.8 Ab	48.5±3.0 Ab
	B2 (456)	RT	57.0±4.0 Ba	49.0±3.6 Ba
		HT	63.6±5.5 Aa	53.9±2.9 Aa

Abbreviations: LED, light-emitting diode; SOF, SonicFill; TBF, Tetric EvoCeram Bulk Fill; B1, blue LED 1; V, violet LED; B2, blue LED 2; RT, regular tip; HT, homogenizer tip.
[a] *Statistical analysis was performed individually for each composite. Means followed by similar characters indicate no significant difference. Uppercase letters compare microhardness within the same composite, LED and surface, using different light guides. Lowercase letters compare LED chips within the same composite, light guide, and surface.*
[b] *KHN was significantly higher on the top surface of all composites within the same LED and tip.*

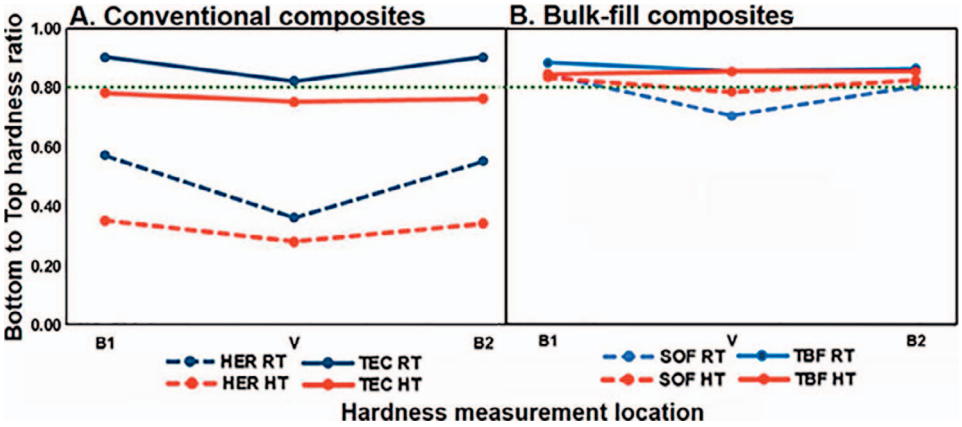


Figure 5. *Bottom to top hardness ratio of the (A): tested conventional and (B): bulk-fill composites with different light guide tips, according to location of Knoop microhardness measurement. RT, regular tip; HT, homogenizer tip.*

and bottom surfaces of the specimens would be observed.

An LCU should be able to adequately photopolymerize up to a 2-mm thickness of conventional composites. However, the B/T hardness ratio of the CQ-based conventional composite (HER) was below 0.6 when using either light guide. This value is below the recommended 0.8 necessary to consider the material adequately cured.[27,30] In the current study, the KHN of HER was higher when the RT was used, which might be a result of the high amount of light irradiating the composite from the center of the LED chips,[2–4,6,9,11] which matched the location of the KHN measurements. The spectral absorption range of CQ ranges from 425 to 490 nm, and matches the peak emission of the blue LEDs at 456 nm, but it has little sensitivity to violet light at 409 nm.[2] In our study, the KHN of HER was higher at the top surface and in the areas related to the output of the blue LEDs, which could be explained by the sensitivity of CQ to blue light and the lower penetration of the shorter-wavelength violet light.[10,16,22] These results diverge from the findings of a previous study where the curing profile of a conventional CQ-based composite was not influenced by using a nonhomogeneous, multiple-peak LCU up to a 2-mm depth.[14] However, it must be considered that the samples in that study were smaller (5×5 mm blocks with 3-mm thickness), and they were polymerized using an LCU producing a beam profile, which, despite not being completely homogeneous, spreads light in the absorption spectrum of CQ across most of the LCU output area.[14, 37] That aspect differs from the beam profile of the Bluephase Style LCU with both types of light guide tips used in this study.

The results for TEC showed that KHN was higher at the top surface and in locations corresponding with the positions of the blue LEDs, while the light guide type had no significant influence on hardness at the bottom surface, although the HT produced a higher KHN at the top surface at all measured locations. Because TEC contains both CQ and TPO photoinitiators, an improved sensitivity to violet light was expected,[10] and confirmed by the results. Using the RT produced a B/T ratio above 0.8 at all LED positions, and when using the HT, the B/T ratio was between 0.78 and 0.75. As explained previously, the higher B/T ratio observed using the RT might be a result of the power concentration at the locations correlated with the LED chips,[2,4,6,9,11] which resulted in lower light dispersion through the material. However, it was unexpected that the HT tip would fail to reach an acceptable B/T ratio at any of the measured locations, despite being used on a composite from the same manufacturer of the LCU, where a high sensitivity of the photoinitiators to the LCU emission spectrum is expected.[2,11,12] However, because KHN at the top surface was higher using the HT, the increase in top surface hardness influenced the B/T ratio calculation. Moreover, the effect of the HT in spreading the light beam produced a higher KHN at the top surface due to better activation of the alternative photoinitiators,[10] but the reduced concentration of irradiance in the measured locations may reduce the amount of light that reaches the bottom surface without dispersion, which along with the low penetrability of violet light[22] to activate TPO at a 2-mm thickness might be responsible for this result. The effect of a curing light on composite resin photopolymerization highly depends on the extent of localized emittance and the spectral homogeneity of the light beam.[12] Finally, the manufacturer of TEC recommends a maximum increment thickness of 1.5 mm for dentin shades, instead of the 2 mm used in the present study; as a result of that difference, KHN at the bottom might

have been diminished, producing also a B/T ratio below the recommended value.

Based on these findings, clinicians should take care when polymerizing 2-mm-thick increments of conventional composites using a multiwave LCU, because the bottom surfaces may not receive sufficient energy to adequately polymerize the material. The reduced activation of photoinitiators due to nonhomogeneity of the light beam is known,[2,10,21] and therefore, it is recommended that clinicians match the emission spectrum of their LCU to the photoinitiator sensitivity of their chosen RBC.[2,3,19]

Analysis of the results using bulk-fill composites produced different findings than those of the conventional composites. Microhardness of SOF was higher at the bottom surface when using the HT in the location of the violet and one of the blue LEDs. Higher KHN at the top surface is an expected result because the top surface received higher irradiance than the bottom surface. Using both light guide types, the B/T ratio was above 0.8 at the locations of the blue LEDs and below 0.8 at the area of the violet LED (0.78 with HT and 0.7 with RT). Because SOF is a CQ-based composite, it could benefit from the better distribution and penetration of blue light when using the HT, especially in the area of the V LED at the bottom of the specimen. As expected from a bulk-fill composite, SOF obtained a near optimal B/T ratio, despite being a CQ only based composite; also, the manufacturer of SOF recommends a maximum increment thickness of 5 mm, and therefore, a thinner increment like the one used in this study is expected to demonstrate sufficient polymerization. The obtained results of KHN for SOF could be explained because this composite demonstrates better light transmission[24,34] and higher penetrability of blue light.[10,22,25,37]

Surface microhardness measurements of TBF showed higher KHN values on the top surface when the HT was used, near the locations of the blue LEDs. This composite contains CQ, TPO, and Ivocerin photoinitiators, which means that the material may have an improved sensitivity to light emitted by the Polywave LCU, especially at the top surface.[10] That assumption was confirmed by the higher KHN values observed at the top of the specimens when using HT because the greater light distribution could produce greater activation of these photoinitiators. For TBF, the beneficial effect of using an LCU matching the spectral sensitivity of the RBC agreed with the results of other studies[2,3,10,19] because the B/T ratio of TBF was above 0.8 at all the measured locations.

A previous study about depth of cure of bulk-fill composites determined that SOF and TBF had a satisfactory depth of cure when polymerized using a monowave blue LED LCU.[25] That result corroborates the findings of this study, where the depth of cure of both materials was satisfactory at the locations of the blue LEDs. Nonetheless, regarding the effects of beam heterogeneity in bulk-fill composites, results differ from those of another study that considered the effect of beam inhomogeneity in bulk-fill RBCs as "minor."[23] However, the authors of that article extended the time of light exposition by twice the manufacturer's indication and used a high-power setting. In addition, that work did not measure beam profile of the LCU used, nor did it mention the characteristics of the light guide; the increase in the radiant exposure and irradiance delivered to the specimen might have compensated for the nonuniform nature of the light beam.

Comparisons between the results of conventional and bulk-fill composites do not seem to be appropriate because HER and TEC are conventional composites designed to be applied with an incremental technique, while SOF and TBF are bulk-fill composites that can be placed and light cured in 4- to 5-mm increments, and therefore are expected to present a greater depth of cure than conventional composites. Thus, different results from conventional and bulk-fill composites may be attributed to modifications in the composition of the latter to include more efficient photoinitiator systems[24,25] and achieve enhanced light transmission in depth[24] by matching the refractive indexes of filler particles and the resin components to increase depth of cure,[25] as was observed in this study. An appropriate resin formulation may thus enhance reactivity and allow for greater depths of cure,[25] which was confirmed from by the B/T ratio obtained from the KHN measurements.

Spectral emission measurements confirm that both light guides succeed in transmitting and preserving the emission spectrum of the LEDs in the LCU.[1–4,36,38] In the current study, the HT performed better in TBF. Nevertheless, for each of the tested RBCs, the nonhomogeneous beam profile of the Polywave LCU, produced differences in the B/T KHN ratio within the different measurement locations, and therefore in the depth of cure regardless of their photoinitiator composition and the light guide used. This result agrees with other studies that indicate that lack of beam homogeneity might affect polymerization in restorative materials.[5–7,9–12,37] As a consequence, the mechanical properties[12,16,30,32] and clinical performance[5,9,12,25,29] of restorations placed

using less than ideal beam homogeneity might be affected even if the top surface of the composite appears to be adequately polymerized.[10,12]

Light-beam heterogeneity is therefore shown to affect the depth of cure of composites by the fact that almost all the tested composites (except for TBF) had a higher B/T ratio in the location of the blue LEDs than in the area of the violet LED. Another important finding was that TEC and TBF showed a higher KHN at the top surface when using the HT, proving that a more homogeneous light beam might be beneficial for the polymerization of superficial composite layers as well.[10] The study results confirm the sensitivity of the microhardness test and the B/T ratio method to detect differences among the surfaces of materials, and it can be described with ease, allowing for a more exact and detailed approach to evaluate depth of cure than other proposed techniques, just as the composite scraping test used in ISO 4049.[10,26,27,30–34]

Regarding the experimental design, microhardness measurements were restricted to locations of the specimens receiving the highest irradiance from the LCU with each light guide tip and would seem to determine if the measured power output and radiant emittance values would be the single factor to influence the KHN results, which was not the case. Future research should consider mapping microhardness of the complete top and bottom surfaces of RBCs and calculating the depth of cure in the regions receiving the lowest irradiance with each light guide type to determine a potential clinical implication produced by the presence of areas receiving very low values of light in the polymerization of restorative composites. Also, for TEC, the less translucent dentin shade used in this study might influence the differences between top and bottom KHN. If enamel or more translucent shades of RBC were used, KHN differences between top and bottom could have been reduced.

CONCLUSIONS

Within the limitations of the experimental design and based on the findings of the present laboratory study, the following conclusions can be made:

1. In general, within the bulk-fill materials tested, use of a homogenizing tip significantly increased KHN at the bottom of the specimens.
2. Regardless of the light guide type used, the wavelength of the lights affected the KHN of composites. Significantly lower KHN was observed in the areas irradiated by violet light, except for the conventional CQ-based composite (HER) at the bottom when the homogenizing tip was used.
3. Regardless of the light guide type used and the type of photoinitiator contained in the formulation of RBCs, there were significant differences in KHN between the top and bottom surfaces of conventional and bulk-fill RBCs.
4. Using a homogenizing tip did not completely compensate for the nonuniformity of light emitted by a multiwave LCU because power differences were still observed at tip locations correlated with the fixed positions of LED chips present at the proximal tip end. However, the homogenizing tip showed better distribution of emittance than that observed using a conventional light guide, as observed for KHN obtained at the top surfaces of TEC and TBF.

Acknowledgements

This study was supported by the International Affairs Bureau of the University of Costa Rica (OAICE-47-2017) and the Coordination for Improvement of Higher Education (CAPES – Brazil, Code 001).

Conflict of Interest

The authors of this manuscript certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

(Accepted 15 July 2019)

REFERENCES

1. Friedman J (1990) Dental Light-curing Unit Lamp Unit With Interchangeable Autofocus Light Guides. United States Patent No. 4,948,215.
2. Rueggeberg FA, Giannini M, Arrais CAG, & Price RBT (2017) Light curing in dentistry and clinical implications: A literature review *Brazilian Oral Research* **31(Supplement 1)** 64-91, http://dx.doi.org/10.1590/1807-3107BOR-2017.vol31.0061
3. Price RBT (2017) Light curing in dentistry *Dental Clinics of North America* **61(4)** 751-778, http://dx.doi.org/10.1016/j.cden.2017.06.008
4. Price RB (2018) The dental curing light In: Miletic V (ed) *Dental Composite Material Direct Restorations* Springer, Gewerbestrasse, Germany 43-62. http://dx.doi.org/10.1007/978-3-319-60961-4_18
5. Price RBT, Rueggeberg FA, Labrie D, & Felix CM (2010) Irradiance uniformity and distribution from dental light curing units *Journal of Esthetic and Restorative Dentistry* **22(2)** 86-101, http://dx.doi.org/10.1111/j.1708-8240.2010.00318.x
6. Michaud PL, Price RBT, Labrie D, Rueggeberg FA, & Sullivan B (2014) Localised irradiance distribution found

in dental light curing units *Journal of Dentistry* **42(2)** 129-139, http://dx.doi.org/10.1016/j.jdent.2013.11.014

7. Haenel T, Hausnerová B, Steinhaus J, Price RBT, Sullivan B, & Moeginger B (2015) Effect of the irradiance distribution from light curing units on the local microhardness of the surface of dental resins *Dental Materials* **31(2)** 93-104, http://dx.doi.org/10.1016/j.dental.2014.11.003
8. Wilson NHF & Lynch CD (2014) The teaching of posterior resin composites: Planning for the future based on 25 years of research *Journal of Dentistry* **42(5)** 503-516, http://dx.doi.org/10.1016/j.jdent.2014.02.014
9. Price R, Shortall A, & Palin W (2014) Contemporary issues in light curing *Operative Dentistry* **39(1)** 4-14, http://dx.doi.org/10.2341/13-067-LIT
10. Shimokawa CAK, Sullivan B, Turbino M, Soares C, & Price R (2017) Influence of emission spectrum and irradiance on light curing of resin-based composites *Operative Dentistry* **42(5)** 537-547. http://dx.doi.org/10.2341/16-349-L
11. Price RBT, Ferracane JL, & Shortall AC (2015) Light-curing units: A review of what we need to know *Journal of Dental Research* **94(9)** 1179-1186. http://dx.doi.org/10.1177/0022034515594786
12. Price RBT, Labrie D, Rueggeberg FA, Sullivan B, Kostylev I, & Fahey J (2014) Correlation between the beam profile from a curing light and the microhardness of four resins *Dental Materials* **30(12)** 1345-1357. http://dx.doi.org/10.1016/j.dental.2014.10.001
13. Lynch CD, Opdam NJ, Hickel R, Brunton PA, Gurgan S, Kakaboura A, Shearer AC, Vanherle G, & Wilson NHF (2014) Guidance on posterior resin composites: Academy of Operative Dentistry - European Section *Journal of Dentistry* **42(4)** 377-383. http://dx.doi.org/10.1016/j.jdent.2014.01.009
14. de Oliveira DCRS, Rocha MG, Correa IC, Correr AB, Ferracane JL, & Sinhoreti MAC (2016) The effect of combining photoinitiator systems on the color and curing profile of resin-based composites *Dental Materials* **32(10)** 1209-1217. http://dx.doi.org/.1016/j.dental.2016.06.010
15. Shimokawa CAK, Harlow JE, Turbino ML, & Price RB (2016) Ability of four dental radiometers to measure the light output from nine curing lights *Journal of Dentistry* **54** 48-55. http://dx.doi.org/10.1016/j.jdent.2016.08.010
16. Sampaio CS, Atria PJ, Rueggeberg FA, Yamaguchi S, Giannini M, Coelho PG, Hirata R, & Puppin-Rontani RM (2017) Effect of blue and violet light on polymerization shrinkage vectors of a CQ/TPO-containing composite *Dental Materials* **33(7)** 796-804. http://dx.doi.org/10.1016/j.dental.2017.04.010
17. Fronza BM, Rueggeberg FA, Braga RR, Mogilevych B, Soares LES, Martin AA, Ambrosano G, & Giannini M (2015) Monomer conversion, microhardness, internal marginal adaptation, and shrinkage stress of bulk-fill resin composites *Dental Materials* **31(12)** 1542-1551. http://dx.doi.org/10.1016/j.dental.2015.10.001
18. Van Landuyt KL, Snauwaert J, De Munck J, Peumans M, Yoshida Y, Poitevin A, Coutinho E, Suzuki K, Lambrechts P, & Van Meerbeek B (2007) Systematic review of the chemical composition of contemporary dental adhesives *Biomaterials* **28(26)** 3757-3785. http://dx.doi.org/10.1016/j.biomaterials.2007.04.044
19. André C, Nima G, Sebold M, Giannini M, & Price R (2018) Stability of the light output, oral cavity tip accessibility in posterior region and emission spectrum of light-curing units *Operative Dentistry* **43(4)** 398-407. http://dx.doi.org/10.2341/17-033-L
20. Gan JK, Yap AU, Cheong JW, & Cbk NA (2018) Bulk-fill composites: Effectiveness of cure with poly- and mono-wave curing lights and modes *Operative Dentistry* **(43)2** 136-143. http://dx.doi.org/10.2341/16-304-L
21. Rueggeberg FA, Price RB, Harlow JE, & Sullivan B (2016) Effect of mold type, diameter, and uncured composite removal method on depth of cure *Clinical Oral Investigations* **20(8)** 2321. http://dx.doi.org/10.1007/s00784-016-1733-3
22. Harlow JE, Rueggeberg FA, Labrie D, Sullivan B, & Price RB (2016) Transmission of violet and blue light through conventional (layered) and bulk cured resin-based composites *Journal of Dentistry* **53** 44-50. http://dx.doi.org/10.1016/j.jdent.2016.06.007
23. Li X, Pongprueksa P, Van Meerbeek B, & De Munck J (2015) Curing profile of bulk-fill resin-based composites *Journal of Dentistry* **43(6)** 664-672. http://dx.doi.org/10.1016/j.jdent.2015.01.002
24. Pfeifer CS (2017) Polymer-based direct filling materials *Dental Clinics of North America* **61** 733-750. http://dx.doi.org/10.1016/j.cden.2017.06.002
25. Alrahlah A, Silikas N, & Watts DC (2014) Post-cure depth of cure of bulk fill dental resin-composites *Dental Materials* **30(2)** 149-154. http://dx.doi.org/10.1016/j.dental.2013.10.011
26. Rueggeberg FA & Craig RG (1988) Correlation of parameters used to estimate monomer conversion in a light-cured composite *Journal of Dental Research* **67(6)** 932-937. http://dx.doi.org/10.1177/00220345880670060801
27. Bouschlicher MR, Rueggeberg FA, & Wilson BM (2004) Correlation of bottom-to-top surface microhardness and conversion ratios for a variety of resin composite compositions *Operative Dentistry* **29(6)** 698-704.
28. Ferracane JL, Mitchem JC, Condon JR, & Todd R (1997) Wear and marginal breakdown of composites with various degrees of cure *Journal of Dental Research* **76(8)** 1508-1516. http://dx.doi.org/10.1177/00220345970760081401
29. Frassetto A, Breschi L, Turco G, Marchesi G, Di Lenarda R, Tay FR, Pashley DH, & Cadenaro M (2016) Mechanisms of degradation of the hybrid layer in adhesive dentistry and therapeutic agents to improve bond durability—A literature review *Dental Materials* **32(2)** e41-e53. http://dx.doi.org/10.1016/j.dental.2015.11.007
30. Ferracane JL, Hilton TJ, Stansbury JW, Watts DC, Silikas N, Ilie N, Heintze S, Cadenaro M, & Hickel R (2017) Academy of Dental Materials guidance—Resin composites: Part II—Technique sensitivity (handling, polymerization, dimensional changes) *Dental Materials* **33(11)** 1171-1191. http://dx.doi.org/10.1016/j.dental.2017.08.188

31. Reis AF, Vestphal M, do Amaral RC, Roulet JF, & Roscoe MG (2017) Efficiency of polymerization of bulk-fill composite resins: A systematic review *Brazilian Oral Research* **31(Supplement 1)** 37-48. http://dx.doi.org/10.1590/1807-3107bor-2017.vol31.0059

32. Lin-Gibson S, Landis FA, & Drzal PL (2006) Combinatorial investigation of the structure-properties characterization of photopolymerized dimethacrylate networks *Biomaterials* **27(9)** 1711-1717. http://dx.doi.org/10.1016/j.biomaterials.2005.10.040

33. ISO (2009) *ISO 4049:2009 Dentistry — Polymer-based Restorative Materials* **4th edition** International Organization for Standardization, Geneva, Switzerland 1-27

34. Alshaa MM, Haenel T, Sullivan B, Labrie D, Alqahtani MQ, & Price RB (2016) Effect of a broad-spectrum LED curing light on the Knoop microhardness of four posterior resin based composites at 2, 4 and 6-mm depths *Journal of Dentistry* **45** 14-18. http://dx.doi.org/10.1016/j.jdent.2015.11.004

35. Issa Y, Watts DC, Boyd D, & Price RB (2016) Effect of curing light emission spectrum on the nanohardness and elastic modulus of two bulk-fill resin composites *Dental Materials* **32(4)** 535-550. http://dx.doi.org/10.1016/j.dental.2015.12.017

36. Senn B & Pauler M (2017) Homogenisierer. European Patent Office No. EP 3 181 988 A1.

37. Shimokawa CAK, Lacalle M, Giannini M, Braga RR, & Price RB (2018) Effect of light curing units on the polymerization of bulk fill resin-based composites *Dental Materials* **34(8)** 1211-1221. http://dx.doi.org/10.1016/j.dental.2018.05.002

38. Price RBT, Labrie D, Rueggeberg F, & Felix C (2010) Irradiance differences in the violet (405 nm) and blue (460 nm) spectral ranges among dental light-curing units *Journal of Esthetic and Restorative Dentistry* **22(6)** 363-377. https://doi.org/10.1111/j.1708-8240.2010.00368.x

Online Only Articles

Online Only Articles

On occasion we receive manuscripts that we would like to publish, but do not have the page room to include in the print journal. For the full article, please go to www.jopdentonline.org or enter the provided address into your address bar.

Physical Properties of Nanohybrid and Microhybrid Resin Composites Subjected to an Acidic Environment: A Laboratory Study

M Ferooz • R Bagheri • D Jafarpour • MF Burrow

Clinical Relevance: Consumption of acidic beverages does not alter the color stability nor decrease the hardness of resin composites in comparison with nonacidic beverages. In general, the type of materials and polishing methods are important factors in the maintenance of resin composites.

https://doi.org/10.2341/18-319-L

Bioactive Materials Subjected to Erosion/Abrasion and Their Influence on Dental Tissues

ÍEL Viana • Y Alania • S Feitosa • AB Borges • RR Braga • T Scaramucci

Clinical Relevance: When restorations are needed in patients with high risk of erosive tooth wear, resin-modified GICs may be considered an alternative. Although they are susceptible to wear under erosion/abrasion, they are capable of reducing enamel loss adjacent to the restorative material.

https://doi.org/10.2341/19-102-L

Do Tooth- and Cavity-related Aspects of Noncarious Cervical Lesions Affect the Retention of Resin Composite Restorations in Adults? A Systematic Review and Meta-analysis

AMO Correia • E Bresciani • AB Borges • DM Pereira • LC Maia • TMF Caneppele

Clinical Relevance: Recognizing the effects related to the teeth and cavities of NCCLs that are relevant to the success of the restoration is important, as clinicians must be aware of them during the procedure and follow-up of the patients.

https://doi.org/10.2341/19-091-L

Effect of Curing Light and Exposure Time on the Polymerization of Bulk-Fill Resin-Based Composites in Molar Teeth

CAK Shimokawa • ML Turbino • M Giannini • RR Braga • RB Price

Clinical Relevance: Light curing a molar bulk-fill mesio-occluso-distal restoration from a single position at the center of the occlusal surface may result in inadequate photopolymerization of the resin-based composite at the bottom of the proximal boxes.

https://doi.org/10.2341/19-126-L

Wear Properties of Different Additive Restorative Materials Used for Onlay/Overlay Posterior Restorations

F De Angelis • C D'Arcangelo • N Malíšková • L Vanini • M Vadini

Clinical Relevance: Recently introduced indirect resin composites and dental ceramics show a wear behavior similar to traditional gold alloys. The present laboratory findings support a successful use of such new materials on load-bearing occlusal surfaces of posterior teeth, even for extensive occlusal rehabilitations.

https://doi.org/10.2341/19-115-L

This page was intentionally left blank.

©Operative Dentistry, 2020, **45-3,** E105-E113

Physical Properties of Nanohybrid and Microhybrid Resin Composites Subjected to an Acidic Environment: A Laboratory Study

M Ferooz • R Bagheri • D Jafarpour • MF Burrow

Clinical Relevance

Consumption of acidic beverages does not alter the color stability nor decrease the hardness of resin composites in comparison with nonacidic beverages. In general, the type of materials and polishing methods are important factors in the maintenance of resin composites.

SUMMARY

Background: This study investigated the hardness and color stability of five resin composites subjected to different polishing methods following immersion in distilled water or lactic acid for up to three months.

Methods and Materials: Three nanohybrid, Paradigm (3M ESPE), Estelite Sigma Quick (Tokuyama), Ice (SDI), and two microhybrid, Filtek P60 and Filtek Z250, composites were examined. Disc-shaped specimens (10×1.5 mm) were prepared and immersed in distilled water for 24 hours then polished using either silicon carbide paper, the Shofu polishing system or were left unpolished (control). The CIE values and microhardness were determined using a spectrophotometer and digital Vickers hardness tester, respectively (n=10) after one, 45, and 90 days of storage in distilled water or lactic acid. Data were analyzed using analysis of variance, Tukey test, and Pearson correlation coefficient.

Results: Ice exhibited the greatest color change, yet Paradigm and Filtek P60 demonstrated the least. Overall, discoloration of tested materials was multifactorial and the effect of storage media depended on the material, polishing method and time interval. The greatest hardness was obtained for Paradigm and the lowest for Estelite. Hardness was

Maryam Ferooz, DDS, BBiomedSc, BEng, dental officer, Royal Australian Air Force, RAAF Base Williamtown, Australia

*Rafat Bagheri, DDS, PhD, associate professor, Department of Dental Materials and Biomaterials Research Centre, Shiraz Dental School, Shiraz University of Medical Sciences, Shiraz, Iran

Dana Jafarpour, DDS, general dentist & research associate, Biomaterials Research Centre, Shiraz Dental School, Shiraz University of Medical Sciences, Shiraz, Iran

Michael F Burrow, DDS, MSc, PhD, professor, Department of Oral Diagnosis and Polyclinics, Faculty of Dentistry, University of Hong Kong, Prince Philip Dental Hospital, Hong Kong, China

*Corresponding author: Ghasrodash St, Shiraz 43111, Iran; e-mail: bagherir@unimelb.edu.au

https://doi.org/10.2341/18-319-L

found to be significantly higher in lactic acid after 45 days (p=0.014) and even higher after 90 days (p<0.001) compared with distilled water.

Conclusions: An acidic environment did not adversely affect color stability or microhardness of the resin composites. There was a significantly mild reverse correlation between hardness and color change in both storage media.

INTRODUCTION

Resin composites are widely used as tooth-colored restorative materials due to excellent color match and ability to attain a highly polished surface. However, a change in color after exposure to the oral environment is a major reason for the replacement of composite restorations.[1] Discoloration of resin composites depends on the composition, surface texture, storage media, mode of cure and degree of conversion.[2-4] The factors related to the composition consist of resin matrix polymers, filler load, size and type, coupling agent, photoinitiator and accelerators.[4-6] The operator's liabilities such as inadequate light curing and improper surface finishing and polishing can also increase discoloration.[4] Furthermore, discoloration of resin composites can occur in the oral environment due to superficial degradation and plasticization as well as adsorption of staining agents from food, beverages, mouthwash, and plaque accumulation.[4,5]

Microhardness, defined as a material's resistance to indentation, is one of the physical properties associated with abrasion and wear resistance of resin composite and may affect a material's clinical performance and long-term durability.[7,8] Surface degradation is also an important factor that necessitates replacement of a restoration.[9] Other factors likely to affect surface hardness include the quality and technique of polishing,[4] material composition, filler loading,[10] and aging in various media.[11]

Previous studies have shown that the hardness and color stability of tooth-colored restorations change during water storage, as water acts as a carrier for staining agents during water sorption.[6,12,13] In addition, water sorption can lead to polymer degradation, which can cause porosity within the microstructure, resulting in further surface softening, filler loss and discoloration.[14,15] In the oral environment, surface biofilm can cause a drop in the local pH[16,17] that may accelerate surface degradation[7,18] and damage the surface integrity of the composite, consequently leading to increased staining susceptibility.[5,6,14]

Previous studies have investigated the effect of acidic beverages containing natural dyes, such as red wine, orange juice, cola, and so forth, on the surface hardness and discoloration of resin composites.[14,15] However, studies are lacking on the effect of organic acids produced by bacterial flora in the oral cavity (eg, lactic acid) on the hardness and color stability of resin composites.[15] Therefore, this study aimed to compare the effect of lactic acid or distilled water, on the color stability and hardness of five nanohybrid and microhybrid resin composites subjected to different finishing and polishing methods.

METHODS AND MATERIALS

Five resin composites (Table 1), two storage media and three finishing and polishing methods (Table 2) were used in this study.

Specimen Preparation

For each material, a total of 60 disc-shaped specimens (10-mm diameter × 1.5-mm thick) of shade A2 were prepared. Resin composite was placed into polyethylene molds, and the bottom and top surfaces were covered with clear Mylar strips (KerrHawe, Scafati, Italy) to prevent the formation of an oxygen-inhibited layer. Two glass slides were placed over the Mylar strips and pressed under finger pressure to extrude any excess material. The glass slides were removed, and the samples were polymerized from each side according to the manufacturers' instructions using an LED curing light (Radii plus LED; SDI, Bayswater, Victoria, Australia) with a wavelength of 440-480 nm and output of 1500 mW/cm^2. The specimen was separated from the mold, and the edges were ground using wet 1000-grit silicon carbide (SiC) paper.

The specimens were then immersed in distilled water at 37°C for 24 hours. The specimens of each material were randomly divided into three groups of 20. One side of two groups was polished, using either SiC papers up to 2000 grit (Zhenjiang Xinya Grinding Tools Co, Yangzhong City, China) or Shofu polishing discs (Shofu Inc, Kyoto, Japan), as displayed in Table 2. The third group was left unpolished after removal of the Mylar strip and acted as the control group. As described below, each specimen was washed and blotted dry with a paper towel, and the baseline color measurements and Vickers hardness test were carried out. Then, specimens of each group were subdivided into two

Table 1: *Description of All Resin Composites Used in the Study*

Resin Composite	Type	Manufacturer	Resin Matrix	Filler Content, Vol%; Type (Sizes)	Lot Number
Paradigm	Nanohybrid	3M ESPE, St Paul, MN, USA	Bis-GMA, UDMA, BISEMA, PEGDMA, TEGDMA	68; zirconia/silica (3 μm), Na Silica (20 nm)	N557215
Filtek P60 (F P60)	Microhybrid	3M ESPE, St Paul, MN, USA	Bis-GMA, UDMA, BISEMA,	61; zirconia/silica (0.01-3.5 μm)	N511095
Estelite Sigma Quick (ESQ)	Nanohybrid	Tokuyama, Dental Co., Tokyo, Japan	Bis-GMA, TEGDMA	63; SiO_2, ZrO_2, PFSC (200 nm and 0.2 μm)	158EY4
Filtek Z250 (F Z250)	Microhybrid	3M ESPE, St Paul, MN, USA	Bis-GMA, UDMA, BISEMA,	60; zirconia/silica (0.19-3.3 μm)	N450445
Ice	Nanohybrid	SDI, Victoria, Australia	UDMA, BISEMA, TEGDMA	61; SAS, AS (0.04-3 μm,)	131192T

Abbreviations: AS, amorphous silica; Bis-EMA, bisphenol A ethylmethacrylate; Bis-GMA, bisphenol A glycidyldimethacrylate; Na, nonagglomerated; PEGDMA, poly(ethylene glycol) dimethacrylate; PFSC, prepolymerized filler of silica composite; SAS, strontium aluminosilicate; TEGDMA, triethylene glycol dimethacrylate; UDMA, urethane dimethacrylate.

subgroups: half were randomly immersed in distilled water (pH=6.8), and the other half were placed into 0.01 mol/L lactic acid at pH 4 (n=10) and incubated at 37°C for a further 45 and 90 days. The solution was refreshed once per week and heated to 37°C before it was placed in the specimen container.

Color Measurement

Color measurements were obtained after each period in the liquids for each specimen using a spectrophotometer (Spectroshade; MHT Optic Research AG, Zurich, Switzerland). At the completion of each storage period (45 and 90 days), the specimens were washed for 10 seconds and blot dried and baseline measurements and CIE values (L_0, a_0, b_0) were recorded. Finally, the color change (ΔE_n) was calculated based on CIE values (L_n, a_n, b_n) using the following formula: $\Delta E_n = (\Delta L_n)^2 + (\Delta a_n)^2 + (\Delta b_n)^2]^{1/2}$

The differences were determined as ΔE_1 (1-45 days), ΔE_2 (45-90 days), and ΔE_3 (1-90 days).

Measurement of the Vickers Hardness

After 24 hour immersion in distilled water and following polishing, three randomly selected specimens of each group were subjected to Vickers hardness measurement using a digital microhardness tester (SCTMC, MHV-10002, Changhai, China) by applying a 300-g load with a dwell time of 15 seconds. Each specimen was subjected to indentation in three different locations, and the average microhardness was calculated. After 45 and 90 days of storage in distilled water or lactic acid, the same measurement procedures were repeated.

Statistical Analysis

The data were analyzed using SPSS software (version 18, SPSS Inc, Chicago, IL, USA). Three-way analysis of variance (ANOVA) was performed to determine if any interaction existed between the storage media, polishing methods and resin composites. Due to the significant interaction effects, subgroup analysis was applied using Student *t*-tests, one-way ANOVA and Tukey HSD tests. The correlation between ΔE and surface microhardness was assessed using the Pearson correlation coefficient. A p value of <0.05 was considered statistically significant.

RESULTS

Color Change

The effect of the three factors (polishing method, storage medium and composite) and their interaction

Table 2: *Polishing Systems and Instructions for Use*

Polishing System	Manufacturer	Instruction for Use
Super-Snap Rainbow Technique Kit (coarse, medium, fine, extra-fine)	Shofu Inc, Kyoto, Japan	Each sequence applied dry with 10 strokes using low speed with 12,000 rpm and light pressure for 30 seconds
Silicon carbide paper (sequence of 600, 1000, 1500, 2000 grit)	Zhenjiang Xinya Grinding Tools Co, China	Wet manual polishing in a single direction with light pressure as follows: coarse 15 strokes, medium 30 strokes, fine 45 strokes; specimen was washed for 10 seconds using an ultrasonic bath between paper grits
Mylar strip	Dentamerica Inc, San Jose, CA, USA	The surface of the resin composite was covered by a clear Mylar strip and glass slab before curing

Table 3: *Interactions Among the Three Factors Using Three-Way ANOVA*

Interaction	*p*-value*				
	Color Change			Hardness	
	ΔE_1	ΔE_2	ΔE_3	45d	90d
Material	<0.001	<0.001	0.010	<0.001	<0.001
Method	0.358	<0.001	0.025	<0.001	<0.001
Storage media	0.028	<0.001	<0.001	<0.001	<0.001
Material × Method	0.009	0.006	0.49	<0.001	<0.001
Storage media × Method	0.024	0.141	0.015	<0.001	<0.001
Material × Storage media	0.914	0.543	0.14	0.014	<0.001
Material × Storage media × Method	0.578	0.001	0.002	<0.001	<0.001

** A p-value <0.05 was considered significant.*

was studied for each storage time (Table 3). The interaction between the combinations of factors is shown graphically in Figure 1A.

For all storage times, regardless of the polishing method and storage medium, there was a significant difference between resin composites ($p<0.001$). Ice demonstrated the greatest color change, followed by Estelite Sigma Quick (ESQ), Filtek Z250 (F Z250), with Paradigm and Filtek P60 (F P60) showing the least color change.

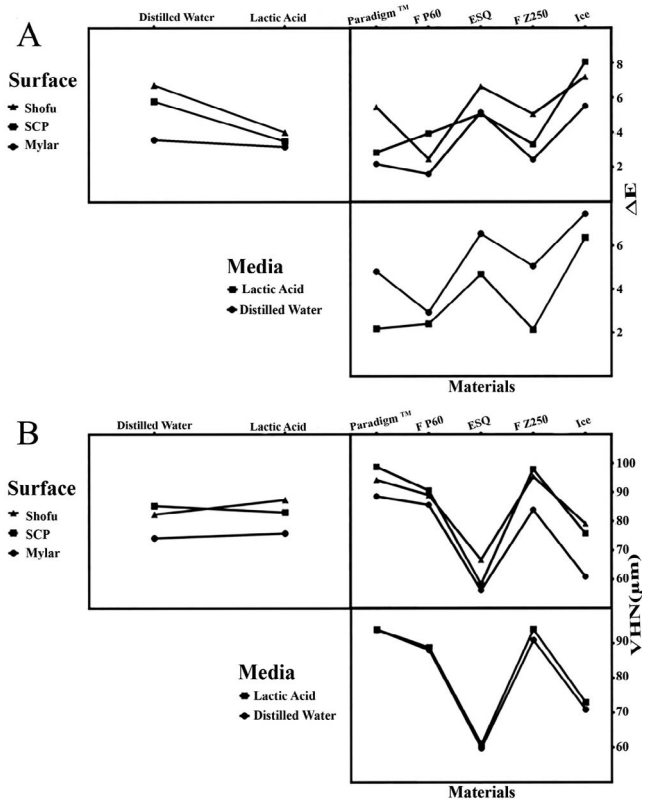


Figure 1. *Interaction plot; data means for color change ΔE (A) and Vickers hardness VHN (B).*

Regardless of the material and storage medium, the comparison between polishing methods showed a significant color change after 45 and 90 days of storage ($p<0.001$ and $p=0.025$, respectively). The specimens polished using the Shofu discs revealed the greatest color change followed by that of SiC paper and Mylar strip. In both distilled water and lactic acid, the effect of the polishing method used was dependent on the material and time of storage (Table 4).

Tables 5 and 6 show the overall means and standard deviations for ΔL_3, Δa_3, and Δb_3 of all polishing methods for each material in distilled water and lactic acid. After 90 days, distilled water immersion resulted in a visible color change ($\Delta E>3.3$) only in Ice ($\Delta E=5.09$) and Estelite ($\Delta E=6.97$) when cured under the Mylar strip. All materials showed a perceptible color change when polished using SiC paper or Shofu. L* differences had the greatest influence on the color change (ΔE) of the specimens. Overall, L* showed a large decrease, and a* and b* varied, showing a large increase for some materials and a slight increase for the remaining material. As an example, Estelite had an increase in b* and decrease in L*, with the specimens becoming darker "yellow." A similar trend of color change was observed for Estelite polished with SiC paper in distilled water. The significant color change of Ice polished with Shofu in distilled water was due to a decrease in L* and an increase in a*, with specimens becoming darker "red," whereas in lactic acid, this was due to only a significant decrease of L*. Significant discoloration of most specimens immersed in distilled water was due to a reduction of L* rather than an increase of a* or b*, resulting in a darker color. Figure 2 illustrates the main effect plot data means for color change after 90 days (ΔE_3).

Table 4: *Mean Color Change (ΔE) ± SD Between Two Different Storage Media for All Materials Using Three Different Finishing and Polishing Systems*[a]

Material	Mylar		Silicon Carbide Paper		Shofu	
	Distilled Water	Lactic Acid	Distilled Water	Lactic Acid	Distilled Water	Lactic Acid
ΔE_1						
Paradigm	1.74 ± 0.93 Aa	2.03 ± 0.58 Aa	0.66 ± 0.28 Ab	1.92 ± 0.93 Aa	3.79 ± 0.89 ABc	3.41 ± 1.61 Ac
F P60	1.04 ± 0.48 Aa	2.55 ± 0.67 Ab	1.31 ± 0.36 Aa	2.37 ± 0.78 Ab	2.94 ± 0.16 ACb	2.29 ± 0.69 Ab
ESQ	1.93 ± 0.53 Aa	3.38 ± 0.86 Ab	3.35 ± 0.44 Bb	4.78 ± 2.00 ABb	4.21 ± 0.93 ABb	2.95 ± 1.24 Ab
F Z250	1.76 ± 0.03 Aa	4.67 ± 0.66 Ab	2.48 ± 1.29 Ba	3.25 ± 1.18 ABb	1.41 ± 0.89 Ca	2.01 ± 0.24 Aa
Ice	4.50 ± 0.99 Ba	4.89 ± 1.00 Aa	5.08 ± 0.28 Ba	6.33 ± 1.76 Bb	5.04 ± 0.65 Ba	4.50 ± 1.20 Aa
ΔE_2						
Paradigm	2.81 ± 1.49 Aa	1.88 ± 0.29 Aa	4.27 ± 0.75 Ab	1.10 ± 0.53 Aa	4.41 ± 1.36 ABb	1.73 ± 1.17 ABa
F P60	1.81 ± 0.53 Aa	2.00 ± 0.97 Aa	4.85 ± 4.38 Ab	3.33 ± 3.60 Ab	2.30 ± 1.03 Aa	0.92 ± 0.18 Aa
ESQ	6.58 ± 0.82 Aa	1.85 ± 0.74 Ab	3.50 ± 0.90 Ac	1.83 ± 1.13 Ab	3.52 ± 2.00 ABc	3.94 ± 0.93 BCc
F Z250	1.58 ± 0.11 Aa	2.95 ± 0.68 Ab	1.70 ± 0.96 Aa	3.72 ± 1.07 Ab	7.61 ± 1.04 Bc	1.79 ± 0.81 ABa
Ice	1.96 ± 0.98 Aa	2.54 ± 0.44 Ab	7.43 ± 0.81 Ac	3.23 ± 0.48 Ab	7.47 ± 1.20 Bc	4.38 ± 0.94 Cb
ΔE_3						
Paradigm	1.85 ± 1.11 Aa	2.50 ± 1.40 ABa	4.44 ± 0.53 Ab	1.25 ± 0.04 Aa	8.11 ± 1.47 Ac	2.79 ± 0.38 Aa
F P60	1.65 ± 0.17 Aa	1.56 ± 0.08 Aa	4.54 ± 0.93 Ab	3.33 ± 1.00 Ab	2.59 ± 1.31 Ba	2.33 ± 0.63 Aa
ESQ	6.97 ± 0.98 Ba	3.30 ± 1.37 ABb	6.18 ± 2.21 Aa	3.93 ± 1.99 ABb	6.45 ± 1.66 ABa	6.81 ± 1.4 Ba
F Z250	2.29 ± 1.44 Aa	2.57 ± 1.42 ABa	4.32 ± 1.15 Ab	2.30 ± 1.30 Aa	8.55 ± 2.28 Ac	1.54 ± 0.07 Aa
Ice	5.09 ± 1.40 ABa	5.93 ± 1.43 Ba	9.40 ± 1.58 Ab	6.65 ± 0.84 Ba	7.85 ± 0.45 Ab	6.52 ± 1.32 Ba

[a] *In each column, mean values with different uppercase letters show a significant difference between the five materials (p<0.05). In each row, mean values with different lowercase letters show a significant difference between polishing methods in two storage media.*

Vickers Hardness

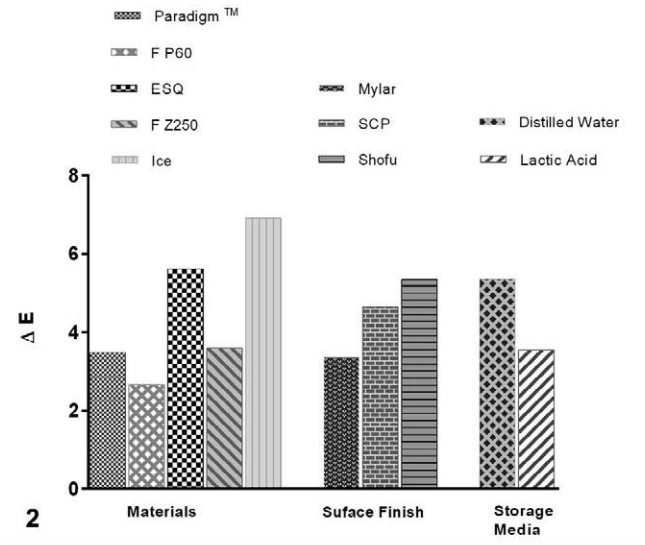
The effect of the three tested factors and the interaction between these factors were significant, as shown in Table 3. In general, hardness was found to be significantly higher in lactic acid ($p<0.001$) compared with distilled water. With an increase in storage time, the hardness value increased significantly ($p<0.001$), except for the specimens polished with SiC paper, which showed a transient decrease after 45 days followed by an increase in hardness after 90 days. Among the resin composites, the greatest hardness value was obtained for Paradigm and the lowest for ESQ followed by Ice (Table 7). The interaction between combinations of factors is shown in Figure 1B. Figure 3 illustrates the main effect plot data means for Vickers hardness values after 90 days.

Correlation Between Color Change and Vickers Hardness

There was a weak and reverse correlation between color change and hardness ($r=-0.264$, $p<0.001$). The same trend was noted for the storage media ($r=-0.282$, $p=0.007$, and $r=-0.232$, $p=0.028$, for distilled water and lactic acid, respectively) and the polishing method ($r=-0.288$, $p=0.026$; $r=-0.366$, $p=0.004$; and $r=-0.397$, $p=0.002$, for Mylar, SiC paper, and Shofu, respectively). There was no significant correlation between the hardness and color change for each material when analyzed separately.

Table 5: *Means and Standard Deviation of Δa, Δb, and ΔL for All Materials in Two Different Storage Media Using Three Different Finishing and Polishing Systems After Water Immersion*

	Polishing Method								
	Mylar			Silicon Carbide Paper			Shofu		
	Δa	Δb	ΔL	Δa	Δb	ΔL	Δa	Δb	ΔL
Paradigm	−0.07 ± 0.55	−1.30 ± 0.96	−0.60 ± 0.61	−1.70 ± 0.40	−3.30 ± 0.35	−2.37 ± 0.74	−2.23 ± 0.38	−6.37 ± 1.04	−4.50 ± 1.04
F P60	−1.33 ± 0.25	0.23 ± 0.75	−0.53 ± 0.58	−1.83 ± 0.87	−2.07 ± 3.51	−2.50 ± 3.54	−0.97 ± 0.31	0.27 ± 0.32	−2.30 ± 1.47
ESQ	−0.70 ± 0.26	−4.80 ± 2.80	−4.87 ± 1.80	−0.10 ± 0.61	−3.77 ± 1.65	−4.87 ± 1.56	−1.70 ± 0.95	−3.57 ± 3.17	−4.77 ± 1.05
F Z250	−0.53 ± 0.45	−0.73 ± 1.24	−1.80 ± 1.47	−0.13 ± 0.42	−2.10 ± 1.77	−3.53 ± 0.83	−1.33 ± 0.29	−4.87 ± 1.70	−6.90 ± 1.59
Ice	−0.87 ± 0.80	0.93 ± 0.55	−4.87 ± 1.40	−2.13 ± 0.68	−3.53 ± 1.45	−8.43 ± 1.10	−3.07 ± 0.15	−0.63 ± 0.85	−7.17 ± 0.49



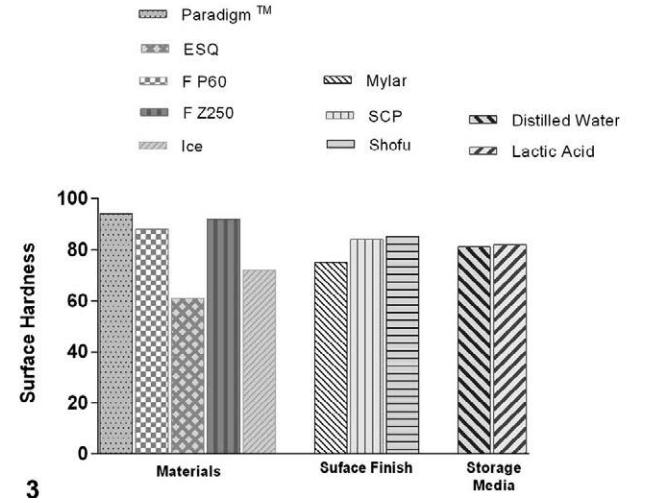


Figure 2. *Main effect plot; data means for color change (ΔE).*

Figure 3. *Main effect plot; data means for Vickers hardness value (VHN).*

DISCUSSION

In the oral environment, restorative materials face an acidic challenge produced by bacterial metabolism or the consumption of acidic foods and beverages. The results of the present study indicated that after 45 days of storage in lactic acid, the color change of the resin composites tested were significantly greater than when stored in distilled water. This may be explained by the direct relationship between water sorption and discoloration of the resin composites.[6,14] In a previous study, it was shown that resin composite immersed in lactic acid had greater sorption/solubility and diffusion coefficient.[19] Conversely, our results revealed that within 90 days of storage, the total color change in distilled water was more pronounced. It has been confirmed that a color difference of $\Delta E \geq 3.3$ is the critical value for visual perception of esthetic restorations.[20,21] Our findings showed that the color stability of only one of the tested composites showed a color change of less than 3.3 when stored in distilled water; however, in lactic acid, three resin composites presented acceptable color stability ($\Delta E < 3.3$).

The effect of storage media on hardness has been investigated in previous studies, showing a greater degree of micromorphological damage when materials were immersed in an acidic medium compared with distilled water. Organic acids can impose a detrimental effect on wear and surface degradation of polymeric resins and resin composites,[19] which may accelerate the degradation process and thus reduce the life span of a restoration.[19] In particular, lactic acid has been shown to decrease the surface hardness of resin composites.[17,22] Chadwick and others[23] determined that after one year storage of three resin composites (Occlusin, ICI Dental; P-30, 3M; and Fulfil, Caulk Dentsply) in distilled water and lactate, the surface microhardness of all composites was reduced.[23] Buchalla and others[24] noticed only minor negative effects on resin-based luting cements when stored in acidic solutions.[24] In contrast, Asmussen and others[25] found no significant change in the hardness of bisphenol A diglycidyl methacrylate (Bis-GMA)–based polymers immersed in lactic acid. Similarly, Munchow and

Table 6: *Means and Standard Deviations of Δa, Δb, and ΔL for All Materials in Two Different Storage Media Using Three Different Finishing and Polishing Systems After Lactic Acid Immersion*

	Polishing Method								
	Mylar			Silicon Carbide Paper			Shofu		
	Δa	Δb	ΔL	Δa	Δb	ΔL	Δa	Δb	ΔL
Paradigm	−0.53 ± 0.21	−0.40 ± 0.20	−2.30 ± 1.65	−0.60 ± 0.44	−0.33 ± 0.98	0.27 ± 0.64	−0.27 ± 0.40	−2.57 ± 0.55	−0.93 ± 0.38
F P60	−0.50 ± 0.10	0.73 ± 0.86	0.43 ± 1.62	−1.27 ± 0.83	−0.73 ± 2.32	−1.10 ± 2.55	−0.97 ± 0.31	−1.43 ± 0.55	−1.47 ± 0.67
ESQ	0.07 ± 0.84	−1.70 ± 1.25	−2.50 ± 1.51	0.00 ± 1.31	−2.53 ± 2.38	−2.30 ± 1.49	−1.70 ± 0.17	−5.07 ± 0.97	−4.20 ± 1.15
F Z250	−1.50 ± 0.36	−1.47 ± 0.90	−1.37 ± 1.29	−1.33 ± 0.06	−0.57 ± 1.59	−0.37 ± 1.93	0.03 ± 0.25	0.63 ± 0.78	−1.10 ± 0.70
Ice	−1.93 ± 0.15	−1.73 ± 1.25	−5.27 ± 1.27	−2.20 ± 0.50	−0.37 ± 0.21	−6.23 ± 1.02	−1.77 ± 0.12	−1.00 ± 1.95	−6.00 ± 1.31

Table 7: *Comparison of Vickers Hardness Value Between Two Different Storage Media for All Materials Using Three Different Finishing and Polishing Systems Analyzed by Independent t-Tests*[a]

Material	Mylar		Silicon Carbide Paper		Shofu	
	Distilled Water	Lactic Acid	Distilled Water	Lactic Acid	Distilled Water	Lactic Acid
Baseline						
Paradigm	84.37 ± 0.13 Aa		92.26 ± 0.32 Aa		89.18 ± 0.21 Aa	
F P60	84.79 ± 2.82 Aa		88.1 ± 0.21 Ba		84.22 ± 0.59 Ba	
ESQ	43.35 ± 0.08 Ba		52.47 ± 0.94 Cb		54.98 ± 0.92 Cb	
F Z250	78.74 ± 1.17 Ca		88.88 ± 1.72 Bb		86.22 ± 0.30 Db	
Ice	52.82 ± 0.41 Da		70.84 ± 1.01 Db		65.15 ± 0.48 Eb	
45 days						
Paradigm	80.69 ± 0.81 Aa	87.45 ± 0.64 Ab	87.75 ± 0.83 Ab	91.44 ± 0.73 Ab	92.63 ± 0.42 Ab	92.17 ± 0.31 Ab
F P60	85.91 ± 0.34 Ba	85.38 ± 0.59 Ba	86.31 ± 0.23 Ba	87.37 ± 2.25 Ba	88.16 ± 0.42 Ba	87.67 ± 0.33 Ba
ESQ	41.39 ± 1.03 Ca	49.51 ± 1.92 Cb	46.28 ± 0.76 Ca	51.03 ± 0.29 Cb	51.50 ± 0.86 Cb	48.47 ± 0.79 Cb
F Z250	82.36 ± 2.73 Aa	82.95 ± 2.31 Da	83.02 ± 3.36 Da	89.54 ± 2.70 Da	83.05 ± 0.75 Aa	85.54 ± 3.31 Da
Ice	57.34 ± 0.60 Da	55.35 ± 0.59 Ea	55.77 ± 3.29 Ea	62.58 ± 1.92 Eb	63.08 ± 0.04 Db	64.49 ± 0.60 Eb
90 days						
Paradigm	84.16 ± 0.25 Aa	93.08 ± 0.17 Ab	105.29 ± 2.26Ac	92.11 ± 0.21 Ab	91.82 ± 0.35 Ab	96.63 ± 0.53 Ab
F P60	85.66 ± 0.34 Ba	85.59 ± 0.32 Aa	92.35 ± 1.15 Aa	88.92 ± 0.45 Aa	86.12 ± 0.57 Ba	91.88 ± 0.70 Ba
ESQ	51.82 ± 0.52 Ca	60.52 ± 0.35 Bb	58.39 ± 0.16 Bb	58.26 ± 0.42 Bb	69.29 ± 0.59 Cc	64.12 ± 0.38 Cb
F Z250	83.74 ± 0.53 ABa	84.06 ± 0.42 Ca	97.96 ± 0.09 Ab	97.86 ± 0.54 Ab	90.89 ± 0.40 Da	100.03 ± 1.35 Bb
Ice	65.76 ± 0.40 D	56.03 ± 0.19 D	73.15 ± 0.49 C	78.36 ± 0.33 C	73.82 ± 0.33 E	84.53 ± 0.16 D

[a] *In each column, mean values with different uppercase letters show a significant difference level in the ANOVA test between five materials ($p<0.05$). Data are represented as mean ± SD*

others[26] reported a slight increase in the surface hardness of Filtek Z250 when immersed in 0.02 N lactic acid compared with distilled water. The results of our study showed no significant difference between distilled water and lactic acid. However, as Table 7 presents, immersion in lactic acid caused a slight increase in hardness dependant on the material and polishing method.

Among the materials tested, regardless of the time interval, polishing method, or the storage medium, Ice had the greatest color change followed by ESQ and F Z250, with the lowest values being observed for F P60 and Paradigm, respectively. Ertas and others[4] reported a similar finding showing less discoloration for F P60 and F Z250 compared with a microhybrid resin composite (Quadrant LC, Cavex) and two nanohybrids (Filtek Supreme, 3M-ESPE; Grandio, Voco). Since the type and compositions of the resin matrix strongly affect the hydrophilicity, it can play an important role in the long-term color stability of restorations.[14] As shown in Table 1, F P60 and F Z250 contain no TEGDMA in their matrix composition. It was acknowledged that the addition of small amounts of TEGDMA into a Bis-GMA–based resin composite significantly increased the water sorption of Bis-GMA–based resins.[27]

Other parameters such as the filler load, size, distribution, and type can influence the surface roughness, polishability, hardness, and water sorption of the resin composite.[14] Although a higher filler-resin ratio has contributed to low water sorption and staining susceptibility of resin composites,[2] the role of filler size, particularly when comparing microhybrid and nanohybrid composites, is still an ongoing controversy.[28,29] It has been indicated that during polishing procedures, voids may be produced by the shaving off of filler particles; hence, in nanohybrids, smaller particles are plucked out; therefore, smaller voids are created on the surface compared with microhybrids.[30] Consequently, it is expected that discoloration would be lower in the composites with smaller particles.[4] Topcu and others[29] in their study on the color change of resin composites after 24 hour immersion in eight staining solutions reported that nanocomposite exhibited the least discoloration. In contrast, others[4,5,28] showed a significantly greater discoloration for a nanohybrid (Grandio Nano, Voco) than a microhybrid (Arabesk top, Voco). In our study, two nanohybrids (Ice and ESQ) showed greater color change compared with two microhybrids (F P60 and F Z250) and a nanohybrid (Paradigm). Paradigm also showed the highest

microhardness followed by F P60 and F Z250. The lowest color change and the highest hardness values for Paradigm can be attributed to its higher filler volume loading (68 vol%) compared with the other resin composites (60-63 vol%) used in this study. The great influence of filler loading on the Vickers hardness of resin composites has been acknowledged previously.[9,31,32] Nevertheless, discoloration of resin composites is multifactorial and seems to be material dependent.

CONCLUSION

Within the limitations of this study, in comparison with distilled water, the color stability and microhardness of the resin composites were superior in lactic acid. The hardness and color stability of two nanohybrids (Ice and ESQ) were found to be lower than those of microhybrids (F Z250 and F P60). Furthermore, Paradigm, a nanohybrid with the highest filler loading in this study, exhibited the greatest hardness and was the second best in terms of color stability. Using Mylar strips caused the lowest hardness and discoloration, and the highest discoloration was reported with the specimens using the Shofu polishing system. The results of the present study are valid for the laboratory conditions used. Laboratory data may provide a perception into clinical performance; however, a direct relationship between laboratory and clinical performance cannot always be assumed.

Acknowledgments

A special thanks to SDI and 3M ESPE Victoria, Australia, for generously providing the materials. The funding granted (14704) to conduct this research was provided by Shiraz University of Medical Sciences.

Conflict of Interest

The authors of this article certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article

(Accepted 31 August 2019)

REFERENCES

1. Wilson NH, Burke FJ, & Mjor IA (1997) Reasons for placement and replacement of restorations of direct restorative materials by a selected group of practitioners in the United Kingdom *Quintessence International* **28(4)** 245-248.
2. Dietschi D, Campanile G, Holz J, & Meyer JM (1994) Comparison of the color stability of ten new-generation composites: an *in vitro* study *Dental Materials* **10(6)** 353-362.
3. Kim HJ, Bagheri R, Kim YK, Son JS, & Kwon TY (2017) Influence of curing mode on the surface energy and sorption/solubility of dental self-adhesive resin cements *Materials* **10(2)** E129.
4. Ertas E, Guler AU, Yucel AC, Kopruu H, & Guler E (2006) Color stability of resin composites after immersion in different drinks *Dental Materials Journal* **25(2)** 371-376.
5. Villalta P, Lu H, Okte Z, Garcia-Godoy F, & Powers JM (2006) Effects of staining and bleaching on color change of dental composite resins *Journal of Prosthetic Dentistry* **95(2)** 137-142.
6. Schulze KA, Marshall SJ, Gansky SA, & Marshall GW (2003) Color stability and hardness in dental composites after accelerated aging *Dental Materials* **19(7)** 612-619.
7. Sunbul HA, Silikas N, & Watts DC (2016) Surface and bulk properties of dental resin-composites after solvent storage *Dental Materials* **32(8)** 987-997.
8. Bagheri R, Taha NA, Azar MR, Burrow MF (2013) Effect of G-Coat Plus on the mechanical properties of glass-ionomer cements *Australian Dental Journal* **58(4)** 448-453.
9. Briso AL, Caruzo LP, Guedes AP, Catelan A, & dos Santos PH (2011) *In vitro* evaluation of surface roughness and microhardness of restorative materials submitted to erosive challenges *Operative Dentistry* **36(4)** 397-402.
10. Kim KH, Ong JL, Okuno O (2002) The effect of filler loading and morphology on the mechanical properties of contemporary composites *Journal of Prosthetic Dentistry* **87(6)** 642-649.
11. Wongkhantee S, Patanapiradej V, Maneenut C, & Tantbirojn D (2006) Effect of acidic food and drinks on surface hardness of enamel, dentine, and tooth-colored filling materials *Journal of Dentistry* **34(3)** 214-220.
12. Bagheri R, Burrow MF, Tyas MJ (2005) Influence of food-simulating solutions and surface finish on susceptibility to staining of aesthetic restorative materials *Journal of Dentistry* **33(5)** 389-398.
13. Jafarpour D, Mese A, Ferooz M, & Bagheri R (2019) The effects of nanofilled resin-based coatings on the physical properties of glass ionomer cement restorative materials *Journal of Dentistry* **July 25** epub ahead of print.
14. Ren YF, Feng L, Serban D, & Malmstrom HS (2012) Effects of common beverage colorants on color stability of dental composite resins: the utility of a thermocycling stain challenge model *in vitro Journal of Dentistry* **40(Supplement 1)** 48-56.
15. Bagheri R, Tyas MJ, & Burrow MF (2007) Comparison of the effect of storage media on hardness and shear punch strength of tooth-colored restorative materials *American Journal of Dentistry* **20(5)** 329-334.
16. Prakki A, Cilli R, Mondelli RF, Kalachandra S, & Pereira JC (2005) Influence of pH environment on polymer based dental material properties *Journal of Dentistry* **33(2)** 91-98.
17. Azar MR, Bagheri R, & Burrow MF (2012) Effect of storage media and time on the fracture toughness of

resin-based luting cements *Australian Dental Journal* **57(3)** 349-354.

18. Valinoti AC, Neves BG, da Silva EM, & Maia LC (2008) Surface degradation of composite resins by acidic medicines and pH-cycling *Journal of Applied Oral Science* **16(4)** 257-265.
19. da Silva EM, Goncalves L, Guimaraes JG, Poskus LT, & Fellows CE (2011) The diffusion kinetics of a nanofilled and a midifilled resin composite immersed in distilled water, artificial saliva, and lactic acid *Clinical Oral Investigations* **15(3)** 393-401.
20. Catelan A, Briso AL, Sundfeld RH, Goiato MC, & dos Santos PH (2011) Color stability of sealed composite resin restorative materials after ultraviolet artificial aging and immersion in staining solutions *Journal of Prosthetic Dentistry* **105(4)** 236-241.
21. Vichi A, Ferrari M, & Davidson CL (2004) Color and opacity variations in three different resin-based composite products after water aging *Dental Materials* **20(6)** 530-534.
22. Rahim TN, Mohamad D, Md Akil H, & Ab Rahman I (2012) Water sorption characteristics of restorative dental composites immersed in acidic drinks *Dental Materials* **28(6)** 63-70.
23. Chadwick RG, McCabe JF, Walls AW, & Storer R (1990) The effect of storage media upon the surface microhardness and abrasion resistance of three composites *Dental Materials* **6(2)** 123-128.
24. Buchalla W, Attin T, & Hellwig E (2000) Brushing abrasion of luting cements under neutral and acidic conditions *Operative Dentistry* **25(6)** 482-487.
25. Asmussen E (1984) Softening of BISGMA-based polymers by ethanol and by organic acids of plaque *Scandinavian Journal of Dental Research* **92(3)** 257-261.
26. Munchow EA, Ferreira AC, Machado RM, Ramos TS, Rodrigues-Junior SA, & Zanchi CH (2014) Effect of acidic solutions on the surface degradation of a micro-hybrid composite resin *Brazilian Dental Journal* **25(4)** 321-326.
27. Kalachandra S & Turner DT (1987) Water sorption of polymethacrylate networks: bis-GMA/TEGDM copolymers *Journal of Biomedical Materials Research* **21(3)** 329-338.
28. Al Kheraif AA, Qasim SS, Ramakrishnaiah R, & Ihtesham ur Rehman (2013) Effect of different beverages on the color stability and degree of conversion of nano and microhybrid composites *Dental Materials Journal* **32(2)** 326-331.
29. Topcu FT, Sahinkesen G, Yamanel K, Erdemir U, Oktay EA, & Ersahan S (2009) Influence of different drinks on the color stability of dental resin composites *European Journal of Dentistry* **3(1)** 50-56.
30. Turssi CP, Ferracane JL, & Serra MC (2005) Abrasive wear of resin composites as related to finishing and polishing procedures *Dental Materials* **21(7)** 641-648.
31. Peutzfeldt A (1997) Resin composites in dentistry: the monomer systems *European Journal of Oral Sciences* **105(2)** 97-116.
32. St Germain H, Swartz ML, Phillips RW, Moore BK, & Roberts TA (1985) Properties of microfilled composite resins as influenced by filler content *Journal of Dental Research* **64(2)** 155-160.

©Operative Dentistry, 2020, **45-3,** E114-E123

Bioactive Materials Subjected to Erosion/Abrasion and Their Influence on Dental Tissues

ÍEL Viana • Y Alania • S Feitosa • AB Borges • RR Braga • T Scaramucci

Clinical Relevance

When restorations are needed in patients with high risk of erosive tooth wear, resin-modified GICs may be considered an alternative. Although they are susceptible to wear under erosion/abrasion, they are capable of reducing enamel loss adjacent to the restorative material.

SUMMARY

Objective: The objective of this study was to evaluate the effect of erosion or erosion-abrasion on bioactive materials and adjacent enamel/dentin areas.

Methods and Materials: Enamel and dentin blocks (4×4×2 mm) were embedded side by side in acrylic resin, and a standardized cavity (1.2×4×1.5 mm) was prepared between them. Preparations were restored with the following materials: composite resin (Filtek Z350, control); experimental composite containing dicalcium phosphate dihydrate particles (DCPD); Giomer (Beautifil II), high viscosity glass ionomer cement (GIC, Fuji IX); and a resin-modified GIC (Fuji II LC). The specimens were submitted to two cycling models (n=10): erosion or erosion-abrasion. The challenges consisted of five-minute immersion in 0.3% citric acid solution, followed by 60-minute exposure to artificial saliva. Toothbrushing was carried out twice daily, 30 minutes after the first and last exposures to acid. Dental and material surface loss (SL, in μm) were determined by optical profilometry. Data were analyzed with Kruskal-Wallis and Dunn tests (α=0.05).

Results: Under erosion, for enamel, only the GIC groups presented lower SL values than Z350 ($p<0.001$ for Fuji IX and $p=0.018$ for Fuji

Ítallo Emídio Lira Viana, DDS, MSc, Department of Restorative Dentistry, University of São Paulo, School of Dentistry, São Paulo, Brazil

Yvette Alania, DDS, MSc, PhD, Department of Biomaterials and Oral Biology, University of São Paulo, School of Dentistry, São Paulo, Brazil

Sabrina Feitosa, DDS, MSc, PhD, assistant clinical professor, Department of Biomedical Sciences and Comprehensive Care, Indiana University School of Dentistry, Indianapolis, IN, USA

Alessandra Bühler Borges, DDS, MSc, PhD, associate professor, Department of Restorative Dentistry at Institute of Science and Technology of São José dos Campos, UNESP, São Paulo State University, São José dos Campos, Brazil

Roberto Ruggiero Braga, DDS, MSc, PhD, full professor, Department of Biomaterials and Oral Biology, University of São Paulo, School of Dentistry, São Paulo, Brazil

*Taís Scaramucci, DDS, PhD, assistant professor, Department of Restorative Dentistry, University of São Paulo, School of Dentistry, São Paulo, Brazil

*Corresponding author: Av Prof Lineu Prestes 2227, São Paulo, SP 05508-000, Brazil; e-mail: tais.sca@usp.br

https://doi.org/10.2341/19-102-L

II LC). For dentin, none of the materials showed significantly lower SL values than Z350 ($p>0.05$). For material, the GICs had significantly higher SL values than those of Z350 ($p<0.001$ for Fuji IX and $p=0.002$ for Fuji II LC). Under erosion-abrasion, the enamel SL value was significantly lower around Fuji II LC compared with the other materials ($p<0.05$). No significant differences were observed among groups for dentin SL ($p=0.063$). The GICs and Giomer showed higher SL values than Z350 ($p<0.001$ for the GICs and $p=0.041$ for Giomer).

Conclusion: Both GIC-based materials were susceptible to erosive wear; however, they promoted the lowest erosive loss of adjacent enamel. Against erosion-abrasion, only Fuji II LC was able to reduce enamel loss. For dentin, none of the materials exhibited a significant protective effect.

INTRODUCTION

Erosive tooth wear (ETW) is a condition causing growing concern among dental professionals.[1] Tissue loss caused by ETW is usually an interplay between acid demineralization and mechanical wear through attrition and abrasion.[2] It has an estimated prevalence of approximately 30% in the permanent teeth of children and adolescents.[3-5] When in the initial stages, ETW lesions appear as shallow defects with a dull surface. As the process continues, concavities and rounding of the cusps become evident. In advanced stages, the morphology of the tooth can be completely affected. If there are restorations present, they look as though they have risen above the adjacent tooth structure, resembling islands of restorative material. This occurs because erosive acids do not affect restorative materials in the same way as they affect dental tissues.[6,7]

In addition to controlling the etiologic factors and implementing specific preventive measures,[8,9] dentists may recommend the restoration of worn tissues when there is considerable loss of tooth structure, to protect the remaining tissues, reduce the risk of pulp exposure, and control dentin hypersensitivity. Additional purposes of performing restorations are to reestablish the esthetic appearance of teeth and recover the vertical occlusal dimension.[10,11] In general, the longevity of these restorations depends on the properties of the restorative material, including the material's resistance to wear, the integrity of the tooth-restoration interface, and extent of dental destruction.[12] Frequent erosive challenges can compromise the mechanical properties of restorative materials, thereby reducing their longevity.[13]

Among the restorative materials available for direct restorations, conventional or resin-modified glass ionomer cements (GICs) and composite resins are those most frequently used to restore erosive lesions.[14] The following are some of the beneficial properties of GICs: their chemical bond to enamel and dentin, coefficient of thermal expansion similar to the tooth structure, and fluoride release.[15] The latter is an important characteristic that can reduce the effects of erosion on the adjacent dental hard tissues.[13] However, studies have shown that this material can undergo a higher degree of degradation than composite resins when exposed to erosive challenges.[13,14,16]

The incorporation of bioactive components into composite resins may be an advantageous alternative for restorations in patients frequently exposed to erosive challenges, due to the release of ions that could play a relevant role in the ETW process. Calcium orthophosphates have been extensively studied due to their role in the mineralization of bones and teeth.[17] Recently, the synthesis of dicalcium phosphate dihydrate (DCPD) particles demonstrated promising results in the remineralization of carious lesions *in vitro*[18] and *in situ*.[19] Considering the positive results obtained with this material, in the context of caries disease, its possible protective effect against erosion also deserves to be explored.

Giomers are resin-based materials containing prereacted glass-ionomer fillers prepared by surface reaction (S-PRG), which are capable of releasing various ions, such as fluoride, silicate, borate, and strontium.[20] They are hybrid materials that were developed to provide resin composites with the cariostatic properties of GICs.[21] Fluoride and strontium, for example, may form an acid-resistant layer and reinforce tooth structure by inducing the formation of fluoride-apatite[22,23] and strontium-apatite[24] complexes. Because Giomers have the ability to neutralize acids and prevent demineralization,[25] they may also be an option to protect the dental hard tissues adjacent to restorations against erosive challenges, but this effect has not yet been thoroughly studied.

The aim of this laboratory study was to evaluate the effect of erosion or erosion-abrasion on fluoride- or calcium-containing restorative materials and on surrounding dental hard tissues (enamel and dentin) through evaluation of surface loss (SL). The null hypotheses were as follows: 1) restorative materials

Table 1: *Specifications of the Restorative Dental Materials Tested*

Material/Group	Manufacturer/Lot Number	Composition
Microhybrid resin composite (Filtek Z350, Shade A2B)	3M-ESPE, St Paul, MN, USA/1635100182	Bis-GMA, UDMA, bis-EMA, TEGDMA, and PEGDMA. 78 wt% (or 59 vol%) of zirconia/silica particles and nonagglomerated silica particles
Experimental material (60% DCPD)	—	Bis-GMA, TEGDMA, CQ, EDMAB, DCPD functionalized with DEGDMA
Giomer (Beautifil II, Shade A2O)	Shofu Dental Corporation, San Marcos, CA, USA/061618	Bis-GMA, UDMA, Bis-MPEPP, TEGDMA 83.3 wt% fluorosilicate glass
High-viscosity GIC (Fuji IX, Shade A2)	GC Corporation, Tokyo, Japan/1610031	Polyacrylic acid, fluoroaluminosilicate glass, polybasic carboxylic acid
RMGI (Fuji II LC, Shade A2)	GC Corporation/1611251	2-Hydroxyethyl methacrylate, polyacrylic acid, and water; 58 wt% fluoroaluminumsilicate

Abbreviations: bis-EMA, ethoxylated bisphenol A dimethacrylate; bis-GMA, bisphenol-A glycidyl dimethacrylate; bis-MPEPP, bisphenol A polyethoxy methacrylate; CQ, camphorquinone; DCPD, di-calcium phosphate dihydrate; EDMAB, ethyl-4-dimethylamino benzoate; PEGDMA, polyethylene glycol dimethacrylate; TEGDMA, triethylene glycol dimethacrylate; UDMA, urethane dimethacrylate.

subjected to erosion or erosion-abrasion would show similar SL values, and 2) surrounding enamel and dentin SL after erosion or erosion-abrasion would not be influenced by the restorative material.

METHODS AND MATERIALS

Study Design

This study was based on a completely randomized design, with restorative material as the main factor, at five levels, as described in Table 1. All the groups were compared with the (nonbioactive material) Z350, because it does not release ions. One hundred specimens were prepared, each one containing one enamel and one dentin slab. Between the two slabs, a standardized cavity was prepared and subsequently filled with one of the tested materials (n=20). The specimens were then submitted to erosion (n=10) or erosion-abrasion (n=10) challenges. At the end of cycling, the SL values (in μm) of the three substrates (enamel, dentin, and restorative material) were determined.

Specimen Preparation

The crowns of bovine incisors were separated from the roots using a double-side diamond disc (KG Sorensen, Barueri, SP, Brazil). Slabs of enamel and dentin (4×4×2 mm) were obtained from their crowns and roots, respectively, using an automatic sectioning machine (Isomet, Buehler, Lake Bluff, IL, USA). A silicone mold was used to position one dentin and one enamel slab 0.5-0.8 mm apart from each other, and, subsequently, they were embedded in acrylic resin (Varidur, Buehler).[13] The embedded enamel-dentin pairs were ground flat with 240-grit paper for five seconds, under constant cooling, to remove any acrylic residue, randomly allocated into five experimental groups according to the restorative materials (n=20), and were then stored under relative humidity condition, at 4°C.

Experimental Composite Formulation

The experimental resin-based material had an organic phase composed of 1:1 in moles of bisphenol-A glycidyl dimethacrylate (BisGMA) and triethylene glycol dimethacrylate (TEGDMA), plus 0.5 wt% of camphorquinone and ethyl-4-dimethylamino benzoate (EDMAB, all components from Sigma–Aldrich, St Louis, MO, USA) as photoinitiators. The filler was composed of 60% di-calcium phosphate dihydrate (DCPD) particles functionalized with TEGDMA. The material was mechanically mixed under vacuum (Speedmixer DAC 150.1 FVZ-K, FlackTek Inc, Landrum, SC, USA) and kept under refrigeration until two hours before use.[26]

Application of Restorative Materials

A standardized cavity (1.2×4×1.5 mm) was prepared between the enamel and dentin fragments using a cylindrical diamond bur (2292, KG Sorensen) in a high-speed handpiece under water cooling, by a single trained operator.[13,14] The cavity dimensions were in accordance with the active tip of the bur. The cavity depth (1.5 mm) was standardized by the stop device of the bur. The cavities were filled with the respective restorative materials, in accordance with the different manufacturers' recommendations. When required, light activation was carried out using a second-generation LED light curing unit (Radii-cal, SDI, Bayswater, VIC, Australia), with an irradiance of 1200 mW/cm^2, which was monitored by radiometer. The specimens were kept under relative humidity for one week prior to testing to allow post irradiation hardening of composite restorations and

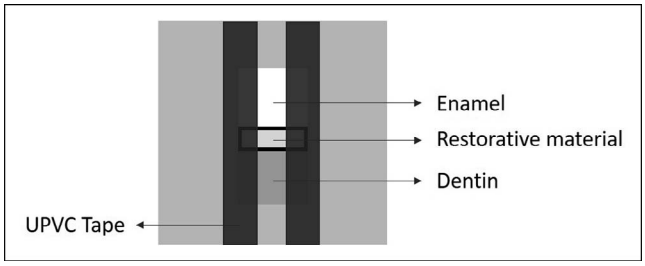


Figure 1. *Representative image of a specimen used in the study. A silicone mold was used to position one dentin and one enamel slab 0.5-0.8 mm apart from each other. Between the slabs, a standard cavity was made and restored with its respective material. After polishing, tape was placed on the specimen's surface, leaving a central area exposed to subsequent testing.*

complete setting of the GIC restorations. Specimens were finished and polished with Al_2O_3 abrasive discs (400-, 600-, 1200-, and 4000-grit, Buehler) under water-cooling, to ensure that the restorative material was at the same level as the enamel and dentin fragments. This procedure allowed the specimens to be evaluated by optical profilometry, as plain and polished surfaces improve the accuracy and sensitivity of the measurements.[27] Specimens were then sonicated for three minutes with distilled water.

The initial curvatures of the enamel, dentin, and restorative fragments were evaluated with an optical profilometer (Proscan 2100, Scantron, Venture Way, Tauton, United Kingdom). Fragments with curvature greater than 0.4 μm and specimens with cracks or surface defects were discarded. Unplasticized polyvinyl chloride (UPVC)-type adhesive tape was applied to the surface of the specimens, leaving approximately 1 mm exposed (Figure 1). The specimens were kept in 100% relative humidity until the next stage of the study.

Erosion and Erosion-Abrasion Cycling

For the erosion cycling, half of the specimens of each group (n=10) were immersed in 0.3% citric acid solution (pH=2.6) for five minutes, followed by immersion in artificial saliva[28] ($CaCl_2 \times 2\ H_2O$ 0.213 g/L, KH_2PO_4 0.738 g/L, KCl 1.114 g/L, NaCl 0.381 g/L, Tris buffer 12 g/L, pH=7) for 60 minutes. This procedure was repeated four times a day for five days. For erosion-abrasion cycling, the other half of the specimens (n=10) were submitted to the same procedures, but the specimens were also brushed in a toothbrushing simulator (MEV-2T Odeme Equipamentos Médicos e Odontológicos Ltda, Joaçaba, SC, Brazil). Brushing was performed twice a day (45 cycles/150g/15 seconds), 30 minutes after the first and fourth erosive challenges, with a suspension of a standard toothpaste (Colgate Total 12 Mint Clean, Colgate-Palmolive, São Bernardo do Campo, SP, Brazil; 1450 ppm F, as NaF) and distilled water, in a ratio of 1:3. The specimens were exposed to the slurries for a total time of two minutes. All procedures were conducted at room temperature (~24°C). At the end of each cycling day, the specimens were stored at 100% relative humidity. The erosive solution and artificial saliva were renewed after each exposure. At the end of the cycling procedures, the specimens were maintained in 100% relative humidity condition at 4°C until the profilometric test was performed.

Surface Loss Measurements

After five days of cycling, the tape was removed from the specimens, and an area 2 mm long (x) × 1 mm wide (y) was scanned at the center of the substrates. This readout covered the eroded area and the reference areas on enamel and dentin. On the x-axis, the step size was set to 0.01 mm and the number of steps was 200. On the y-axis, these values were 0.1 mm and 10, respectively. The depth of the eroded area was calculated based on subtracting the mean height of the test area from the mean height of the two reference areas, using the system software (Proscan Application software v. 2.0.17, Scantron, Venture Way, Tauton, United Kingdom). The specimens were scanned moist to avoid retraction of the eroded dentin collagen matrix.[29]

Statistics

For each model (erosion and erosion-abrasion), the data of surface loss of enamel, dentin, and restoration were analyzed independently. Considering that the data of enamel after erosion and restorative material after both challenges did not follow a normal distribution, data were analyzed by the Kruskal-Wallis and Dunn's tests, adopting the level of significance of 5%. Sigma Plot 13.0 software (Systat Sotware Inc, Chicago, IL, USA) was used for calculations.

RESULTS

The medians (interquartile intervals) of material surface loss obtained in both erosive and erosive-abrasive challenges are presented in Table 2. For erosion, Fuji IX presented the highest material loss value ($p<0.001$ for Z350; $p<0.001$ for Beautifil II; and $p=0.050$ for DCPD), statistically similar to that of Fuji II LC only ($p=0.727$). The composite containing DCPD showed values similar to those of Fuji II LC ($p=1.000$) and to those of the commercial

Table 2: *Medians (Interquartile Intervals) of Material Surface Loss (in μm) for Erosion and Erosion-Abrasion Models*[a]

Groups	Erosion	Erosion-Abrasion
DCPD	1.31 (0.88-1.87) BC	0.57 (0.32-1.01) BC
Z350	0.29 (0.13-0.44) C	0.26 (0.19-0.35) C
Beautifil II	0.34 (0.07-0.60) C	1.59 (1.42-2.29) B
Fuji II LC	2.35 (1.99-2.58) AB	2.86 (2.29-4.12) AB
Fuji IX	16.60 (14.42-17.09) A	13.39 (11.98-15.25) A

[a] *Different letters in columns imply significant difference among groups (p<0.05).*

composite (p=0.066). For erosion-abrasion, Fuji IX again presented the highest material loss (p<0.001 for Z350; p<0.001 for DCPD; and p=0.022 for Beautifil II), with values statistically similar to those of Fuji II LC (p=0.657). The Giomer and the DCPD-containing composite both showed values similar to those of Fuji II LC (p=1.000 and p=1.000, respectively), whereas the values of the latter were significantly higher than those of Z350 (p<0.001). The medians (interquartile intervals) of enamel surface loss obtained in both challenge conditions are presented in Table 3. For erosion, the enamel adjacent to Fuji IX and Fuji II LC showed the lowest surface loss values (p<0.05), without significant difference between them (p=1.000). The use of Beautifil II resulted in enamel loss value similar to those of both Fuji II LC (p=0.135) and the other two resin-based materials (p=1.000 for Z350 and p=1.000 for DCPD). For erosion-abrasion, the enamel adjacent to Fuji II LC presented the lowest surface loss values (p=0.001 for DCPD; p=0.009 for Fuji IX; p=0.011 for Z350; and p=0.020 for Beautifil II) that differed significantly from those of all the other groups, which showed no significant differences among them (p>0.05).

The medians (interquartile intervals) of dentin surface loss obtained in both challenge conditions

Table 3: *Medians (Interquartile Intervals) of Enamel Surface Loss (in μm) Adjacent to Studied Materials for Erosion and Erosion-Abrasion Models*[a]

Groups	Erosion	Erosion-Abrasion
DCPD	16.36 (14.22-18.12) A	10.84 (10.20-11.96) A
Z350	13.95 (12.88-14.50) A	10.63 (10.13-11.36) A
Beautifil II	13.44 (12.13-13.78) AB	10.76 (8.51-11.57) A
Fuji II LC	10.01 (9.26-11.10) BC	8.02 (7.23-8.81) B
Fuji IX	9.27 (8.76-9.67) C	10.54 (10.16-11.84) A

[a] *Different letters imply significant difference among groups, in columns (p<0.05).*

Table 4: *Medians (Interquartile Intervals) of Dentin Surface Loss (in μm) Adjacent to Studied Materials for Erosion and Erosion-Abrasion Models*[a]

Groups	Erosion	Erosion-Abrasion
DCPD	18.77 (18.10-22.40) A	5.85 (4.65-7.74) A
Z350	14.74 (13.34-15.80) BC	8.69 (7.56-9.49) A
Beautifil II	16.83 (15.52-18.10) AB	7.77 (6.86-9.51) A
Fuji II LC	12.48 (11.03-12.93) C	8.63 (6.23-9.27) A
Fuji IX	12.11 (8.25-13.02) C	8.85 (6.60-10.48) A

[a] *Different letters in columns imply significant difference among groups (p<0.05).*

are presented in Table 4. For erosion, Fuji IX and Fuji II LC presented the lowest SL values that did not differ significantly from those of Z350 (p=0.886 and p=1.000, respectively), which in turn did not differ from those of Beautifil II (p=0.858). DCPD showed the highest SL values (p<0.001 for Fuji IX, p<0.001 for Fuji II LC; and p=0.014 for Z350) that did not differ from those of Beautifil II (p=0.100). For erosion-abrasion, there were no significant differences among the groups (p=0.063).

DISCUSSION

After analyzing the data, the first study hypothesis was rejected, as the restorative materials did not present a similar degree of SL after the erosive or erosive-abrasive challenges. This result was expected, because different categories of restorative materials were tested. In agreement with previous investigations, the GICs presented the highest SL values after erosive cycling.[13,14] This could be explained by the dissolution of the peripheral silicate hydrogel lattice of their glass particles.[30,31] It should be also considered that, because of their composition, GICs are also known to have an inherent increased solubility in aqueous medium.[32] However, there were no significant differences in surface loss between the GICs. It was hypothesized that the acid challenges would affect the glass ionomer portion of the material with a higher level of intensity than it would affect its resin component; thus, conventional GICs would present significant higher susceptibility to erosion than resin-modified GICs[16]; however, this was not observed in the present study. Although there was a great numerical difference between these groups (median and interquartile interval of 16.60 and 14.42-17.09 for Fuji IX and 2.35 and 1.99-2.58 for Fuji II LC, respectively), a significant difference could not be detected with the nonparametric approach used.

Although studies have suggested that composites could also be affected by erosive challenges, which would degrade the resin matrix or the silane-coupling agent, resulting in the loss of filler particles,[33,34] the composite Z350 was only minimally impacted by the acid challenges, also in agreement with previous investigations.[13,14,35] Although the surface loss from DCPD did not significantly differ from that of Z350, it also did not differ from that of Fuji II LC, probably due to the absence of reinforcing particles and the higher solubility of DCPD in acidic environments.[36] The Giomer exhibited similar behavior to that of Z350 under erosion. This could be attributed to high filler content (78% wt and 83.3% wt of Z350 and Giomer, respectively), whereas, for resin-based materials, a linear relationship between wear resistance by acids and the filler volume has previously been observed.[33] In addition, the authors could suggest that the buffering capacity promoted by the ions released by the S-PRG fillers of Giomer[25] reduced the effect of the acid on the material. However, a previous study observed that the Giomer has higher susceptibility to reduction in hardness under citric acid challenge than a microhybrid composite resin with nanoparticles has.[37] The authors related this fact to the type of filler in the Giomer–alumino-fluoro-borosilicate glass, which was found to be more susceptible to degradation by weak acids than the zirconia-silicate filler of the composite. These different results could be explained by the lower contact time with the acid in the present study when compared with the seven days of acid exposure of this previously cited investigation, which might have reduced the effect of the acid on the Giomer. Furthermore, in our study, the impact of the acid on the materials was evaluated by means of surface loss and not hardness; therefore, to clearly see some effect, a prolonged exposure time would be required.

In the erosion-abrasion model, Fuji IX again underwent the highest level of wear, but it was no different from Fuji II LC and Giomer. It could be hypothesized that the citric acid negatively affected the hardness of Giomer, leaving the material more vulnerable to the mechanical action of toothbrushing.[38] For the composites, it was shown that prolonged toothbrushing could result in the wear of the polymeric matrix and the loosening of the filler particles.[39] Nevertheless, when considering only a few brushing cycles, as was the case of the present study, this should not be an issue.[40]

The restorative materials selected for this study contained either fluoride or calcium phosphate in their formulations. These are relevant compounds for caries prevention, which may also positively act on the dental erosion process. Fluoride products can induce the formation of fluor-hydroxyapatite (a less soluble mineral) and the precipitation of CaF_2-like compounds, which will protect the underlying dental tissues against erosive acids and serve as a fluoride deposit.[41] Additionally, fluoride has the ability to form a nonspecific adsorbed fluoride phase over hydroxyapatite,[42] which can make this ion readily available to influence demineralization and remineralization.[43] However, it is questionable whether fluoride-releasing materials would induce the precipitation of CaF_2-like material, due to their low amount of fluoride release.[44,45] Moreover, it should be taken into account that remineralization is a limited process in dental erosion, most probably confined to the softened eroded layer.[46] Calcium phosphates can promote tooth remineralization, acting as an external source of calcium and phosphate ions, which will deposit in the empty spaces of the demineralized structure, resulting in mineral gain.[47] In the context of erosion, the presence of these ions in the tooth surroundings at the time of the acid challenge could potentially contribute to reducing the demineralization rate.

The resin-modified glass ionomer cement Fuji II LC was the only material able to protect the enamel adjacent to the restorations against the erosive and erosive-abrasive challenges; therefore, the second null hypothesis of this study was also rejected. Although fluoride release from the materials were not evaluated in the present investigation, based on a previous report, this result could be related to the higher quantity of fluoride release of Fuji II LC when compared with the other materials.[44] Studies have stated that fluoride release was affected by the formulation, solubility, and porosity of the material. The resin-modified GICs showed an initial burst of fluoride release, which was possibly induced by a superficial rinsing effect. During the subsequent days, the fluoride release was lower and attributed to its ability to diffuse through the cement pores and cracks.[48] The hydroxyethylmethacrylate (HEMA) present in the resin-modified GICs composition is thought to slowly absorb water and allow the diffusion of fluoride.[49] This result is in agreement with a previous investigation, in which not only the resin-modified GIC, but also a high viscosity GIC, was able to reduce enamel loss by erosion in the areas adjacent to the restoration.[13] Nevertheless, the aggressiveness of the erosive challenges must also be considered, because with lower exposure to the acidic

solution, no protective effect on enamel adjacent to resin-modified GICs could be observed.[50] This could be related to correlation between the ability of GICs to release fluoride and the acid erosion.[51] The fluoride release of Giomer was observed to be lower than that of other fluoride-containing materials, such as Fuji II LC, with no effect of initial burst of fluoride release.[44] This may justify the lack of erosion or erosion-abrasion protection provided by the Giomer.

Unlike the results obtained for dental caries, in which a DCPD-containing experimental composite was able to provide protection in the surroundings of the restoration, resulting in enamel remineralization,[18] no significant effect against erosive wear was observed in the present investigation. Although in erosion, rehardening is a process limited to the softened layer,[52] we hypothesized that the release of these ions would help to improve the mineral gain of the enamel and dentin surface after each erosive episode, which would result in a lower surface loss in the end of cycling. Additionally, and more importantly, these ions would also act during the erosive challenge, by increasing the saturation in relation to tooth minerals in the tooth surroundings, thereby reducing demineralization. Nevertheless, the results suggested that the experimental composite had insufficient calcium release for producing this type of effect.

None of the materials showed a protective effect on dentin, which may be explained by the high aggressiveness of the erosive challenges used; this was in agreement with the outcomes of a previous report.[53] It should be noted that significant protection against dentin erosion was observed at the margins of GIC restorations when milder erosive challenges were used.[13]

Unexpectedly, the surface loss values for enamel and dentin were not higher under erosion-abrasion condition compared with erosion only.[54] Although the data from both challenges were not compared (because they were independent experiments), this could be attributed to the use of fluoridated toothpaste during toothbrushing, which may have offered some protection against erosive wear.[55] It has also to be taken into account that in the erosion-abrasion condition, the presence of fluoride in the toothpaste may have masked the effect of the nonactive material Z350, by providing it with a false protective action. One option to avoid this issue would be to perform the brushing with a nonfluoridated dentifrice. However, this would not be a realistic representation of what happens in the clinic, as the use of fluoride toothpastes is recommended from the time that the first deciduous tooth erupts. It should be mentioned that, as other erosion-abrasion studies, specimens from bovine teeth were used as replacement for human teeth.[13,53,56] Although there are some reported structural differences between substrates,[57] it was concluded that the use of bovine teeth is acceptable, especially for the comparison of the relative effect of agents or materials.[58] Another point is the use of optical profilometry to measure surface loss from eroded dentin without the removal of the organic matrix. Although the presence of the organic matrix could interfere with the readings, care was taken to perform the readings in standardized moist conditions, thus avoiding its shrinkage.[29]

Ideally, restorative materials should be able to withstand all adverse conditions present at the oral environment, such as acid challenges, brushing and masticatory forces, increasing the longevity of the restoration. In patients with erosive wear, if the implementation of preventive measures is not established, the progression of the lesion is more likely to occur. Hence, for these patients, the search for a material that can protect the dental tissues at the vicinity of the restoration and, at the same time, be resistant to constant chemical and mechanical challenges is desirable. Despite the greater surface loss under the challenges and the lower mechanical resistance than composites,[59,60] Fuji II LC presented promising results regarding the protection of substrates in both proposed models. This material can thus be used in a temporary restoration, during the transitional period in which the patient is changing his/her habits or treating a medical condition. Later on, replacement with a resin composite could be performed, because this material was more resistant to surface wear.

CONCLUSIONS

According to the findings of this laboratory study, it was concluded that the resin-modified GIC (Fuji II LC) was the restorative material associated with the lowest loss of adjacent enamel due to erosion and erosion-abrasion challenges. However, it was one of the materials that underwent higher surface loss in the face of both challenges. For dentin, none of the materials exhibited a significant protective effect.

Acknowledgements

This study was supported by the "Coordenação de Aperfeiçoamento de Pessoal de Nível Superior-Brasil" (CAPES)-Finance Code 001 and the National Council for Scientific and Technological Development (Process 141068/2018-3), which provided the first author with a scholarship. This study was

part a thesis submitted by the first author to the University of São Paulo, School of Dentistry, in fulfillment of the requirements for the MS degree in Restorative Dentistry."

Conflict of Interest

The authors of this manuscript certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

(Accepted 16 September 2019)

References

1. Lussi A & Carvalho TS (2014) Erosive tooth wear: A multifactorial condition of growing concern and increasing knowledge *Monographs in Oral Science* **25** 1-15.
2. Shellis RP & Addy M (2014) The interactions between attrition, abrasion and erosion in tooth wear *Monographs in Oral Science* **25** 32-45.
3. Salas MMS, Nascimento GG, Huysmans MC, & Demarco FF (2015) Estimated prevalence of erosive tooth wear in permanent teeth of children and adolescents: an epidemiological systematic review and meta-regression analysis *Journal of Dentistry* **43(1)** 42-50.
4. Bartlett DW, Lussi A, West NX, Bouchard P, Sanz M, & Bourgeois D (2013) Prevalence of tooth wear on buccal and lingual surfaces and possible risk factors in young European adults *Journal of Dentistry* **41(11)** 1007-1013.
5. Loomans B & Opdam N (2018) A guide to managing tooth wear: the Radboud philosophy *British Dental Journal* **224(5)** 348-356.
6. Lussi A, Schlueter N, Rakhmatullina E, & Ganss C (2011) Dental erosion: an overview with emphasis on chemical and histopathological aspects *Caries Research* **45(Supplement 1)** 2-12.
7. Schlueter N, Jaeggi T, & Lussi A (2012) Is dental erosion really a problem *Advances in Dental Research* **24(2)** 68-71.
8. Magalhães AC, Wiegand A, Rios D, Honório HM, & Buzalaf MAR (2009) Insights into preventive measures for dental erosion *Journal of Applied Oral Science* **17(2)** 75-86.
9. Carvalho JC, Scaramucci T, Aimée NR, Mestrinho HD, & Hara AT (2018) Early diagnosis and daily practice management of erosive tooth wear lesions *British Dental Journal* **224(5)** 311-318.
10. Lambrechts P, Van Meerbeek B, Perdigão J, Gladys S, Braem M, & Vanherle G (1996) Restorative therapy for erosive lesions *European Journal of Oral Science* **104(2 Pt 2)** 229-240.
11. Varma S, Preiskel A, & Bartlett D (2018) The management of tooth wear with crowns and indirect restorations *British Dental Journal* **224(5)** 343-347.
12. Peutzfeldt A, Jaeggi T, & Lussi A (2014) Restorative therapy of erosive lesions *Monographs in Oral Science* **25** 253-261.
13. Alghilan MA, Cook NB, Platt JA, Eckert GJ, & Hara AT (2015) Susceptibility of restorations and adjacent enamel/dentine to erosion under different salivary flow conditions *Journal of Dentistry* **43(12)** 1476-1482.
14. Honório HM, Rios D, Francisconi LF, Magalhães AC, Machado MAAM, & Buzalaf MAR (2008) Effect of prolonged erosive pH cycling on different restorative materials *Journal of Oral Rehabilitation* **35(12)** 947-953.
15. Hu JY, Li YQ, Smales RJ, & Yip KHK (2002) Restoration of teeth with more-viscous glass ionomer cements following radiation-induced caries *International Dental Journal* **52(6)** 445-448.
16. Soares LES, Lima LR, Vieira LDS, Do Espírito Santo AM, & Martin AA (2012) Erosion effects on chemical composition and morphology of dental materials and root dentin *Microscopy Research and Technique* **75(6)** 703-710.
17. Dickens SH, Flaim GM, & Takagi S (2003) Mechanical properties and biochemical activity of remineralizing resin-based Ca-PO4 cements *Dental Materials* **19(6)** 558-566.
18. Alania Y, Natale LC, Nesadal D, Vilela H, Magalhães AC, & Braga RR (2019) In vitro remineralization of artificial enamel caries with resin composites containing calcium phosphate particles *Journal of Biomedical Materials Research. Part B, Applied Biomaterials* **107(5)** 1542-1550.
19. Melo MAS, Weir MD, Rodrigues LKA, & Xu HHK (2013) Novel calcium phosphate nanocomposite with caries-inhibition in a human in situ model *Dental Materials* **29(2)** 231-240.
20. Fujimoto Y, Iwasa M, Murayama R, Miyazaki M, Nagafuji A, & Nakatsuka T (2010) Detection of ions released from S-PRG fillers and their modulation effect *Dental Materials Journal* **29(4)** 392-397.
21. Nedeljkovic I, De Munck J, Slomka V, Van Meerbeek B, Teughels W, & Van Landuyt KL (2016) Lack of buffering by composites promotes shift to more cariogenic bacteria *Journal of Dental Research* **95(8)** 875-881.
22. Cochrane NJ, Saranathan S, Cai F, Cross KJ, & Reynolds EC (2008) Enamel subsurface lesion remineralisation with casein phosphopeptide stabilised solutions of calcium, phosphate and fluoride *Caries Research* **42(2)** 88-97.
23. Jima Y & Koulourides T (1989) Fluoride incorporation into and retention in remineralized enamel *Journal of Dental Research* **68(8)** 1289-1292.
24. Dedhiya MG, Young F, & Higuchi WI (1973) Mechanism for the retardation of the acid dissolution rate of hydroxapatite by strontium *Journal of Dental Research* **52(5)** 1097-1109.
25. Kaga M, Kakuda S, Ida Y, Toshima H, Hashimoto M, Endo K, & Sano H (2014) Inhibition of enamel demineralization by buffering effect of S-PRG filler-containing dental sealant *European Journal of Oral Science* **122(1)** 78-83.
26. Rodrigues MC, Natale LC, Arana-Chaves VE, & Braga RR (2015) Calcium and phosphate release from resin-based materials containing different calcium orthophosphate nanoparticles *Journal of Biomedical Materials Research. Part B, Applied Biomaterials* **103(8)** 1670-1678.
27. Schlueter N, Hara A, Shellis RP, & Ganss C (2011) Methods for the measurement and characterization of

erosion in enamel and dentine *Caries Research* **45(1)** 13-23.

28. Scaramucci T, Hara AT, Zero DT, Ferreira SS, Aoki I V, & Sobral MAP (2011) In vitro evaluation of the erosive potential of orange juice modified by food additives in enamel and dentine *Journal of Dentistry* **39(12)** 841-848.
29. Attin T, Becker K, Roos M, Attin R, & Paqué F (2009) Impact of storage conditions on profilometry of eroded dental hard tissue *Clinical Oral Investigations* **13(4)** 473-478.
30. Turssi CP, Hara AT, Serra MC, & Rodrigues AL (2002) Effect of storage media upon the surface micromorphology of resin-based restorative materials *Journal of Oral Rehabilitation* **29(9)** 864-871.
31. El-Badrawy WA & McComb D (1998) Effect of home-use fluoride gels on resin-modified glass-ionomer cements *Operative Dentistry* **23(1)** 2-9.
32. Kuhn AT & Wilson AD (1985) The dissolution mechanisms of silicate and glass-ionomer dental cements *Biomaterials* **6(6)** 378-382.
33. Han L, Okamoto A, Fukushima M, & Okiji T (2008) Evaluation of flowable resin composite surfaces eroded by acidic and alcoholic drinks *Dental Materials Journal* **27(3)** 455-465.
34. Lim BS, Ferracane JL, Condon JR, & Adey JD (2002) Effect of filler fraction and filler surface treatment on wear of microfilled composites *Dental Materials* **18(1)** 1-11.
35. Francisconi LF, Honório HM, Rios D, Magalhães AC, Machado MAAM, & Buzalaf MAR (2008) Effect of erosive pH cycling on different restorative materials and on enamel restored with these materials *Operative Dentistry* **33(2)** 203-208.
36. Xu HHK, Weir MD, & Sun L (2009) Calcium and phosphate ion releasing composite: effect of pH on release and mechanical properties *Dental Materials* **25(4)** 535-542.
37. Kooi TJM, Tan QZ, Yap AUJ, Guo W, Tay KJ, & Soh MS (2012) Effects of food-simulating liquids on surface properties of giomer restoratives *Operative Dentistry* **37(6)** 665-671.
38. Yu H, Wegehaupt FJ, Wiegand A, Roos M, Attin T, & Buchalla W (2009) Erosion and abrasion of tooth-colored restorative materials and human enamel *Journal of Dentistry* **37(12)** 913-922.
39. Al Khuraif AAA (2014) An in vitro evaluation of wear and surface roughness of particulate filler composite resin after tooth brushing *Acta Odontologica Scandinavica* **72(8)** 977-983.
40. Teixeira ECN, Thompson JL, Piascik JR, & Thompson JY (2005) In vitro toothbrush-dentifrice abrasion of two restorative composites *Journal of Esthetic and Restorative Dentistry* **17(3)** 172-180.
41. Magalhães AC, Wiegand A, Rios D, Buzalaf MAR, & Lussi A (2011) Fluoride in dental erosion *Monographs in Oral Science* **22** 158-170.
42. Wong L, Cutress TW, & Duncan JF (1987) The influence of incorporated and adsorbed fluoride on the dissolution of powdered and pelletized hydroxyapatite in fluoridated and non-fluoridated acid buffers *Journal of Dental Research* **66(12)** 1735-1741.
43. White DJ, Nelson DGA, & Faller RV (1994) Mode of action of fluoride: application of new techniques and test methods to the examination of the mechanism of action of topical fluoride *Advances in Dental Research* **8(2)** 166-174.
44. Garoushi S, Vallittu PK, & Lassila L (2018) Characterization of fluoride releasing restorative dental materials *Dental Materials Journal* **37(2)** 293-300.
45. Petzold M (2001) The influence of different fluoride compounds and treatment conditions on dental enamel: a descriptive in vitro study of the CaF(2) precipitation and microstructure *Caries Research* **35(Supplement 1)** 45-51.
46. Lussi A & Carvalho TS (2015) The future of fluorides and other protective agents in erosion prevention *Caries Research* **49(1)** 18-29.
47. Cochrane NJ, Cai F, Huq NL, Burrow MF, & Reynolds EC (2010) New approaches to enhanced remineralization of tooth enamel *Journal of Dental Research* **89(11)** 1187-1197.
48. Tiwari S, Kenchappa M, Bhayya D, Gupta S, Saxena S, Satyarth S, Singh A, & Gupta M (2016) Antibacterial activity and fluoride release of glass-ionomer cement, compomer and zirconia reinforced glass-ionomer cement *Journal of Clinical and Diagnostic Research* **10(4)** ZC90-ZC93.
49. Forsten L (1998) Fluoride release and uptake by glass-ionomers and related materials and its clinical effect *Biomaterials* **19(6)** 503-508.
50. Salas CFC, Guglielmi CAB, Raggio DP, & Mendes FM (2011) Mineral loss on adjacent enamel glass ionomer cements restorations after cariogenic and erosive challenges *Archives of Oral Bioliogy* **56(10)** 1014-1019.
51. Bueno LS, Silva RM, Magalhães APR, Navarro MFL, Pascotto RC, Buzalaf MAR, Nicholson JW, Sidhu SK, & Borges AFS (2019) Positive correlation between fluoride release and acid erosion of restorative glass-ionomer cements *Dental Materials* **35(1)** 135-143.
52. Ganss C, Lussi A, & Schlueter N (2014) The histological features and physical properties of eroded dental hard tissues *Monographs in Oral Science* **25** 99-107.
53. Turssi CP, Hara AT, Domiciano SJ, & Serra MC (2008) Study on the potential inhibition of root dentine wear adjacent to fluoride-containing restorations *Journal of Materials Science. Materials in Medicine* **19(1)** 47-51.
54. Scaramucci T, João-Souza SH, Lippert F, Eckert GJ, Aoki I V, & Hara AT (2016) Influence of toothbrushing on the antierosive effect of film-forming agents *Caries Research* **50(2)** 104-110.
55. Scaramucci T, Borges AB, Lippert F, Frank NE, & Hara AT (2013) Sodium fluoride effect on erosion-abrasion under hyposalivatory simulating conditions *Archives of Oral Biology* **58(10)** 1457-1463.
56. Bezerra SJC, João-Souza SH, Aoki IV, Borges AB, Hara AT, & Scaramucci T (2019) Anti-erosive effect of solutions

containing sodium fluoride, stannous chloride, and selected film-forming polymers *Caries Research* **53(3)** 305-313.

57. Yassen GH, Platt JA, & Hara AT (2011) Bovine teeth as substitute for human teeth in dental research: a review of literature *Journal of Oral Science* **53(3)** 273-282.
58. Shellis RP, Ganss C, Ren Y, Zero DT, & Lussi A (2011) Methodology and models in erosion research: discussion and conclusions *Caries Research* **45(Supplement 1)** 69-77.
59. Shabanian M & Richards LC (2002) In vitro wear rates of materials under different loads and varying pH *Journal of Prosthetic Dentistry* **87(6)** 650-656.
60. Attin T, Vataschki M, & Hellwig E (1996) Properties of resin-modified glass-ionomer restorative materials and two polyacid-modified resin composite materials *Quintessence International* **27(3)** 203-209.

©Operative Dentistry, 2020, **45-3,** E124-E140

Do Tooth- and Cavity-related Aspects of Noncarious Cervical Lesions Affect the Retention of Resin Composite Restorations in Adults? A Systematic Review and Meta-analysis

AMO Correia • E Bresciani • AB Borges • DM Pereira • LC Maia • TMF Caneppele

Clinical Relevance

Recognizing the effects related to the teeth and cavities of NCCLs that are relevant to the success of the restoration is important, as clinicians must be aware of them during the procedure and follow-up of the patients.

SUMMARY

Purpose: The purpose was to perform a systematic review and meta-analysis based on the following research question: do tooth- and cavity-related aspects of noncarious cervical lesions (NCCLs) affect the retention of composite restorations?

Methods: Randomized clinical trials (RCTs) that evaluated the retention rate of resin restorations in NCCLs were included for the identification and comparison of their characteristics. The search was conducted in PubMed and adapted for Scopus, Web of Science, Latin

Ayla Macyelle de Oliveira Correia, PhD student, Department of Restorative Dentistry, São Paulo State University (Unesp), Institute of Science and Technology, São José dos Campos, São Paulo, Brazil

Eduardo Bresciani, associate professor, Department of Restorative Dentistry, São Paulo State University (Unesp), Institute of Science and Technology, São José dos Campos, São Paulo, Brazil

Alessanda Buhler Borges, associate professor, Department of Restorative Dentistry, São Paulo State University (Unesp), Institute of Science and Technology, São José dos Campos, São Paulo, Brazil

Daniele Masterson Pereira, librarian, Centro de Ciências da Saúde, Federal University of Rio de Janeiro–UFRJ, Rio de Janeiro, Brazil

Lucianne Cople Maia, professor, Department of Pediatric Dentistry and Orthodontic, Federal University of Rio de Janeiro–UFRJ, Rio de Janeiro, Brazil

*Taciana Marco Ferraz Caneppele, associate professor, Department of Restorative Dentistry, São Paulo State University (Unesp), Institute of Science and Technology, São José dos Campos, São Paulo, Brazil

*Corresponding author: Av Eng Francisco José Longo, 777 Jardim São Dimas, São José dos Campos/SP 12245-000, Brazil; e-mail: taciana.caneppele@unesp.br

https://doi.org/10.2341/19-091-L

American and Caribbean Health Sciences Literature database (LILACS), Brazilian Library in Dentistry (BBO), Cochrane Library, and System for Information on Grey Literature in Europe (SIGLE) without restrictions until July 2018. Unpublished and ongoing trial registries were also searched. The Cochrane Collaboration tool was used for assessing risk of bias. The quality of the evidence was graded using the Grading of Recommendations: Assessment, Development and Evaluation. Using the random effects model, a meta-analysis was conducted for each aspect (arch distribution, tooth location, wear facets, dentin sclerosis, shape, size, depth, occluso-gingival distance, and margin location).

Results: We retrieved 6738 articles. After removal of duplicates and nonrelevant articles, 24 RCTs remained. The anterior tooth location favored the retention rates of restoration of NCCLs (relative risk [RR], 1.08; 95% confidence interval [CI], 1.00-1.16). The presence of wear facets is a risk factor for the retention of restorations (RR, 0.91; 95% CI, 0.83-0.99). The evidence was moderate for arch distribution and low or very low for all other factors because of heterogeneity, imprecision, and inconsistency.

Conclusion: The tooth location and the presence of wear facets can affect the retention of composite resins in NCCLs.

INTRODUCTION

Noncarious cervical lesions (NCCLs) are commonly observed in clinical dental practice and are characterized by the cervical loss of hard dental tissue, with no occurrence of dental caries or trauma. They may be superficial or deep and can present as extensive defects with various shapes.[1] The etiology of NCCLs has been described as multifactorial, resulting from the combination of different processes, including stress (abfraction), friction (abrasion), and biocorrosion (chemical, biochemical, and electrochemical degradation).[2-4] Initially, NCCLs develop in enamel with slow progression into dentin, leading to gradual dentin sclerosis.[1,5] Sclerosis occurs as a response to low intensity and chronic stimuli from physiologic aging, which is a characteristic consistent with the more frequent occurrence of NCCLs in an elderly population.[6-8]

NCCLs are often restored to treat dental hypersensitivity, to improve esthetics, and to prevent further loss of dental tissues.[9,10] However, NCCL restorations have a high index of failure, resulting from loss of retention, secondary caries, marginal discoloration, and marginal adaptation, compromising the longevity of the restorative treatment.[5,11] Problems with NCCL restorations include nonretentive characteristics and the location of lesion margins in dentin or cementum, as well as the presence of dentin sclerosis, which compromises the adhesive process.[10,12-14]

Approaches to improving the clinical performance of NCCL restorations, focusing mainly on restorative materials and dentin substrate treatment, have been described.[1,14-21] Although these findings are promising, cavity geometry (shape and size) has been reported to play an important role in the longevity of NCCL restorations.[5,22-25] Also, dentin sclerosis,[25] tooth location,[26,27] and the presence of wear facets[26] have been reported to be relevant to the retention of NCCL restorations. Others[28,29] have reported that these factors do not influence retention. Therefore, because of the inconsistent results available, a systematic review was conducted with the focused question: Do tooth- and cavity-related aspects of NCCLs affect the retention of resin composite restorations in adults?

METHODS

Protocol and Registration

The study protocol was registered at the PROSPERO database (www.crd.york.ac.uk/PROSPERO) under the number CRD42016039569 and followed the recommendations of the PRISMA statement for reporting the present systematic review.[30]

Eligibility Criteria

The research question was as follows: do tooth- and cavity-related aspects of noncarious cervical lesions affect the retention of resin composite restorations? Randomized clinical trials (RCTs) that evaluated the retention rate (follow-up period of at least two years) of resin composite restorations in participants with NCCLs were included for the identification and comparison of their characteristics. Eligible studies reported one or more of the following factors in relation to restoration retention rate: 1) arch distribution; 2) tooth location; 3) wear facets; 4) dentin sclerosis; 5) shape; 6) size; 7) depth; 8) occluso-gingival distance; and 9) margin location. Non-RCTs, observational studies, case reports, reviews, and *in vitro* studies were excluded.

Table 1: *Electronic Database and Search Strategy (5 December 2016, Updated in July 2018)*

PUBMED
((((((((((((Dental Restoration, Permanent[MeSH Terms]) OR Restoration*[Title/Abstract]) OR Dental Filling*[Title/Abstract]) OR Composite Resins[MeSH Terms]) OR Composite Resin*[Title/Abstract]) OR Resin composite*[Title/Abstract])))))) AND ((((((((((((((((Tooth abrasion[Title/Abstract]) OR Tooth Cervix[MeSH Terms]) OR Cementoenamel Junction*[Title/Abstract]) OR CEJ[Title/Abstract]) OR Tooth Erosion*[Title/Abstract]) OR Dental Erosion[Title/Abstract]) OR Tooth Wear[MeSH Terms]) OR Tooth Wear[Title/Abstract]) OR Cervical lesion*[Title/Abstract]) OR Class V [Title/Abstract]))))
Scopus
TITLE-ABS-KEY (“Tooth abrasion” OR “Tooth Cervix” OR “Cementoenamel Junction” OR CEJ OR “Tooth Erosion” OR “Dental Erosion” OR “Tooth Wear” OR “Dental Wear” OR “Cervical lesion” OR “Class V”) AND (restoration OR “Dental Filling” OR “Composite Resin” OR “Resin composite”) AND (LIMIT-TO (DOCTYPE, “ar”) OR LIMIT-TO (DOCTYPE, “re”)) AND (LIMIT-TO (SUBJAREA, “DENT”))
Web of Science
#1 TS= (“Tooth abrasion” OR “Tooth Cervix” OR “Cementoenamel Junction” OR CEJ OR “Tooth Erosion” OR “Dental Erosion” OR “Tooth Wear” OR “Dental Wear” OR “Cervical lesion” OR “Class V”) #2 TS= (restoration OR “Dental Filling” OR “Composite Resin” OR “Resin composite”) #1 AND #2
LILACS and BBO
(MH:” tooth abrasion” or MH: “Tooth cervix” or MH: “tooth erosion” or “erosão dentária” or MH: “tooth wear” or “desgaste dentário”) and (MH: “Dental Restoration, permanent” or MH: “Composite resins” or “resinas compostas” or compósitos)
Cochrane Library
#1 “Tooth abrasion" #2 MeSH descriptor: [Tooth Cervix] explode all trees #3 “Cementoenamel Junction” or CEJ #4 #2 or #3 #5 “Tooth Erosion" #6 “Cervical lesion” or “cervical lesions” or “Noncarious lesions” or “Class V” or NCCL #7 #1 or #4 or #5 or #6 #8 MeSH descriptor: [Dental Restoration, Permanent] explode all trees #9 Restoration* or “Dental Fillings" #10 #8 or #9 #11 MeSH descriptor: [Composite Resins] explode all trees #12 “Composite Resin” or “Composite Resins” or “Resin composite” or “Resin composites" #13 #11 or #12 #14 #10 or #13 #15 #7 and #14

Information Sources and Search Strategy

To define the search strategy, a preliminary search for studies was conducted using some specific keywords on the characteristics of NCCLs (shape, depth). However, the search did not retrieve relevant results. Therefore, we decided to use terms related to lesions in general and restoration with resin composite. Information on aspects of interest was only determined during the full-text reading of the studies.

The search strategy was conducted using multiple combinations of MeSH terms and free keywords (Table 1). An electronic search was performed in MEDLINE via PubMed, citation databases (Scopus and Web of Science), Latin American and Caribbean Health Sciences Literature database (LILACS), Brazilian Library in Dentistry (BBO), Cochrane Library, and ongoing trial databases, including ClinicalTrials.gov (www.clinicaltrials.gov) and ReBEC (The Brazilian Clinical Trials Registry; www.rebec.gov.br). The non–peer-reviewed literature was searched using the database System for Information on Grey Literature in Europe (SIGLE). Additionally, the reference lists of the included studies were checked to identify possible relevant studies. An expert librarian (DM) supervised the search strategy. No restrictions were placed on the publication date or language. The search strategy was appropriately modified for each database to identify eligible studies.

A “Search Alert” with the search strategy in the PubMed, Scopus, Web of Science databases, and Cochrane Library was created, and the search was updated weekly until July 2018.

Study Selection and Data Collection Process

The studies were selected by title and abstract according to the described search strategy (Table 1). Articles that appeared in more than one database were considered only once. Full-text articles were

also obtained when the title and abstract contained insufficient information for a clear decision. The search in the Cochrane Library retrieved some abstracts from conferences. The authors were contacted for further information about the publication of the entire study. Subsequently, two reviewers classified those that met the inclusion criteria. Each eligible article received a study identification number, which combined the first author name and year of publication.

Relevant information about the study design, participants, number of treated teeth, follow-up time, dropouts, and factors reported were extracted independently using customized extraction forms by two authors (Table 2); in cases of disagreement, a decision was reached by consensus.

When multiple reports of the same study (eg, reports with different follow-up times) were found, the study with the highest long-term follow-up time was included for data extraction. When more than one resin composite or adhesive was included in the study, their values were combined to make a single entry. Three attempts to contact the authors by e-mail were made when data not described in the articles were necessary.

Regarding the retention rate, we collected data from the studies and grouped them according to the factors reported: arch distribution, tooth location, wear facets, dentin sclerosis, shape, size, depth, occluso-gingival distance, and margin location.

Risk of Bias in Individual Studies

Two independent reviewers performed the quality assessment of the included studies using the Cochrane Collaboration tool for assessing risk of bias in randomized trials.[47] During data selection and quality assessment, any disagreements between the reviewers were solved through discussion and, if needed, consultation with a third reviewer (LCM).

The risk of bias of each domain was classified following the recommendations of the Cochrane Handbook for Systematic Reviews of Interventions 5.1.0 (http://handbook.cochrane.org). The criteria for judging risk of bias covers six items: selection bias (sequence generation and allocation concealment), detection bias (blinding of outcome assessment), attrition bias (incomplete outcome data), reporting bias (selective reporting), and other sources of bias.[47] The studies were classified as having low, high, or unclear risk of bias.[47]

Data Synthesis and Statistical Analysis

According to tooth- and cavity-related aspects of NCCLs, the data analyzed were dichotomized, as shown in Table 3. The extracted data were analyzed using the R statistical language R Studio (version 3.4.4; Studio Team, Boston, MA, USA).

Differences observed between the groups were expressed as pooled relative risk (RR), with 95% confidence interval (CI). The retention rate for each tooth- and cavity-related aspect of NCCLs was evaluated with an intention-to-treat protocol. When not reported in the article, the retention rate was calculated according to intention-to-treat. The factor effect on the defined outcome measurement was calculated from the study data using the random-effects model. Statistical heterogeneity of the treatment effects among studies was assessed using the Cochran Q test and the inconsistency I^2 test, in which values greater than 50% were considered indicative of substantial heterogeneity.[47] No subgroup analyses were performed.

Publication Bias

We assessed publication bias using funnel plot techniques and, given the known limitations of these methods, the Egger regression test as appropriate.[52,53]

Certainty of Evidence

The quality of the evidence was graded for each outcome across studies (certainty of evidence) using the Grading of Recommendations: Assessment, Development and Evaluation (GRADE; http://www.gradeworkinggroup.org/) to determine the overall strength of the evidence for each meta-analysis.[52] For RCTs, the GRADE approach addresses five possible reasons (risk of bias, imprecision, inconsistency, indirectness of evidence, and publication bias) to downgrade the quality of the evidence (one or two levels). Each domain was assessed as having no limitation, serious limitations, or very serious limitations to categorize the quality of the evidence as high, moderate, low, or very low. The GRADEpro Guideline Development Tool, available online (https://gradepro.org/), was used to create a Summary of Findings table.

RESULTS

Study Selection

The search in the databases led to 6738 articles (Figure 1). After the removal of duplicates, 3715 results remained. By screening title and abstract, articles not related to the topic of this systematic

Table 2: *Data Extraction From Selected Studies*

Study ID	Evaluation Criteria	Split-Mouth	Number of Subjects	Subjects' Age Mean [range] (y)	Number of Teeth
Abdalla and Sayed 2008[16]	Modified USPHS	Yes	42	n.r. [35-65]	125
Aw and others 2005[31]	Modified USPHS	Yes	57	51 [29-75]	171
Çelik and others 2007[15]	Modified USPHS	No	37	n.r. [29-67]	252
Dall'Orologio and others 2010[32]	Modified USPHS	No	50	46 [30-52]	150
Dall'Orologio and Lorenzi 2014[33]	Modified USPHS	No	50	n.r. [21-66]	150
Fagundes and others 2014[19]	Modified USPHS	No	30	n.r. [18-50]	35
Häfer and others 2015[18]	FDI	Yes	40	46.7 [18-66]	110
Hörsted-Bindslev and others 1996[34]	USPHS	Yes	26	47 [n.r.]	80
Karaman and others 2012[20]	Modified USPHS	Yes	21	60 [48-70]	134
Kubo and others 2006[35]	Modified USPHS	Yes	8	61.3 [45-78]	72
Kubo and others 2010[36]	Modified USPHS	No	22	61.9 [29-78]	98
Loguercio and others 2015[37]	Modified USPHS and FDI	No	39	n.r. [20-n.r.]	200
Oginni and Adelek 2014[26]	Modified USPHS	No	89	46 [29-76]	287
Özgünaltay and Onen 2002[38]	Modified USPHS	Yes	24	n.r. [40-65]	48
Sartori and others 2013[39]	Modified USPHS	Yes	20	46.7 [33-64]	70
Torres and others 2014[40]	Modified USPHS	Yes	30	40.70 [21-60]	138
Tuncer and others 2013[41]	Modified USPHS	No	24	58 [38-73]	123
Tuncer and others 2017[42]	Modified USPHS	Yes	20	58.9 [27-83]	97
van Dijken 2004[43]	Modified USPHS	No	90	58 [46-72]	144
van Dijken 2005[44]	Modified USPHS	Yes	35	58 [34-84]	73
van Dijken 2010[45]	Modified USPHS	Yes	72	60.1 [42-84]	119
van Dijken 2013[17]	Modified USPHS	Yes	67	64.7 [39-84]	169
Van Meerbeek and others 1993[27]	Vanherlemethod	No	35	n.r. [n.r.]	132
Zanatta and others 2019[46]	FDI	No	34	n.r. [21-n.r.]	152

Abbreviations: ER, etch-and-rinse adhesive; FC, flowable compomer; FO: flowable ormocer; ID, identification; n.r., not reported; PAMR, poly-acid modified resin composite; RMGI, resin-modified glass-ionomer adhesive; SE, self-etch adhesive.

Table 2: *Data Extraction From Selected Studies (ext.)*

Study ID	Mechanical Preparation	Adhesive systems/Composite Resin	Follow-up Time (y)	Aspect	Dropouts at Follow-up (%)
Abdalla and Sayed 2008[16]	Dentin walls were roughened	SE/microhybrid	2	Arch distribution; tooth location	15
Aw and others 2005[31]	Enamel beveling (0.5-1 mm)	ER/microhybrid and microfill	3	Arch distribution; tooth location; wear facets; dentin sclerosis; depth	15
Çelik and others 2007[15]	No	ER/FO, FC, flowable and microhybrid	2	Arch distribution; tooth location	31.75
Dall'Orologio and others 2010[32]	Dentin roughening and enamel beveling (1 mm)	SE and ER/microhybrid	7	Dentin sclerosis; depth; margin location	16
Dall'Orologio and Lorenzi 2014[33]	Dentin roughening and enamel beveling (1 mm)	ER/nano-ceramic and microhybrid	8	Dentin sclerosis; shape; margin location	20
Fagundes and others 2014[19]	No	ER/hybrid	7	Arch distribution; tooth location	28.57
Häfer and others 2015[18]	Hypermineralized dentin and the marginal enamel were prepared	SE and ER/nano-hybrid	3	Arch distribution; tooth location; depth	25.45
Hörsted-Bindslev and others 1996[34]	No	ER/hybrid	3	Arch distribution; tooth location	12.5
Karaman and others 2012[20]	No	SE/nano-hybrid	2	Arch distribution; tooth location	0
Kubo and others 2006[35]	Most of the enamel and dentin walls were lightly roughened + enamel beveling (n.r.)	SE and ER/microhybrid	5	Arch distribution; tooth location	0
Kubo and others 2010[36]	Dentin roughening and enamel beveling (1 mm)	SE/flowable and microhybrid	3	Arch distribution; depth; size	0
Loguercio and others 2015[37]	No	SE and ER/nanofilled	3	Arch distribution; tooth location; wear facets; dentin sclerosis; shape; occluso-gingival distance	12.82
Oginni and Adelek 2014[26]	No	ER/microhybrid	2	Arch distribution; tooth location; wear facets	34.14
Özgünaltay and Onen 2002[38]	Enamel beveling (1 mm)	ER/microhybrid	3	Arch distribution	16.67
Sartori and others 2013[39]	n.r.	ER/Nanofilled	3	Tooth location; wear facets; dentin sclerosis; shape; occluso-gingival distance	28.57
Torres and others 2014[40]	n.r.	ER/microfilled	5	Arch distribution; tooth location; wear facets; dentin sclerosis; shape; depth; occluso-gingival distance	23.1
Tuncer and others 2013[41]	No	SE and ER/nanohybrid	2	Arch distribution; tooth location	0
Tuncer and others 2017[42]	No	ER/microhybrid	2	Arch distribution; tooth location	12.37
van Dijken 2004[43]	Part of the lesions were lightly roughened	SE and ER/microhybrid and hybrid	2	Depth; dentin sclerosis	1.4
van Dijken 2005[44]	Part of the lesions were slightly roughened	RMGI/hybrid and PAMR	6	Dentin sclerosis; depth	8.2
van Dijken 2010[45]	Part of the lesions were roughened	SE and ER/hybrid	8	Dentin sclerosis; depth; size	5.88
van Dijken 2013[17]	Lesions were slightly roughened	SE and ER/microhybrid	5	Arch distribution; tooth location; dentin sclerosis; depth; size	5.92
Van Meerbeek and others 1993[27]	Part of the lesions had the bevelled enamel	SE and ER/hybrid	2	Arch distribution; toth location	3.78
Zanatta and others 2019[46]	No	SE and ER/nanofilled	2	Arch distribution; tooth location; dentin sclerosis; occluso-gingival distance	12.5

Table 3: *Dichotomy of Results According to the Evaluation Criteria of the Studies*

Study	Aspect	
	Arch Distribution	
	Maxillary	**Mandibular**
Abdalla and Sayed 2008[16]; Aw and others 2005[31]; Çelik and others 2007[15]; Özgünaltay and Önen 2002[38]	Maxillary	Mandibular
Häfer and others 2015[18]; Karaman and others 2012[20]; Kubo and others 2006[35]; Kubo and others 2010[36]; Oginni and Adelek 2014[26]; Tuncer and others 2013[41]; Tuncer and others 2017[42]; van Dijken 2013[17]	Maxilla	Mandible
Fagundes and others 2014[19]; Hörsted-Bindslev and others 1996[34]	Upper	Lower
	Tooth Location	
	Anterior	**Posterior**
Abdalla and Sayed 2008[16]	Anterior	Premolar
Aw and others 2005[31]	Central incisors; lateral incisors; canines	First premolars; second premolars; first molars
Çelik and others 2007[15]; Karaman and others 2012[20]	Anterior	Posterior
van Dijken 2013[17]	Incisor/cuspidate	Premolar; molar
Fagundes and others 2014[19]; Kubo and others 2006[35]; Van Meerbeek and others 1993[27]	Incisor; canine	Premolar; molar
Oginni and Adelek 2014[26]	Anterior	Premolars; molars
Tuncer and others 2013[41]; Tuncer and others 2017[42]	Anterior (central, lateral and canine)	Posterior (premolar and molar)
	Wear Facets	
	With Wear Facets	**Without Wear facets**
Aw and others 2005[31]	Present	Absent
Oginni and Adeleke 2014[26]	With	Without
	Dentin Sclerosis	
	Dentin Sclerosis	**No Dentin Sclerosis**
Aw and others 2005[31*a*]	Mild; moderate; heavy	None
Zanatta and others 2019[46]; Dall'Orologio and others 2010[32]; Loguercio and others 2015[37]; Sartori and others 2013[39*b*]	2; 3; 4	1
Dall'Orologio and Lorenzi 2014[33]	Moderate; severe	No evidence
van Dijken 2004[43]; van Dijken 2005[44]; van Dijken 2010[45]; van Dijken 2013[17*c*]	<50%; >50%	None
Torres and others 2014[40*d*]	Slightly; moderately; severely	No
	Shape	
	Wedge	**Saucer**
Aw and others 2005[31]	<45; 45-90	90-135; >135
Zanatta and others 2019[46]	<90	90-135; >135
Sartori and others 2013[39]	V shaped	U shaped
	Size	
	Small/Moderate	**Large**
van Dijken 2010[45]	Small; moderate	Deep
van Dijken 2013[17]	Small; medium	Large

review were excluded. Thus, 235 articles were assessed to verify their eligibility. Among them, 211 were excluded for the following reasons: 1) the study did not report factors related to NCCLs; 2) the study did not compare the factors in the results; 3) they were conference meeting abstracts without full-text publication; 4) the study tested resin composite and other material, but the factors related to NCCLs were not presented for each material; 5) the study reported on lesions with the same characteristics; and 6) a study with longer-term follow-up was selected.

Study Characteristics

The characteristics of the 24 selected studies are listed in Table 2. The split-mouth study design was used in most of the studies. The number of

Table 3: *Dichotomy of Results According to the Evaluation Criteria of the Studies (cont.)*

Study	Depth	
	Shallow/Moderate	**Deep**
Aw and others 2005[31]	1-2 mm	2-3; 3-4; >4 mm
Zanatta and others 2019[46]	Flat (1-1.5 mm); medium (1.5-2 mm)	Deep (> 2 mm)
Dall'Orologio and others 2010[32]	1-2 mm	>2 <3; 3 mm
van Dijken 2010[45]	Shallow; moderate	Deep
van Dijken 2013[17]	Superficial; medium	Deep
Häfer and others 2015[18]	Shallow (<1 mm); medium (1-2 mm)	Deep (>2 mm)
Sartori and others 2013[39]	≤1.5 mm	>1.5 mm
	Occluso-gingival Distance	
	Short	**Long**
Aw and others 2005[31]	1-2; 2-3	3-4; >4 mm
Zanatta and others 2019[46]	<1.5; 1.5-2.5 mm	2.6-4; >4 mm
	Margin Location	
	Above/Aligned	**Intrasulcus**
Dall'Orologio and others 2010[32]	>1-2; > 2 mm	Intrasulcus
Dall'Orologio and Lorenzi 2014[33]	Above/aligned	1 mm below

[a] *Scale of Duke and others.*[48]
[b] *According to the criteria described by Swift and others.*[49]
[c] *Scale of Heymann and Bayne.*[50d] *According to the criteria described by Van Landuyt and others.*[51]

participants ranged from 8 to 90, with 35 to 287 treated teeth in these studies. Considerable variability was found in the age of the participants, with ages ranging from about 18 to 84 years old.

Mechanical preparation of the cervical lesions was common. Dentin roughening, removal of sclerotic dentin, enamel beveling, or their combination was reported in more than half of the studies.

Risk of Bias Within Studies

The results of the risk of bias assessment of the 24 included studies are presented in Figures 2 and 3. All the judgments in a cross-tabulation of the study by entry are presented in Figure 2. All the items in four studies were judged as low risk of bias.[33,37,41,46] Figure 3 illustrates the proportion of studies with each of the judgments for each entry. The risk of bias of selective reporting was judged as low, whereas blinding of outcome assessment was judged as unclear. The risk of bias of random sequence generation, allocation concealment, and incomplete outcome data were judged as high; however, the proportion was so small that it would not seriously weaken confidence in the results.

Meta-analysis and Summary of Findings

For the meta-analysis, studies were grouped according to the factors related to NCCLs (Figures 4 and 5). All studies for each tooth- and cavity-related aspect were included, despite their risk of bias. The impact of this decision was evaluated in a sensitivity analysis, where only studies with low risk of bias were included. No change in the overall significance was shown (data not shown).

Arch Distribution—For arch distribution (maxillary vs mandibular), 14 studies were included.[15-20,26,31,34-36,38,41,42] The overall results were RR, 1.01; 95% CI, 0.98-1.05; $I^2 = 23\%$, suggesting that the arch distribution of the NCCL does not affect the success rate of the resin composite restoration (Figure 4A).

Tooth Location—The forest plot of the meta-analysis for tooth location can be seen in Figure 4B. Eleven studies were included.[15-17,19,20,26,27,31,35,41,42] The overall results were RR, 1.08; 95% CI, 1.00-1.16. The heterogeneity was high ($I^2 = 82\%$, $p<0.001$). Therefore, anterior tooth location favors the retention rates of resin restoration of NCCLs by a factor of 1.08.

Wear Facets—For wear facets, only two studies were included.[26,31] The results were RR, 0.91; 95% CI, 0.83-0.099; $I^2 = 0\%$ (Figure 4C). The presence of wear facets is a risk factor for the retention rate of resin composite restorations.

Dentin Sclerosis—For dentin sclerosis (with vs without), 11 studies were included.[17,31-33,37,39,40,43-46] The overall results were RR, 0.99; 95% CI, 0.93-1.05

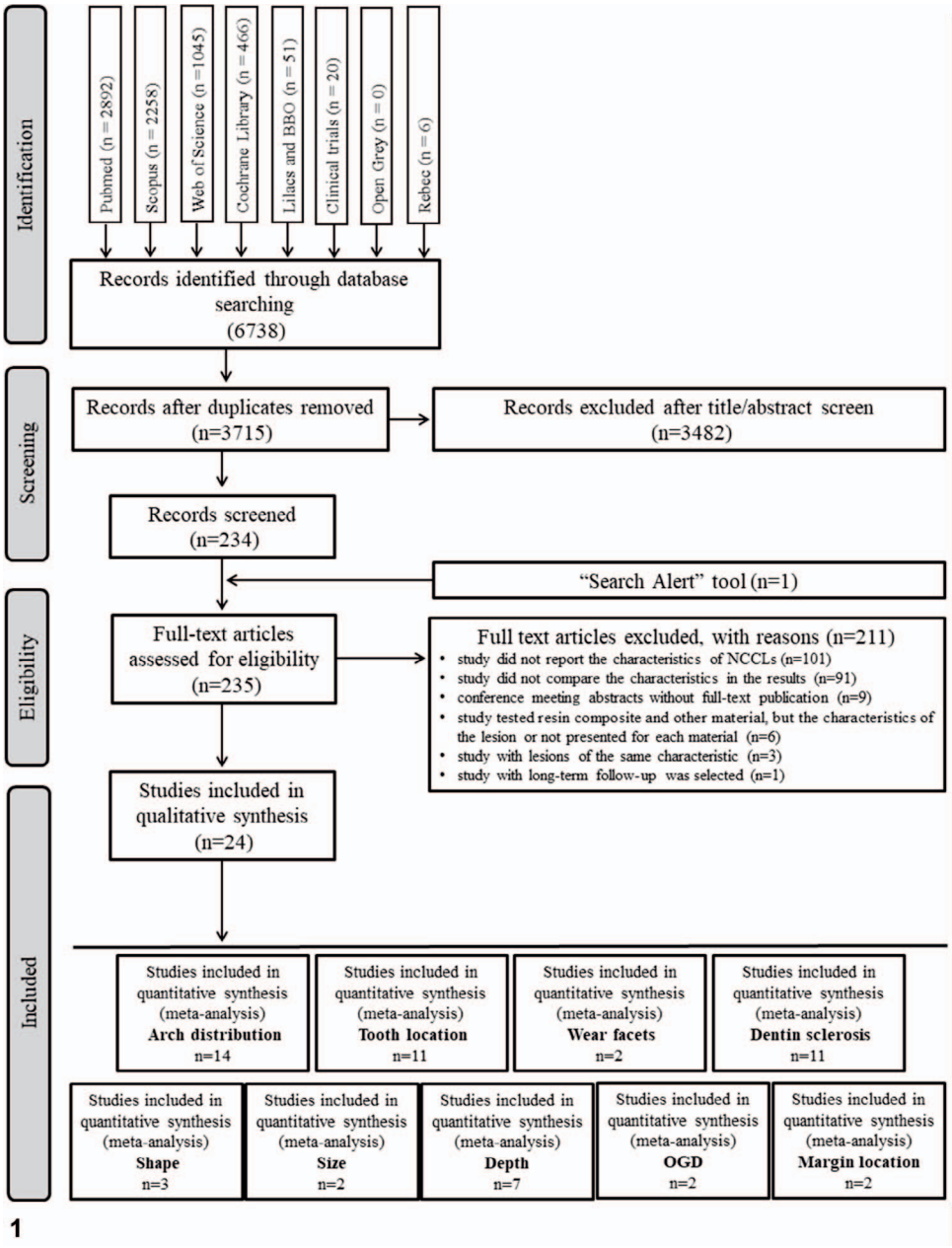


Figure 1. *Flow diagram of the study identification.*

Figure 2. *Risk of bias summary: review authors' judgments about each risk of bias item for each included study.*

(Figure 4D). The heterogeneity was 60%, suggesting dentin sclerosis does not affect the success rate of the resin composite restoration of NCCLs.

Shape—The forest plot of the meta-analysis for shape can be seen in Figure 5A. Three studies were included.[31,39,46] The overall results were RR, 1.03; 95% CI, 0.91-1.18. The heterogeneity was 51% (p=0.13), suggesting the shape of NCCL does not affect the success rate of resin composite restorations.

Size—For the size of lesions, two studies by the same author were included.[17,45] The size of NCCL does not affect the retention rate of the composite restorations (RR, 0.97; 95% CI, 0.88-1.08; I^2 = 0%; p=0.44; Figure 5B).

Depth—For the depth (shallow/moderate vs deep) of NCCL, seven studies were included,[17,18,31,32,39,45,46] and this characteristic does not seem to affect the retention rate of composite

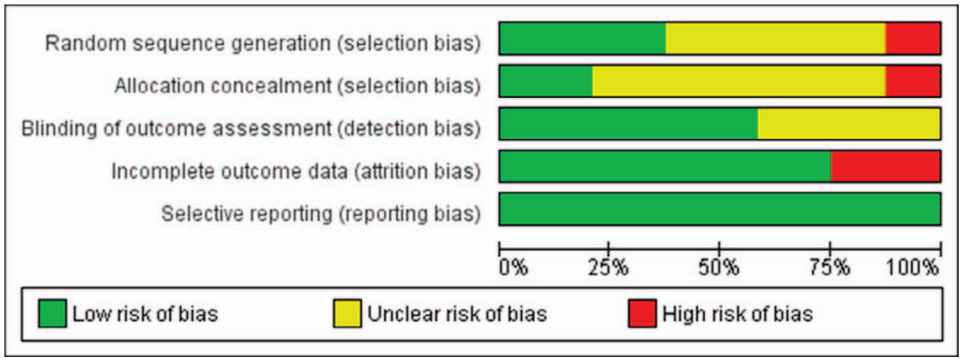


Figure 3. *Risk of bias graph: authors' judgments about each risk of bias item presented as percentages across all included studies.*

restorations (RR, 0.98; 95% CI, 0.92-1.04; I^2 = 0%; Figure 5C).

Occluso-gingival Distance—Two studies[31,46] reported the occluso-gingival distance of lesions and its influence on the retention rate of restorations (Figure 5D). The results of the meta-analysis for this characteristic showed no effect on the retention rate of restorations (RR, 1.03; 95% CI, 0.93-1.13; I^2 = 0%).

Margin Location—For margin location (above/aligned vs intrasulcus), only two studies were included.[32,33] High heterogeneity was detected (I^2=83%; p=0.02). With an RR, 4.14; 95% CI, 0.17-99.76, the margin location of the NCCL did not influence the retention rate of the resin composite restorations (Figure 5E).

Publication Bias

For the factors arch distribution, tooth location, and dentin sclerosis, it was possible to assess publication bias using funnel plot techniques and the Egger regression test. No statistical signs of publication bias (arch distribution: p=0.693; tooth location: p=0.489; dentin sclerosis: p=0.174 Egger) were found; this was confirmed using funnel plot inspection (data not shown). For other characteristics, publication bias was not assessed because there were inadequate numbers of included trials to properly assess with a funnel plot or more advanced regression-based measures.

Grading the Body of Evidence

Table 4 displays a summary of the various aspects used to rate the quality of the evidence according to the GRADE working group.[52]

The indirect evidence was responsible for downgrading the quality of the evidence by one level for all factors related to NCCLs. For some characteristics (wear facets, shape, size, and occluso-gingival distance), the strength of evidence was also downgraded one level due to imprecision (the optimal information size criterion was not met). Moreover, the inconsistency in the data due to high and nonexplained heterogeneity was responsible for downgrading the results for tooth location, dentin sclerosis, shape, depth, and margin location.

DISCUSSION

To the best of our knowledge, this is the first systematic review to synthesize the influence of tooth and cavity-related aspects of NCCLs on the retention rate of resin composite restorations.

The results of the review suggest that the location of the tooth in the dental arch and the presence of wear facets interfere with the retention rate of resin restorations in NCCLs. In contrast, other aspects such as dentin sclerosis, shape, size, depth, occluso-gingival distance, and margin location of the cavity showed no influence on the retention rate. We set out to identify the best clinical evidence available to answer the focused question and performed an extensive search with careful quality assessment. However, as we could not find primary studies that answered our specific research question, we drew indirect conclusions by using randomized clinical trials testing different adhesive approaches for the resin restoration of NCCLs.

This type of lesion may be present in different shapes and sizes and may affect any tooth (anterior or posterior).[1,2,8,54-56] Moreover, they are considered a significant restorative challenge because they are in general nonretentive and the cervical area concentrates high stresses caused by masticatory forces.[10,57-60]

Several clinical trials have attempted to study the longevity of resin restoration of NCCLs. Participants were recruited with different types of NCCLs, and the researchers usually reported the charac-

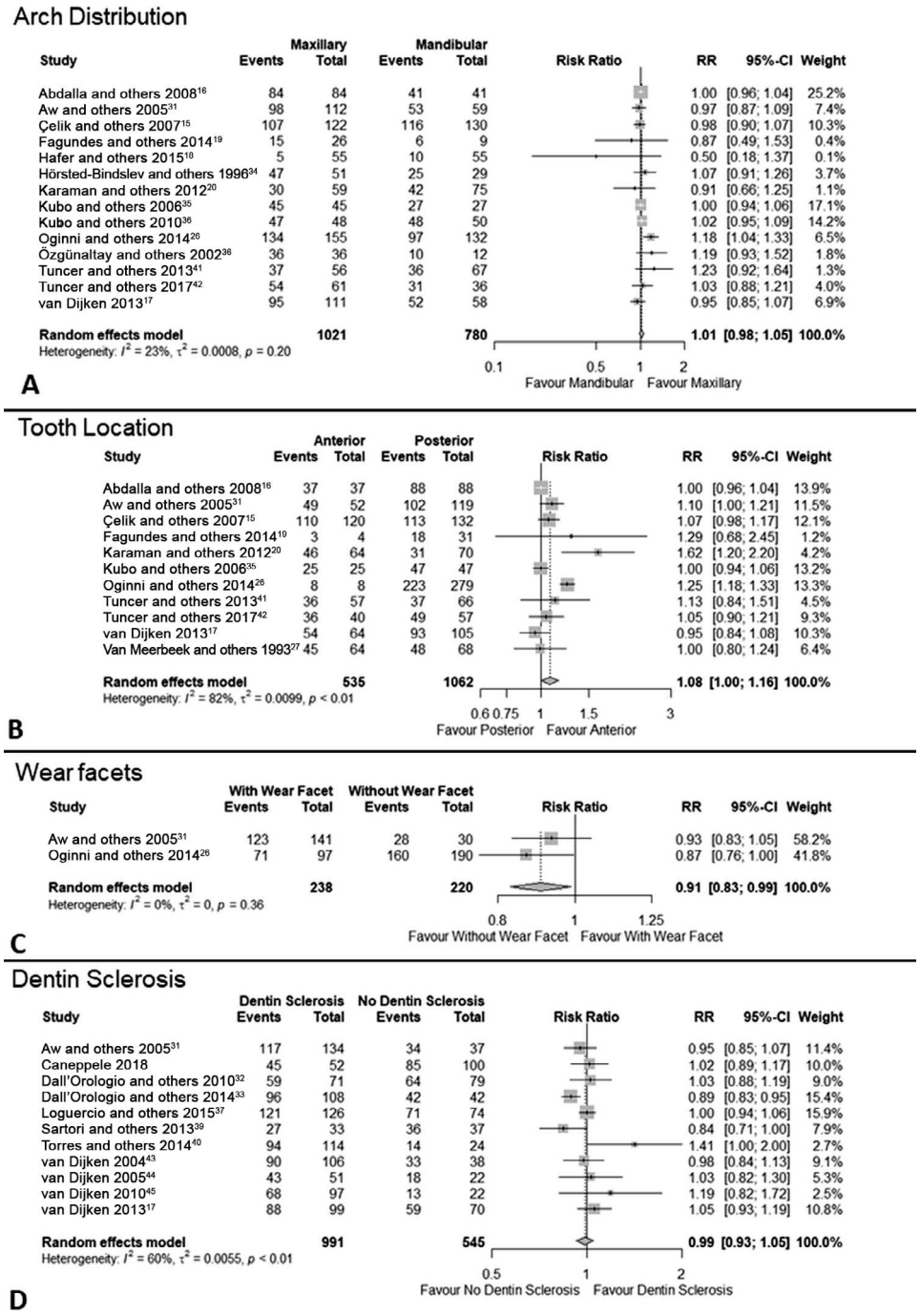


Figure 4. *Meta-analysis considering (A) arch distribution, (B) tooth location, (C) wear facets, and (D) dentin sclerosis.*

teristics of the lesions that would be restored. However, they infrequently related restorative success with the aspect of the lesion. In our search strategy, we found 91 studies that reported the characteristics of the lesions but that did not correlate the success rate with the observed characteristics. Although this would be only a complementary analysis, without statistical power in individual studies, grouping the results in a systematic review such as the current one could provide important findings.

We found only 24 manuscripts that related some aspects with the success rate of the restorations. Although we found reports for nine different aspects, not all included articles reported all of them, making some aspects meta-analyzed with minimal data. In addition, the variability in reporting the character-

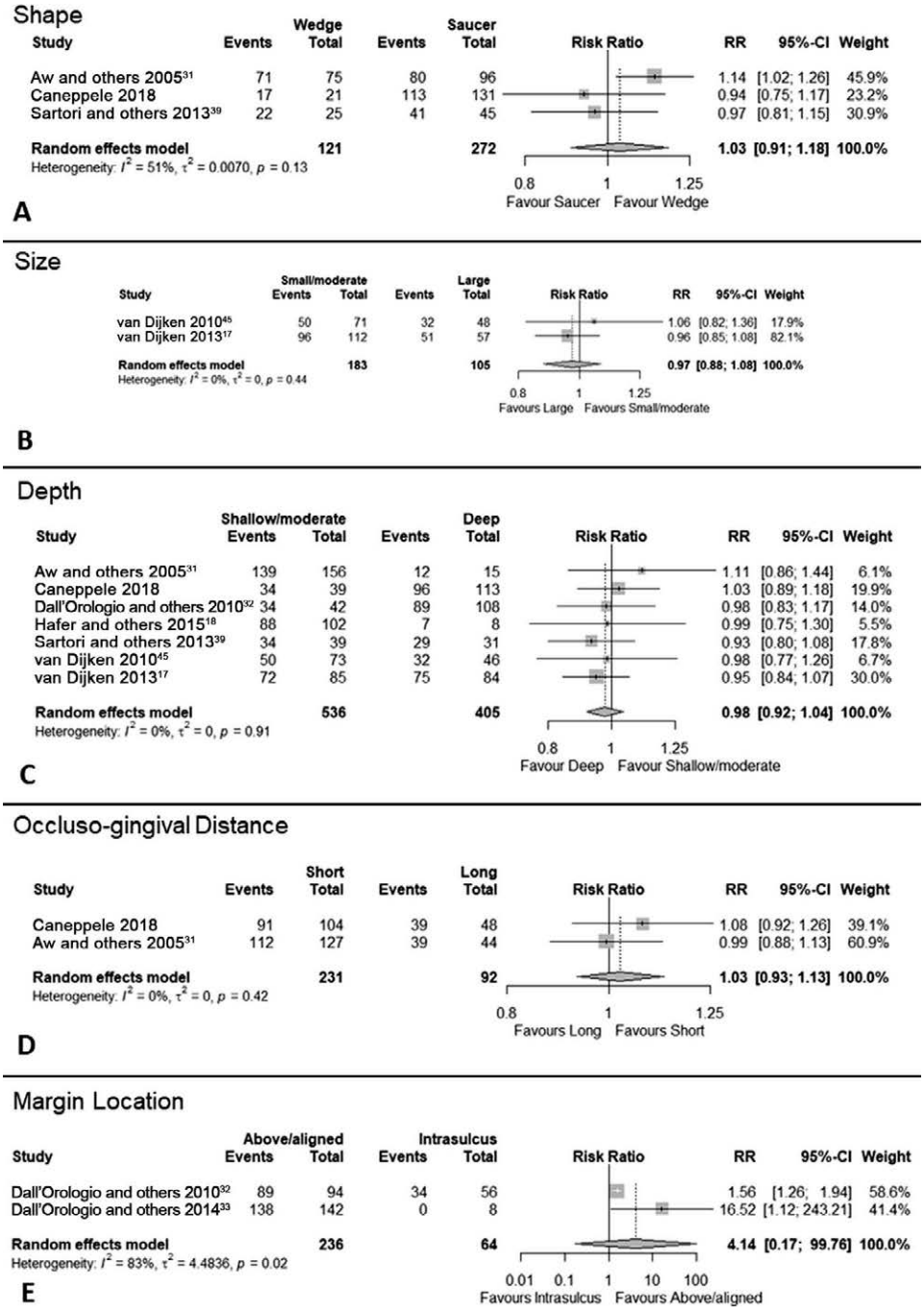


Figure 5. *Meta-analysis considering (A) shape, (B) size, (C) depth, (D) occluso-gingival distance, and (E) margin location.*

istics made it difficult to group the data, and, as a result, the information was dichotomized to allow the meta-analysis. Some aspects already had a dichotomous nature, such as arch distribution (maxillary vs mandibular), tooth location (anterior vs posterior), wear facets (with vs without). However, other characteristics had more than two data possibilities, and for that, we created cutoff points to dichotomize and group the studies (Table 3).

A critical point to be considered in this systematic review is that the findings were derived from indirect evidence. The primary objective of the included studies was to compare different adhesive strategies or different resin composites for NCCL restoration, and this may have contributed to the heterogeneity found in some meta-analyses. An important factor that influences retention of NCCL restoration is the kind of adhesive system (etch &

Table 4: *Summary of Finding and Quality of the Evidence*

Factor	Anticipated Absolute Effects[a] (95% CI)		Relative Effect, RR (95% CI)	No. of Participants (Studies)	Certainty of the Evidence (GRADE)[b]
Arch distribution	Mandibular	Maxillary	1.01 (0.98-1.05)	1801 (14 RCTs)	⊕⊕⊕○ Moderate[c]
	76 per 100	77 per 100 (75 to 80)			
Tooth location	Posterior	Anterior	1.08 (1.00-1.16)	1597 (11 RCTs)	⊕⊕○○ Low[c,d]
	80 per 100	86 per 100 (80 to 93)			
Wear facet	Without wear facet	With wear facet	0.91 (0.83-0.99)	458 (2 RCTs)	⊕⊕○○ Low[c,e]
	85 per 100	78 per 100 (71 to 85)			
Dentin sclerosis	No dentin sclerosis	Dentin sclerosis	0.99 (0.93-1.05)	1536 (11 RCTs)	⊕⊕○○ Low[c,d]
	86 per 100	85 per 100 (80 to 90)			
Shape	Saucer	Wedge	1.03 (0.91-1.18)	393 (3 RCTs)	⊕○○○ Very low[c,d,e]
	86 per 100	89 per 100 (78 to 100)			
Size	Large	Small/moderate	0.97 (0.88-1.08)	288 (2 RCTs)	⊕⊕○○ Low[c,e]
	79 per 100	77 per 100 (70 to 85)			
Depth	Deep	Shallow/moderate	0.98 (0.92-1.04)	941 (7 RCTs)	⊕⊕○○ Low[c,d]
	84 per 100	82 per 100 (77 to 87)			
Occluso-gingival distance	Long	Short	1.03 (0.93-1.13)	323 (2 RCTs)	⊕⊕○○ Low[c,e]
	85 per 100	87 per 100 (79 to 96)			
Margin location	Intrasulcus	Above/aligned	4.14 (0.17-99.76)	300 (2 RCTs)	⊕⊕○○ Low[c,d]
	53 per 100	100 per 100 (9 to 100)			

[a] *The risk in the intervention group (and its 95% CI) is based on the assumed risk in the comparison group and the relative effect of the intervention (and its 95% CI).*
[b] *GRADE Working Group guidelines for evidence.*
High certainty: We are very confident that the true effect lies close to that of the estimate of the effect.
Moderate certainty: We are moderately confident in the effect estimate: the true effect is likely to be close to the estimate of the effect, but there is a possibility that it is substantially different.
Low certainty: Our confidence in the effect estimate is limited: The true effect may be substantially different from the estimate of the effect.
Very low certainty: We have very little confidence in the effect estimate: the true effect is likely to be substantially different from the estimate of effect.
[c] *Indirect evidence (the main objectives of the included studies were not compare the characteristics of the lesions and relate it with the success rate of the restorations.*
[d] *Inconsistency in the data due to high and non-explained heterogeneity.*
[e] *The optimal information size criterion was not met.*

rinse or self-etch) used. However, due to the small number of included studies, the results of this study could not be controlled for this confounder. This limits the external validity and generalizability of findings.

In the analysis of risk of bias using the Cochrane tool,[47] some studies were categorized as high risk of bias in the selection bias domains. Although this domain is fundamental for the analysis of the RCTs, for this study, we do not consider it to be of primary importance, because the groups compared in the meta-analysis were not those being randomized.

Some studies[8,60-62] showed a higher prevalence of NCCLs in maxillary teeth. Those teeth seem more prone to NCCLs, possibly due to their lingual inclination.[8] In our study, 14 studies were included, totaling 1021 restored teeth in the maxilla vs 780 restored teeth in the mandible. Although the distribution in the arch influenced the development of NCCLs, this factor did not seem to affect the restorative success of these lesions.

Regarding the tooth location in the arch, posterior teeth are more likely to present NCCLs, possibly because occlusal and nonaxial forces are exerted on that group of teeth.[8] The referred forces could also stress the adhesive area, decreasing the longevity of the adhesive restorations, because from this meta-analysis, we found an RR of 1.08, favoring the success rate of restoration in anterior teeth. However, the meta-analysis of these data showed high heterogeneity; thus, the results should be considered with caution. Then, the quality of the evidence was downgraded due to the inconsistency.

The presence of wear facets also influenced restorative success and is strongly related to the development of NCCLs.[26,57,63-65] In a three-dimensional finite element model, some authors observed in malocclusion scenarios that tensile stresses generated on the cervical areas were higher compared with stresses generated under normal occlusion conditions, those possibly being capable of producing NCCLs.[7] Moreover, in patients with untreated malocclusion, restoration success might also be affected, because the stress in the cervical

area could be higher than the adhesive resistance of the restorations, possibly leading to restoration displacement. Therefore, the treatment of these lesions should go beyond their restoration, because if the causes of lesions persist, premature failure of the restoration might ensue.[66] The meta-analysis of this characteristic included only two articles, and despite the low heterogeneity, the quality of the evidence was downgraded as the Optimal Information Size (OIS) criterion was not met, that is, only a very small sample supported the evidence.

Different classifications for the shape of the lesions have been reported, with some formats relating to more specific causes of lesions.[2,3,8,54-56,67] The studies included in this meta-analysis used different methods to classify the format of the lesions, which may have contributed to the heterogeneity of the data. We dichotomized in wedge and saucer formats and used an internal angle of 90° as the division between the two formats. The wedge format may be more related to occlusal stress, and, considering that occlusal stress indirectly observed on the wear facets influenced restorative success, one might suppose similar observations would be detected for the present characteristics; however, the influence of cavity format was not observed to influence restoration success. The quality of this evidence was considered very low because, in addition to the indirectness of evidence and the inconsistency (due to high heterogeneity), the reduced number of articles included with a small sample size meant the OIS criterion was not met.

As the development of NCCLs tends to be a slow and chronic process, dentin sclerosis is commonly found on the surface of the lesions.[1,5,8] Secondary dentin, the occlusion of open dentinal tubules, pulpal retreat, and other tooth protective measures slowly take place in the presence of noxious stimuli, thereby minimizing clinical symptoms and maintaining pulpal integrity. As for the shape characteristic, the different criteria for and methods of measuring dentin sclerosis are fraught with subjectivity and susceptible to inter- and intraexaminer variation with regard to features such as discoloration, smoothness, and translucency. In restorative procedures, sclerotic dentin is a substrate that can lead to adhesion difficulties, because, with some types of adhesives, hypermineralization can prevent the formation of a hybrid layer.[10,68] In this meta-analysis, there was great variability in the types of adhesives studied, which might have contributed to the high heterogeneity and lack of influence of this characteristic on restorative success.

The characteristics of size, depth, and occluso-gingival distance are all related to the dimension of the lesion. To allow the grouping of studies, we dichotomized some points. All these characteristics were shown not to affect restorative success. Evidence was downgraded to low for the three characteristics.

Only two articles reported the margin location and related it to restorative success. The high heterogeneity found allowed a wide confidence interval, overlapping the no effect line of this characteristic in restorative success. Despite the greater difficulty in isolating the operative field for subgingival lesions, this seems not to affect restorative success.[66,69,70]

To minimize bias, we followed the guidelines provided in the Cochrane Handbook for Systematic Reviews of Interventions.[47] However, our findings and interpretations are limited by the quality and quantity of the available indirect evidence on the effects of tooth- and cavity-related aspects of NCCLs on the success rate of resin restorations. We assessed the risk of bias of the included trials by using the published data, which ultimately may not reflect the actual situation and may lead to publication bias. Also, to minimize publication bias, we did not restrict our search to the English language. For three aspects, we were able to evaluate publication bias by inspecting funnel plots and the Egger analysis, and no problem was detected. However, publication bias could not be determined for other studied aspects, as there was an insufficient number of studies to allow this inspection through a funnel plot. This would reflect on any conclusions drawn from this review.

A knowledge of tooth- and cavity-related aspects of NCCLs that could affect restorative success could help clinicians understand the prognosis of restorations. For future research, investigators are encouraged to collect information from RCTs regarding the tooth- and cavity-related aspects of NCCLs and relate them to success rates. In addition, future RCTs should follow the CONSORT guidelines to improve evidence quality and transparency in reporting.[71]

CONCLUSION

The results of the meta-analysis suggest that NCCLs restored in anterior teeth are more likely to succeed than in posterior teeth. The presence of wear facets can reduce the retention rate of resin restoration in NCCLs. Arch distribution, dentin sclerosis, shape, size, depth, occluso-gingival distance, and margin

location did not affect the restorative success of resin restorations. However, the quality of evidence of the outcomes ranged from moderate to very low.

Acknowledgements

The authors thank CAPES (Coordination of Training of Higher Education Graduate) for the first author's scholarship and the following authors who kindly provided information not available in their full texts: G D Dall'Orologio, F Fazzi, and R Lorenzi. This study was supported by Grant 2016/14429-7, São Paulo Research Foundation (FAPESP).

Conflict of Interest

The authors of this manuscript certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

(Accepted 28 August 2019)

References

1. Stojanac IL, Premovic MT, Ramic BD, Drobac MR, Stojsin IM, & Petrovic LM (2013) Noncarious cervical lesions restored with three different tooth-colored materials: two-year results *Operative Dentistry* **38(1)** 12-20.
2. Walter C, Kress E, Götz H, Taylor K, Willershausen I, & Zampelis A (2014) The anatomy of non-carious cervical lesions *Clinical Oral Investigations* **18(1)** 139-146.
3. Grippo JO, Simring M, & Coleman TA (2012) Abfraction, abrasion, biocorrosion, and the enigma of noncarious cervical lesions: a 20-year perspective *Journal of Esthetic and Restorative Dentistry* **24(1)** 10-23.
4. Michael JA, Townsend GC, Greenwood LF, & Kaidonis JA (2009) Abfraction: separating fact from fiction *Australian Dental Journal* **54(1)** 2-8.
5. Kubo S, Yokota H, Yokota H, & Hayashi Y (2013) Challenges to the clinical placement and evaluation of adhesively-bonded, cervical composite restorations *Dental Materials* **29(1)** 10-27.
6. Que K, Guo B, Jia Z, Chen Z, Yang J, & Gao P (2013) A cross-sectional study: non-carious cervical lesions, cervical dentine hypersensitivity and related risk factors *Journal of Oral Rehabilitation* **40(1)** 24-32.
7. Borcic J, Anic I, Urek MM, & Ferreri S (2004) The prevalence of non-carious cervical lesions in permanent dentition *Journal of Oral Rehabilitation* **31(2)** 117-123.
8. Aw TC, Lepe X, Johnson GH, & Mancl L (2002) Characteristics of noncarious cervical lesions: a clinical investigation *Journal of the American Dental Association* **133(6)** 725-733.
9. Perez CR, Gonzalez MR, Prado NAS, de Miranda MSF, Macêdo MA, & Fernandes BMP (2012) Restoration of noncarious cervical lesions: when, why, and how *International Journal of Dentistry* **2012** 1-8.
10. Tay FR & Pashley DH (2004) Resin bonding to cervical sclerotic dentin: a review *Journal of Dentistry* **32(3)** 173-196.
11. Peumans M, Kanumilli P, De Munck J, Van Landuyt K, Lambrechts P, & Van Meerbeek B (2005) Clinical effectiveness of contemporary adhesives: a systematic review of current clinical trials *Dental Materials* **21(9)** 864-881.
12. Peumans M, De Munck J, Mine A, & Van Meerbeek B (2014) Clinical effectiveness of contemporary adhesives for the restoration of non-carious cervical lesions. A systematic review *Dental Materials* **30(10)** 1089-1103.
13. Santos MJ, Ari N, Steele S, Costella J, & Banting D (2014) Retention of tooth-colored restorations in non-carious cervical lesions: a systematic review *Clinical Oral Investigations* **18(5)** 1369-1381.
14. Luque-Martinez IV, Mena-Serrano A, Muñoz MA, Hass V, Reis A, & Loguercio AD (2013) Effect of bur roughness on bond to sclerotic dentin with self-etch adhesive systems *Operative Dentistry* **38(1)** 39-47.
15. Çelik Ç, Özgünaltay G, & Attar N (2007) Clinical evaluation of flowable resins in non-carious cervical lesions: two-year results *Operative Dentistry* **32(4)** 313-321.
16. Abdalla AI & El Sayed HY (2008) Clinical evaluation of a self-etch adhesive in non-carious cervical lesions *American Journal of Dentistry* **21(5)** 327-330.
17. van Dijken JW (2013) A randomized controlled 5-year prospective study of two HEMA-free adhesives, a 1-step self etching and a 3-step etch-and-rinse, in non-carious cervical lesions *Dental Materials* **29(11)** e271-280.
18. Häfer M, Jentsch H, Haak R, & Schneider H (2015) A three-year clinical evaluation of a one-step self-etch and a two-step etch-and-rinse adhesive in non-carious cervical lesions *Journal of Dentistry* **43(3)** 350-361.
19. Fagundes TC, Barata TJE, Bresciani E, Santiago SL, Franco EB, Lauris JRP, & Navarro MF (2014) Seven-year clinical performance of resin composite versus resin-modified glass ionomer restorations in noncarious cervical lesions *Operative Dentistry* **39(6)** 578-587.
20. Karaman E, Yazici AR, Ozgunaltay G, & Dayangac B (2012) Clinical evaluation of a nanohybrid and a flowable resin composite in non-carious cervical lesions: 24-month results *Journal of Adhesive Dentistry* **14(5)** 485-492.
21. Rocha AC, Da Rosa W, Cocco AR, Da Silva AF, Piva E, & Lund RG (2018) Influence of surface treatment on composite adhesion in noncarious cervical lesions: systematic review and meta-analysis *Operative Dentistry* **43(5)** 508-519.
22. Borges ALS, Borges AB, Xavier TA, Bottino MC, & Platt JA (2014) Impact of quantity of resin, c-factor, and geometry on resin composite polymerization shrinkage stress in class V restorations *Operative Dentistry* **39(2)** 144-151.
23. Eliguzeloglu E, Eraslan O, Omurlu H, Eskitascioglu G, & Belli S (2011) The effect of cavity shape and hybrid layer on the stress distribution of cervical composite restorations *European Journal of Dentistry* **5(2)**180-185.
24. Braga RR, Boaro LCC, Kuroe T, Azevedo CLN, & Singer JM (2006) Influence of cavity dimensions and their derivatives (volume and "C" factor) on shrinkage stress

development and microleakage of composite restorations *Dental Materials* **22(9)** 818-823.

25. Van Meerbeek B, Perdigão J, Lambrechts P, & Vanherle G (1998) The clinical performance of adhesives *Journal of Dentistry* **26(1)** 1-20.
26. Oginni AO & Adeleke AA (2014) Comparison of pattern of failure of resin composite restorations in non-carious cervical lesions with and without occlusal wear facets *Journal of Dentistry* **42(7)** 824-830.
27. Van Meerbeek B, Braem M, Lambrechts P, & Vanherle G (1993) Two-year clinical evaluation of two systems in cervical lesions *Journal of Dentistry* **21(4)** 195-202.
28. Peumans M, De Munck J, Van Landuyt KL, Poitevin A, Lambrechts P, & Van Meerbeek B (2010) Eight-year clinical evaluation of a 2-step self-etch adhesive with and without selective enamel etching *Dental Materials* **26(12)** 1176-1184.
29. Peumans M, De Munck J, Van Landuyt KL, Kanumilli P, Yoshida Y, Inoue S, Lambrechts P, & Van Meerbeek B (2007) Restoring cervical lesions with flexible composites *Dental Materials* **23(6)** 749-754.
30. Liberati A, Altman DG, Tetzlaff J, Mulrow C, Gøtzsche PC, Ioannidis JPA, Clarke M, Devereaux PJ, Kleijnen J, & Moher D (2009) The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate healthcare interventions: explanation and elaboration *BMJ* **339** b2700.
31. Aw TC, Lepe X, Johnson GH, & Mancl LA (2005) A three-year clinical evaluation of two-bottle versus one-bottle dentin adhesives *Journal of the American Dental Association* **136(3)** 311-322.
32. Dall'Orologio GD, Fazzi F, & Lorenzi R (2010) Restoration of cervical lesions: 7-year results of a RCT *Journal of Dental Research* **89(Special Issue B)** 688.
33. Dall'Orologio GD & Lorenzi R (2014) Restorations in abrasion/erosion cervical lesions: 8-year results of a triple blind randomized controlled trial *American Journal of Dentistry* **27(5)** 245-250.
34. Hörsted-Bindslev P, Knudsen J, & Baelum V (1996) 3-year clinical evaluation of modified Gluma adhesive systems in cervical abrasion/erosion lesions *American Journal of Dentistry* **9(1)** 22-26.
35. Kubo S, Kawasaki K, Yokota H, & Hayashi Y (2006) Five-year clinical evaluation of two adhesive systems in non-carious cervical lesions *Journal of Dentistry* **34(2)** 97-105.
36. Kubo S, Yokota H, Yokota H, & Hayashi Y (2010) Three-year clinical evaluation of a flowable and a hybrid resin composite in non-carious cervical lesions *Journal of Dentistry* **38(3)** 191-200.
37. Loguercio AD, de Paula EA, Hass V, Luque-Martinez I, Reis A, & Perdigão J (2015) A new universal simplified adhesive: 36-month randomized double-blind clinical trial *Journal of Dentistry* **43(9)** 1083-1092.
38. Özcgünaltay G & Onen A (2002) Three-year clinical evaluation of a resin modified glass–ionomer cement and a composite resin in non-carious class V lesions *Journal Oral Rehabilitation* **29(11)** 1037-1041.
39. Sartori N, Stolf SC, Silva SB, Lopes GC, & Carrilho M (2013) Influence of chlorhexidine digluconate on the clinical performance of adhesive restorations: a 3-year follow-up *Journal of Dentistry* **41(12)** 1188-1195.
40. Torres CRG, Barcellos DC, Batista GR, Pucci CR, Antunes MJ, de La Cruz DB, & Borges AB (2014) Five-year clinical performance of the dentine deproteinization technique in non-carious cervical lesions *Journal of Dentistry* **42(7)** 816-823.
41. Tuncer D, Yazici AR, Özgünaltay G, & Dayangac B (2013) Clinical evaluation of different adhesives used in the restoration of non-carious cervical lesions: 24-month results *Australian Dental Journal* **58(1)** 94-100.
42. Tuncer D, Çelik C, Yamanel K, & Arhun N (2017) Clinical evaluation of microhybrid composites in noncarious cervical lesions: 24-month results. *Nigerian Journal of Clinical Practice* **20(2)** 176-181.
43. van Dijken JW (2004) Durability of three simplified adhesive systems in Class V non-carious cervical dentin lesions *American Journal of Dentistry* **17(1)** 27-32.
44. van Dijken JW (2005) Retention of a resin-modified glass ionomer adhesive in non-carious cervical lesions. A 6-year follow-up *Journal of Dentistry* **33(7)** 541-547.
45. van Dijken JW (2010) A prospective 8-year evaluation of a mild two-step self-etching adhesive and a heavily filled two-step etch-and-rinse system in non-carious cervical lesions *Dental Materials* **26(9)** 940-946.
46. Zanatta RF, Silva TM, Esper M, Bresciani E, Gonçalves S, & Caneppele T (2019) Bonding performance of simplified adhesive systems in noncarious cervical lesions at 2-year follow-up: a double-blind randomized clinical trial *Operative Dentistry* **44(5)** 476-487.
47. Higgins JP, Altman DG, Gøtzsche PC, Jüni P, Moher D, Oxman AD, Savovic J, Schulz KF, Weeks L, Sterne JA, Cochrane Bias Methods Group, & Cochrane Statistical Methods Group (2011) The Cochrane Collaboration's tool for assessing risk of bias in randomised trials *BMJ* **343** d5928.
48. Duke ES, & Lindemuth J (1991) Variability of clinical dentin substrates *American Journal of Dentistry* **4(5)** 241-246.
49. Swift EJ Jr., Perdigão J, Heymann HO, Wilder AD Jr., Bayne SC, May KN Jr., Sturdevant JR, & Roberson TM (2001) Eighteen-month clinical evaluation of a filled and unfilled dentin adhesive *Journal of Dentistry* **29 (1)** 1-6.
50. Heymann HO, & Bayne SC (1993) Current concepts in dentin bonding *Journal of the American Dental Association* **124(5)** 26-36.
51. Van Landuyt KL, Peumans M, Fieuws S, De Munck J, Cardoso MV, Ermis RB, Lambrechts P, & Van Meerbeek B (2008) A randomized controlled clinical trial of a HEMA-free all-in-one adhesive in non-carious cervical lesions at 1 year *Journal of Dentistry* **36(10)** 847-55.
52. Guyatt G, Oxman AD, Akl EA, Kunz R, Vist G, Brozek J, Norris S, Falck-Ytter Y, Glasziou P, Debeer H, Jaeschke R, Rind D, Meerpohl J, Dahm P, & Schünemann HJ (2011) GRADE guidelines: 1. introduction: GRADE evidence profiles and summary of findings tables *Journal of Clinical Epidemiology* **64(4)** 383-394.

53. Egger M & Smith GD (1998) Bias in location and selection of studies *BMJ* **316(7124)** 61-66.
54. Hur B, Kim HC, Park JK, & Versluis A (2011) Characteristics of non-carious cervical lesions: an *ex vivo* study using micro computed tomography *Journal Oral Rehabilitation* **38(6)** 469-474.
55. Michael JA, Kaidonis JA, & Townsend GC (2010) Non-carious cervical lesions on permanent anterior teeth: a new morphological classification *Australian Dental Journal* **55(2)** 134-137.
56. Sugita I, Nakashima S, Ikeda A, Burrow MF, Nikaido T, Kubo S, Tagami J, & Sumi Y (2017) A pilot study to assess the morphology and progression of non-carious cervical lesions *Journal of Dentistry* **57** 51-56.
57. Brandini DA, Trevisan CL, Panzarini SR, & Pedrini D (2012) Clinical evaluation of the association between noncarious cervical lesions and occlusal forces *Journal of Prosthetic Dentistry* **108(5)** 298-303.
58. Rees JS (2002) The effect of variation in occlusal loading on the development of abfraction lesions: a finite element study *Journal Oral Rehabilitation* **29(2)** 188-193.
59. Soares PV, Machado AC, Zeola LF, Souza PG, Galvão AM, Montes TC, Pereira AG, Reis BR, Coleman TA, & Grippo JO (2015) Loading and composite restoration assessment of various non-carious cervical lesions morphologies: 3D finite element analysis *Australian Dental Journal* **60(3)** 309-316.
60. Teixeira DNR, Zeola LF, Machado AC, Gomes RR, Souza PG, Mendes DC, & Soares PV (2018) Relationship between noncarious cervical lesions, cervical dentin hypersensitivity, gingival recession, and associated risk factors: a cross-sectional study *Journal of Dentistry* **76** 93-97.
61. Lussi A, Schaffner M, Hotz P, & Suter P (1991) Dental erosion in a population of Swiss adults *Community Dentistry and Oral Epidemiology* **19(5)** 286-290.
62. Mayhew RB, Jessee SA, & Martin RE (1998) Association of occlusal, periodontal, and dietary factors with the presence of non-carious cervical dental lesions *American Journal of Dentistry* **11(1)** 29-32.
63. Pegoraro LF, Scolaro JM, Conti PC, Telles D, & Pegoraro TA (2005) Noncarious cervical lesions in adults: prevalence and occlusal aspects *Journal of the American Dental Association* **136(12)** 1694-1700.
64. Takehara J, Takano T, Akhter R, & Morita M (2008) Correlations of noncarious cervical lesions and occlusal factors determined by using pressure-detecting sheet *Journal of Dentistry* **36(10)** 774-779.
65. Telles D, Pegoraro LF, & Pereira JC (2006) Incidence of noncarious cervical lesions and their relation to the presence of wear facets *Journal of Esthetic and Restorative Dentistry* **18(4)** 178-183.
66. Ichim I, Schmidlin PR, Kieser JA, & Swain MV (2007) Mechanical evaluation of cervical glass-ionomer restorations: 3D finite element study *Journal of Dentistry* **35(1)** 28-35.
67. Igarashi Y, Yoshida S, & Kanazawa E (2017) The prevalence and morphological types of non-carious cervical lesions (NCCL) in a contemporary sample of people *Odontology* **105(4)** 443-452.
68. Lopes GC, Vieira LC, Araújo E, Bruggmann T, Zucco J, & Oliveira G (2011) Effect of dentin age and acid etching time on dentin bonding *Journal of Adhesive Dentistry* **13(2)** 139-145.
69. Daudt E, Lopes GC, & Vieira LC (2013) Does operatory field isolation influence the performance of direct adhesive restorations? *Journal of Adhesive Dentistry* **15(1)** 27-32.
70. Loguercio AD, Luque-Martinez I, Lisboa AH, Higashi C, Queiroz VA, Rego RO, & Reis A (2015) Influence of isolation method of the operative field on gingival damage, patients' preference, and restoration retention in noncarious cervical lesions *Operative Dentistry* **40(6)** 581-593.
71. Schulz KF, Altman DG, Moher D, & CONSORT Group (2011) CONSORT 2010 statement: updated guidelines for reporting parallel group randomised trials *International Journal of Surgery* **9(8)** 672-677.

©Operative Dentistry, 2020, **45-3,** E141-E155

Effect of Curing Light and Exposure Time on the Polymerization of Bulk-Fill Resin-Based Composites in Molar Teeth

CAK Shimokawa • ML Turbino • M Giannini • RR Braga • RB Price

Clinical Relevance

Light curing a molar bulk-fill mesio-occluso-distal restoration from a single position at the center of the occlusal surface may result in inadequate photopolymerization of the resin-based composite at the bottom of the proximal boxes.

SUMMARY

Objectives: This study examined the influence of different light-curing units (LCUs) and exposure times on the microhardness across bulk-fill resin-based composite (RBC) restorations in a molar tooth.

Methods and Materials: Tip diameter, radiant power, radiant exitance, emission spectra, and light beam profile were measured on two single-emission-peak LCUs (Celalux 3 and DeepCure-S) and two multiple-peak LCUs (Bluephase 20i and Valo Grand). A mold was made using a human molar that had a 12-mm mesial-distal length, a 2.5-mm deep occlusal box, and two 4.5-mm deep proximal boxes. Two bulk-fill RBCs (Filtek Bulk Fill Posterior and Tetric EvoCeram Bulk Fill) were photoactivated for 10 seconds and for 20 seconds, with the light guide positioned at the center of the occlusal surface. Microhardness was then measured across the transverse surface of the restorations. The light that reached the bottom of the proximal boxes was examined. Data were statistically analyzed with the Student *t*-test, two-way analysis of variance, and the Tukey *post hoc* test (α=0.05).

Results: The four LCUs were different regarding all the tested characteristics. Even when using LCUs with wide tips and a homogeneous beam profile, there were significant differences in the microhardness results obtained at the

*Carlos Alberto Kenji Shimokawa, postdoctoral researcher, Restorative Dentistry, School of Dentistry, University of São Paulo, São Paulo, Brazil

Míriam Lacalle Turbino, full professor, Restorative Dentistry, School of Dentistry, University of São Paulo, São Paulo, Brazil

Marcelo Giannini, associate professor, Restorative Dentistry, Piracicaba Dental School, State University of Campinas, Piracicaba, Brazil

Roberto Ruggiero Braga, full professor, Biomaterials and Oral Biology, School of Dentistry, University of São Paulo, São Paulo, Brazil

Richard Bengt Price, professor, Dental Clinical Sciences, Faculty of Dentistry, Dalhousie University, Halifax, Nova Scotia, Canada

*Corresponding author: Avenida Professor Lineu Prestes, 2227, São Paulo, São Paulo 05508-000, Brazil; e-mail: carlos.shimokawa@usp.br

https://doi.org/10.2341/19-126-L

central and proximal regions of the RBCs ($p<0.05$). LCUs with wider tips used for 20 seconds produced higher microhardness values ($p<0.05$). The multiple-peak LCUs produced greater hardness values in Tetric EvoCeram Bulk Fill than did the single-emission-peak LCUs (Celalux 3 and DeepCure-S). Results for the light measured at the bottom of proximal boxes showed that little light reached these regions when the light tip was positioned at the center of restorations.

Conclusions: Curing lights with wide tips, homogeneous light beam profiles, and longer exposure times are preferred when light-curing large MOD restorations. Light curing from more than one position may be required for adequate photopolymerization.

INTRODUCTION

The manufacturers of light-cured bulk-fill resin-based composites (RBCs) advocate that their RBCs can be adequately light-cured in just one increment that may be up to 5 mm thick, thus saving time and potentially reducing defects and porosity within the bulk of the restoration. Consequently, bulk-fill RBCs have gained in popularity, and some studies have already reported that bulk-fill RBCs have both adequate depth of cure and mechanical properties.[1-5] Satisfactory clinical performance has been reported after six years when each 4-mm-thick increment of one brand of flowable bulk filled composite was light-cured for 20 seconds, and the occlusal parts of Class I and II restorations were covered with a conventional resin composite material.[6] However, bulk curing from just one position may be inadequate when extensive restorations are photoactivated using a small light tip because some regions of the restorations that are not covered by the light tip may show reduced polymerization.

There are many light-curing units (LCUs) available for dentists to use. These LCUs have different tip diameters, they deliver different radiant powers, radiant exitance, emission spectra, and have different light beam profiles.[7-9] Even if the LCU tip covers the entire restoration, the resin polymerization may be adversely affected if the light is not uniformly emitted across the light tip, since some regions of the restoration may receive insufficient light and some regions may receive very high irradiance values.[10,11] Thus, the light-curing of extensive bulk-fill RBC restorations in molar teeth from just one position should be evaluated.

The exposure time is a critical factor that influences the polymerization of RBC restorations.[12] Longer exposure times should improve the polymerization and ultimately reduce the effects of any light beam inhomogeneity. Different RBCs are also available, and factors regarding their composition, shade, thickness, and translucency can all influence their interaction with the light from the LCU.[13] Also, depending on the photoinitiators that are present within the RBCs, the photopolymerization of the RBC will be affected by the emission spectra from the LCU.[14,15]

The mold used when fabricating the specimens for *in vitro* tests has a substantial effect on the polymerization of RBCs.[16,17] The International Organization for Standardization (ISO) has an international standard for testing depth of cure of dental polymer-based materials, but this standard uses a 4-mm-diameter metal mold that does not reproduce how bulk-fill RBCs are used clinically.[18] Ideally, a mold that closely simulates clinical situations should be used, but there exists a significant heterogeneity regarding different methods used to test the depth of cure of bulk-fill RBCs.[4]

The aim of this study was to examine the influence of the tip diameter, radiant power, radiant exitance, emission spectrum, light beam profile, and two different exposure times (10 and 20 seconds) from four different LCUs on the curing profile of mesio-occluso-distal (MOD) restorations made from two different bulk-fill RBCs light-cured in a human molar tooth. The null hypotheses of this study were the following:

1) The characteristics of the LCUs will not influence the curing profile of the bulk-fill RBC restorations.
2) A longer exposure time will not influence the curing profile of bulk-fill RBC restorations.

In addition, the effect of light guide position on the light reaching the bottom of the proximal boxes was assessed.

METHODS AND MATERIALS

Four light-emitting-diode (LED) LCUs from major manufacturers were used: Bluephase 20i (Ivoclar Vivadent, Schaan, Liechtenstein), Celalux 3 (VOCO, Cuxhaven, Germany), Elipar DeepCure-S (3M Oral Care, St Paul, MN, USA), and Valo Grand (Ultradent Products Inc, South Jordan, UT, USA) (Table 1). These LCUs were used to photoactivate two bulk-fill RBCs: one that uses only camphorquinone (CQ)

Table 1: *Light-Curing units, measured external tip diameter (mm), measured effective tip diameter (mm), mean ± standard deviation of the radiant power results (mW), mean ± standard deviation of the calculated radiant exitance results (mW/cm^2), and mean ± standard deviation of the calculated radiant exposure results (J/cm^2) for a 10-second exposure (mean ± standard deviation of calculated radiant exposure results for a 20-second exposure (J/cm^2) also reported;* n = *5 repeats made for radiant power measurements)*

Light-Curing Unit (Serial Number)	External Tip Diameter (mm)	Effective Tip Diameter (mm)	Mean Radiant Power (mW)	Mean Radiant Exitance (mW/cm^2)	Mean Radiant Exposure, 10 s (J/cm^2)	Mean Radiant Exposure, 20 s (J/cm^2)
Bluephase 20i (P626170S548780)	8.0	7.2	570.0 ± 2.7	1399.9 ± 6.6	14.0 ± 0.1	28.0 ± 0.1
Celalux 3 (1637091)	8.0	7.1	432.4 ± 4.4	1092.1 ± 11.2	10.9 ± 0.1	21.8 ± 0.2
Elipar DeepCure-S (933112-001111)	9.8	9.0	792.9 ± 4.5	1246.3 ± 7.1	12.5 ± 0.1	24.9 ± 0.1
Valo Grand (MFG3277-5)	15.0	11.6	1007.6 ± 13.0	953.4 ± 12.2	9.5 ± 0.1	19.1 ± 0.2

as photoinitiator (Filtek Bulk Fill Posterior Restorative, shade A2, 3M Oral Care) and one that contains CQ plus an additional photoinitiator (Ivocerin)[14] (Tetric EvoCeram Bulk Fill, shade IVA, Ivoclar Vivadent).

Characterization of the LCUs

The tip diameter, radiant power, radiant exitance, emission spectrum, and light beam profile of the LCUs were examined, as previously described.[19] In summary, the effective internal tip diameter from where the light was emitted was measured with a digital caliper (Mitutoyo, Kawasaki, Japan). The radiant power and the emission spectra of the LCUs were measured with a six-inch integrating sphere (Labsphere, North Sutton, NH, USA) coupled to a fiber-optic spectrometer USB-4000 (Ocean Optics, Dunedin, IL, USA) with the tip 2-mm away from the entrance of the sphere (n=5 measurements). The radiant exitance was calculated as the quotient of the radiant power and the effective tip area. The light beam profile of the LCUs was assessed with a Laser Beam Profiler (Ophir Spiricon, Logan, UT, USA), at a 2-mm distance from a 40-degree holographic screen. The two-dimension (2D) Flatness Top-Hat results for the four LCUs were calculated by the BeamGage software (Ophir Spiricon) according to the formula $Fn_{(Z)} = E_n/E_{max}$, where E_n is the effective average power of the light beam and E_{max} is the peak power in the light beam.[20] The threshold power/energy density was set to a value of 0 to ensure that all of the light emitted by the LCU was used in the Top-Hat calculations. Data were exported to OriginPro 2017 software (OriginLab, Northampton, MA, USA) to produce scaled images of the light that reached the top surface of the RBC specimens when the LCU tip was 2-mm away from the RBC. The distribution of the light across its tip surface was examined both with and without a 400 ± 5-nm narrow bandpass filter (#65-132, Edmund Industrial Optics, Barrington, NJ, USA) to verify the distribution of just the violet portion of the light (~400 nm) across the tip compared to all of the light from the LCU.

Tooth Mold and Specimen Preparation

After receiving Dalhousie University research ethics board approval to collect and use human teeth (#2015-3632), a human mandibular first molar that was 12-mm in mesio-distal length was used to make the mold for the specimens (Figure 1). The tooth cusps were ground flat, and the tooth was embedded in autocuring acrylic resin. Then, the tooth was cut into three slices in the mesio-distal direction. The central slice was 2-mm wide in the bucco-lingual direction and had the acrylic resin removed up to the cemento-enamel junction to expose the clinical crown. An impression of the external contour of the tooth at the central slice was taken with vinyl polysiloxane (VPS) Extrude XP Heavy Body (Kerr Corp, Orange, CA, USA) that was used later as a guide so that all the specimens would be made to the same external contour (Figure 1a). The central tooth slice received a MOD preparation that was 12-mm mesio-distal width, 2-mm bucco-lingual width, 2.5-mm occlusal box depth, and 4.5-mm proximal box depth (Figure 1b). Then, the three slices were clamped together with a 0.14-mm-thick microscope cover glass (Globe Scientific Inc, Paramus, NJ, USA) between each slice. The mold was then filled with the RBCs, and a jig was used to place the specimens in the same position under the tip of the LCU. The RBC was then photoactivated for either 10 or 20 seconds with the LCU fixed with the tip positioned at the center of the restoration and 2-mm away from the top surface of the RBC (Figure 1c). After photoactivation, specimens were removed from the mold, the cover glass slips were removed, and the specimens were stored in the dark for 24 hours in air at 37°C before hardness testing.

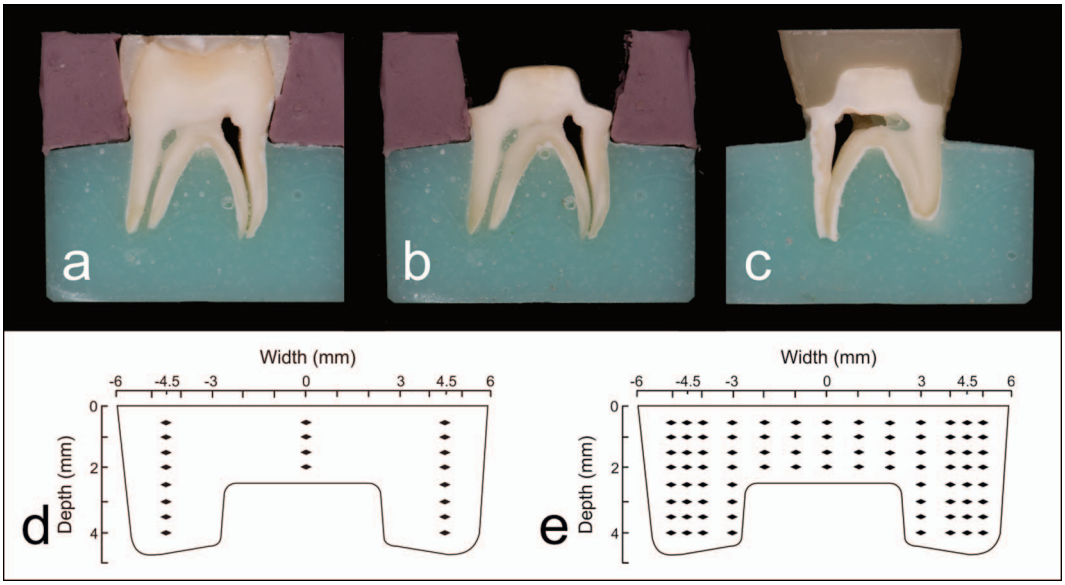


Figure 1. *Molar human tooth mold and indentation scheme. (a): Impression taken with vinyl polysiloxane to guide the anatomical contour of the restorations. (b): MOD preparation with the guide in position. (c): Restoration made using the mold. (d): Indentation scheme used for the low-resolution hardness maps. (e): Indentation scheme used for the high-resolution hardness maps.*

Microhardness Measurements

The Knoop microhardness of the transverse surface of the specimens was measured every 0.5 mm in depth at three positions: center, mesial, and distal (4.5 mm away from the center) for a total of 20 indents per specimen (four at the center and eight at each proximal position; Figure 1d). To avoid damaging the specimens, a load of 15 gf was applied for eight seconds (HMV123 microhardness tester, Mitutoyo). In addition, high-resolution microhardness maps were produced using the indentation scheme shown in Figure 1e (where a total of 84 indents were made per specimen). Two specimens for each RBC and LCU were used for that purpose, and the results were averaged. One transverse surface of the central slice was analyzed per specimen, and this surface was standardized.

Light Transmission Through the Specimen

To evaluate the light transmitted through the RBC to the bottom of the proximal boxes, a second mold was made using another human molar. The tooth had its cusps ground flat, and a MOD restoration was made in this tooth. The tooth was then embedded in opaque acrylic resin up to the restoration surface, and its cervical region was ground away to reach the bottom of the proximal boxes of each resin restoration. The specimen was then positioned in the beam profiler to measure the light that reached down through the RBC to the bottom of the proximal boxes when the light tip was 2 mm away from the surface in three positions over the restoration (center, mesial, and distal).

Statistical Analysis

The Kolmogorov-Smirnov test was applied to verify the normal distribution of hardness data. Then, two-way repeated measures analysis of variance and Tukey *post hoc* tests were used (α=0.05). The two different RBCs and exposure times were analyzed separately. Also, means of the shallower depths (0.5, 1.0, 1.5, and 2.0 mm) were used to compare the central region and both proximal boxes of the RBC. The Student *t*-test was used to compare the effects of the two exposure times (α=0.05). Light transmission through the specimens was visually analyzed but was not subjected to statistical analysis.

RESULTS

The characterization results of the four LCUs are shown in Table 1. The LCUs varied regarding their effective tip diameters: The Valo Grand had the widest tip (Ø 11.6 mm, area 105.7 mm^2), and Celalux 3 had the narrowest tip (Ø 7.1 mm, area 39.6 mm^2). The Valo Grand delivered the lowest radiant exitance (953 mW/cm^2), and Bluephase 20i delivered the highest radiant exitance (1400 mW/cm^2). The Celalux 3 and Elipar DeepCure-S delivered an emission spectrum that had a single peak, while Bluephase 20i and Valo Grand delivered an emission spectrum with multiple wavelength peaks (Figure 2). Regarding the light beam profile, Celalux 3

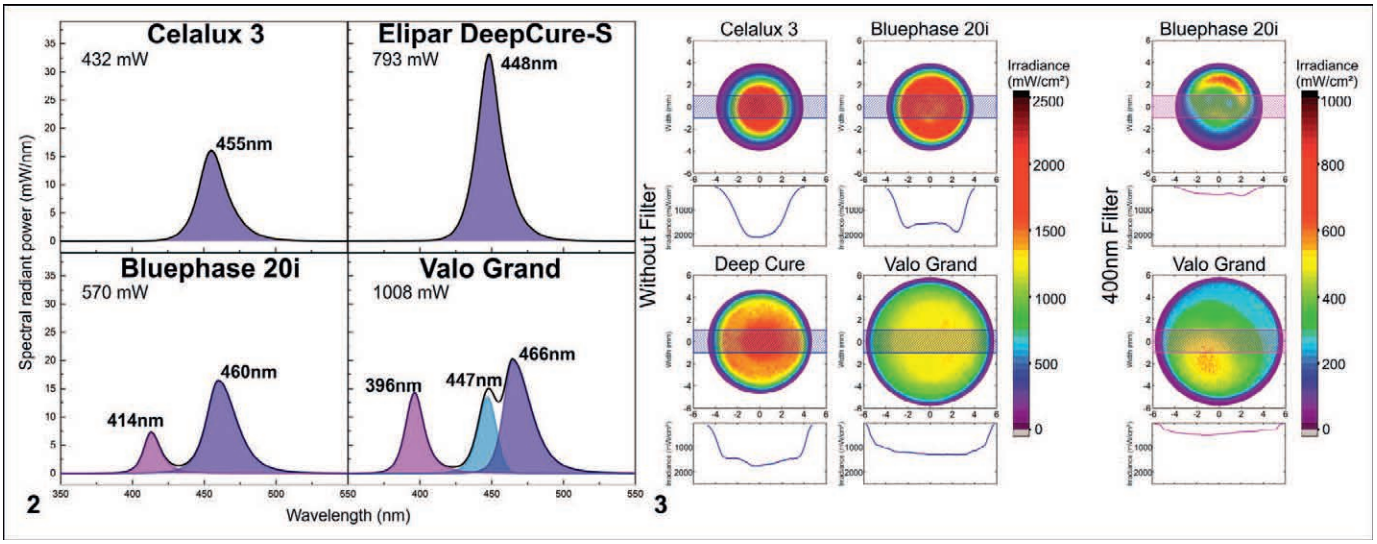


Figure 2. *Emission spectrum of the light-curing units. Violet areas (below 425 nm) represent the wavelengths of violet light, while blue areas (above 425 nm) represent the wavelengths of blue light.*

Figure 3. *Light beam profile of the light-curing units measured at a 2-mm distance from the screen. The beam profile of the light that adequately covered the restorations was evaluated without filter (blue lines) and with a 400-nm filter (violet lines on the right side) to show the violet light only.*

delivered an inhomogeneous beam, with most of the radiant exitance concentrated in a 4-mm region at the center of the light tip, while Valo Grand delivered a more homogeneous beam profile that was evenly distributed across the 11.6-mm tip (Figure 3). The Flatness Top-Hat results of the light beam from each LCU from worst to best were: Celalux 3: 0.380; Bluephase 20i: 0.547; Elipar DeepCure-S: 0.600; and Valo Grand: 0.675.

Tables 2 and 3 show that even when using LCUs that had wide tips and homogeneous beam profiles, such as Deep Cure and Valo Grand, there was a difference between the microhardness values measured in the first 2 mm of the occlusal and the proximal boxes of the restorations ($p<0.05$). The microhardness maps also illustrate these differences, with the center of the specimen displaying more red or yellow color (higher hardness), while the proximal boxes had more green or blue colors, indicating lower hardness values (Figure 4).

The use of an increased exposure time (20 seconds) always produced greater hardness values ($p<0.05$) for both RBCs. As the exposure time increased, the hardness maps became more uniform, as illustrated by the improved color uniformity (Figure 4). Table 4 shows that, overall, when photoactivated for 10 seconds with the different LCUs positioned at the center of the restorations, the Filtek Bulk Fill Posterior specimens were not significantly different ($p\geq0.05$). When the exposure time was increased to 20 seconds, the Deep Cure and Valo Grand LCUs that both had wider tips, produced greater hardness values (Table 5).

When using the 10-second exposure time, the Valo Grand produced the highest hardness values ($p<0.05$) on the specimens of Tetric EvoCeram Bulk

Table 2: *Overall Means ± Standard Deviations of the Knoop microhardness values to a depth of 2 mm, measured in the central, mesial (4.5 mm from the center), and distal (4.5 mm from the center) regions of the specimens made with Filtek Bulk Fill Posterior (each exposure time analyzed separately)*[a]

Light-Curing Unit	10-s Exposure			20-s Exposure		
	Mesial	Central	Distal	Mesial	Central	Distal
Bluephase 20i	42.3 ± 3.3 Bb	53.2 ± 0.1 Aa	31.1 ± 1.9 Cc	46.6 ± 0.2 Bb	54.0 ± 0.4 Ba	45.0 ± 0.2 Bc
Celalux 3	37.3 ± 1.5 Cb	52.0 ± 1.8 Aa	30.6 ± 1.6 Cc	46.6 ± 0.2 Bb	54.3 ± 0.3 Ba	45.5 ± 0.4 Bb
DeepCure-S	48.0 ± 1.4 Ab	54.1 ± 1.0 Aa	39.6 ± 1.4 Bc	53.3 ± 0.6 Ab	56.5 ± 0.5 Aa	50.8 ± 0.2 Ac
Valo Grand	48.6 ± 0.8 Ab	52.4 ± 1.6 Aa	44.3 ± 2.0 Ac	54.0 ± 0.5 Ab	57.3 ± 0.4 Aa	52.1 ± 0.6 Ac

[a] *Different uppercase letters indicate statistical differences within columns (light curing units); different lowercase letters indicate statistical differences within rows ($p<0.05$). N = 5 repeats.*

Table 3: *Overall Means ± Standard Deviations of the Knoop Microhardness Values to a depth of 2 mm, measured in the central, mesial (4.5 mm from the center), and distal (4.5 mm from the center) regions of the specimens made with Tetric Evoceram Bulk Fill (each exposure time analyzed separately)*[a]

Light-Curing Unit	10-s Exposure			20-s Exposure		
	Mesial	Central	Distal	Mesial	Central	Distal
Bluephase 20i	32.4 ± 1.6 Bb	42.5 ± 0.9 Ba	26.7 ± 2.2 Bc	34.2 ± 1.5 Cb	45.5 ± 0.5 Ba	32.5 ± 1.6 Cc
Celalux 3	24.7 ± 1.7 Cb	38.8 ± 1.2 Ca	20.4 ± 1.2 Cc	31.7 ± 1.0 Db	40.2 ± 0.6 Ca	30.6 ± 0.6 Db
DeepCure-S	33.0 ± 0.5 Bb	39.1 ± 0.8 Ca	27.5 ± 0.6 Bc	40.3 ± 0.8 Bb	44.4 ± 0.7 Ba	36.6 ± 1.2 Bc
Valo Grand	40.9 ± 1.3 Ab	45.9 ± 1.7 Aa	36.9 ± 1.9 Ac	45.5 ± 0.5 Ab	49.8 ± 0.7 Aa	45.6 ± 1.1 Ab

[a] *Different uppercase letters indicate statistical differences within columns (light curing units); different lowercase letters indicate statistical differences within rows ($p<0.05$). N = 5 repeats.*

Fill followed by the Bluephase 20i, and no significant difference was found between Celalux 3 and Deep Cure-S (Table 6). When the exposure time was increased to 20 seconds, the Valo Grand still produced the highest hardness results, followed by Deep Cure, Bluephase 20i, and Celalux 3. At the 1.5- and 2.0-mm depths, the specimens photocured using Valo Grand reached the highest hardness values, and there was no difference between the Bluephase 20i and Deep Cure. The Celalux 3 produced the lowest Knoop hardness values (Table 7).

The light transmission results show that even when the wide tip diameter of the Valo Grand was placed at the center of the 12-mm wide restoration, very little light reached down to the bottom of the 4-mm deep proximal boxes. When the tip of the LCUs

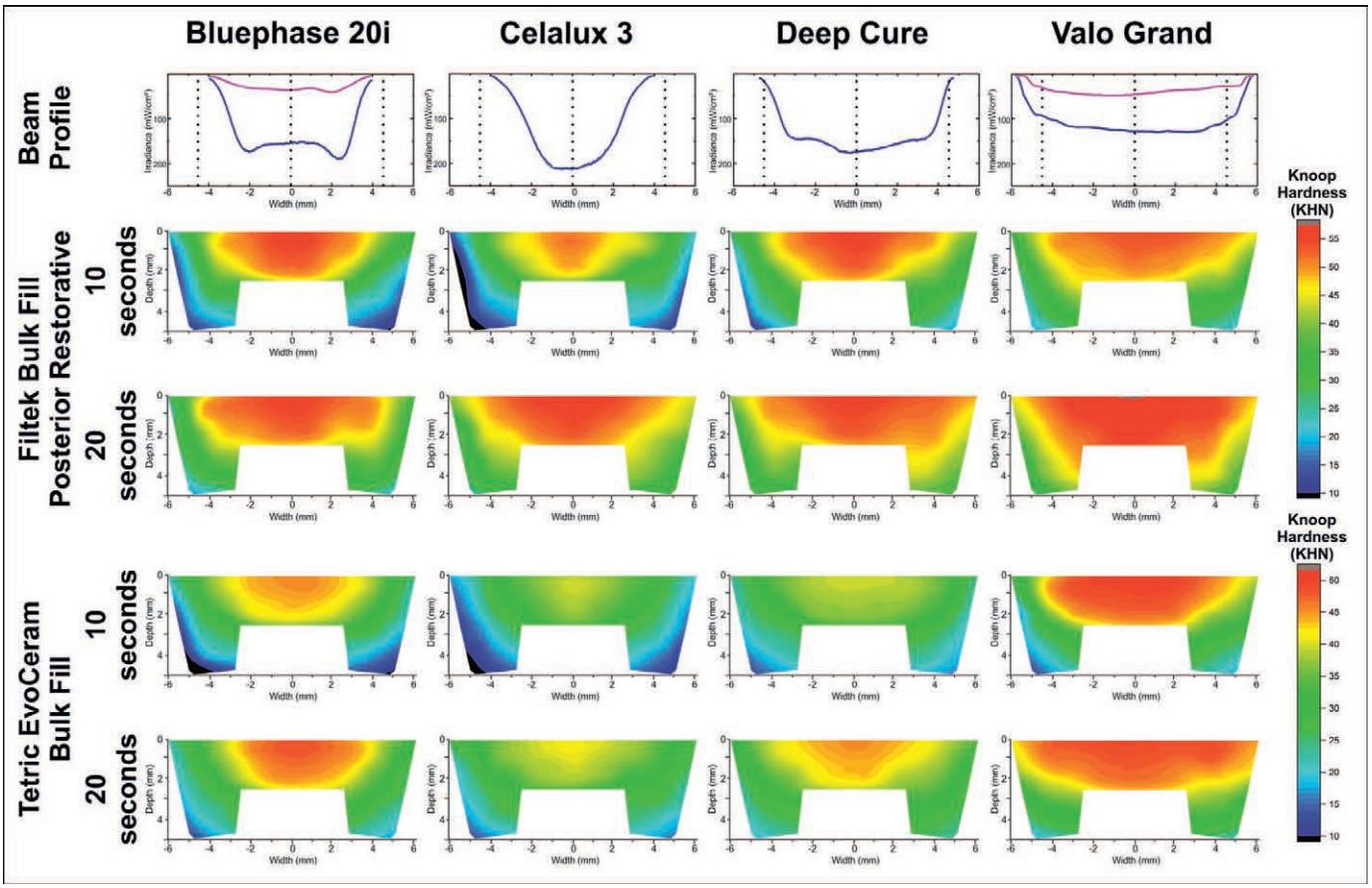


Figure 4. *Hardness maps made for both resin-based composites (RBCs) and both exposure times compared to the profile of the light that covered the restorations. Dotted lines over the beam profile of the lights represent the regions (central, mesial, and distal) where the indentations of the microhardness tests were made in the RBC specimens. The violet lines in the beam profile images indicate the violet light emission (<425 nm), and the blue lines indicate the blue light emission across the light tip.*

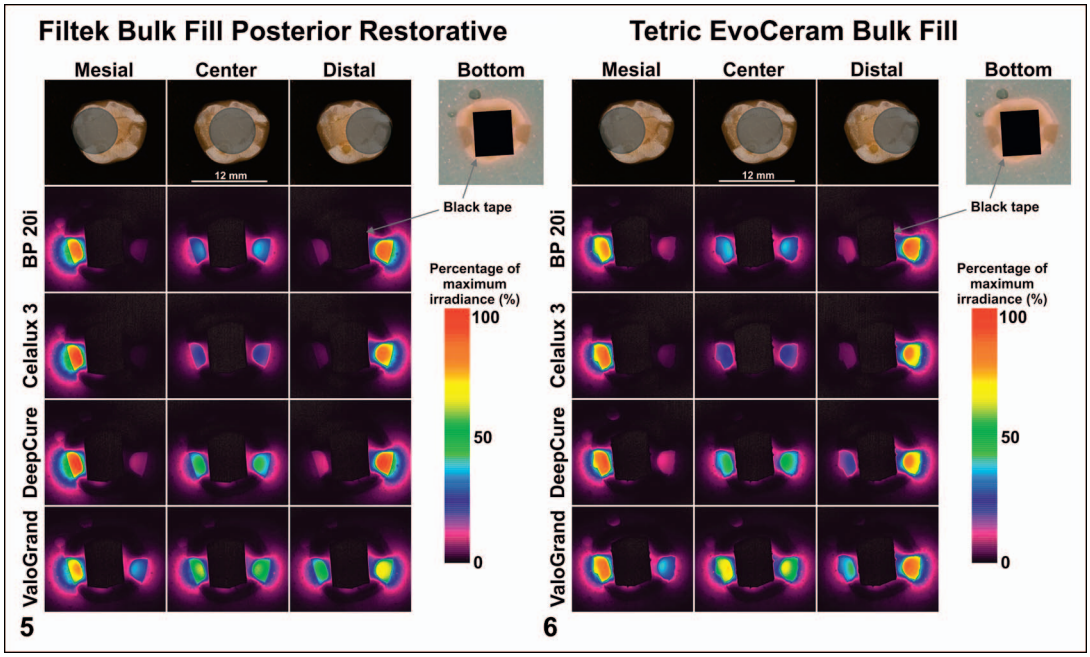


Figure 5. *Light transmission through restorations made with Filtek Bulk Fill Posterior, varying the position of the light-curing unit tip over the restoration. The image shows the light that reached the bottom of the proximal boxes in each light condition. An image of the bottom of the mold is also presented. Opaque black tape was used to prevent light from being transmitted through the occlusal region. BP 20i, Bluephase 20i; CL 3, Celalux 3; DC-S, Elipar Deep Cure-S; VG, Valo Grand.*

Figure 6. *Light transmission through restorations made with Tetric EvoCeram Bulk Fill, varying the position of the light-curing unit tip over the restoration. The image shows the light that reached the bottom of the proximal boxes in each light condition. An image of the bottom of the mold is also presented. Opaque black tape was used to prevent light from being transmitted through the occlusal region. BP 20i, Bluephase 20i; CL 3, Celalux 3; DC-S, Elipar Deep Cure-S; VG, Valo Grand.*

was positioned over one of the proximal boxes, more light reached to the bottom of that box, but very little light reached the opposite proximal box, independent of which of the RBC was used (Figures 5 and 6).

DISCUSSION

The LCUs used in this study were chosen because they had different light tip diameters and different light-emitting characteristics (Table 1). These differences influenced the Knoop microhardness results, and thus, the first null hypothesis that the LCUs would not affect the curing profile of the bulk-fill RBC restorations was rejected. The exposure time also influenced the microhardness results. Thus, the second null hypothesis, that a 20-second exposure time would not improve the curing profile of the bulk-fill RBC restorations was also rejected.

Influence of Tip Diameter

The observation that the different LCUs would have different effects on the hardness maps of the two RBCs was anticipated and supported previous studies.[10,11,19] In general, the use of LCUs with wider tips (Elipar Deep Cure-S and Valo Grand) produced more homogeneous hardness maps, as evidenced by the higher hardness values measured at the proximal boxes, compared to the Bluephase 20i and Celalux 3 LCUs that had the smaller diameter light tips (Tables 4 to 7). When the light tip diameter and the curing profiles are examined, it can be seen that the RBC under the center of the LCU was hard. Thus, the tip diameter would not be an issue when using a filling technique that places and photocures 2-mm increments of RBC into cavities or when using the ISO 4049 4-mm diameter mold because the LCU tip would cover the entire increment of the RBC. However, the tip diameter does become a problem when the operator attempts to photocure an entire molar MOD restoration in a tooth using a single exposure from the occlusal surface.[7]

It is important to consider the difference between the external tip diameter and the regions of the LCUs tip from where light is actually emitted since even a small decrease in the tip diameter will produce a substantial reduction in the area and thus increase the radiant exitance.[7] All the evaluated LCUs had discrepancies between the effective and

Table 4: *Means ± Standard Deviations of the Knoop Microhardness results for Filtek Bulk Fill Posterior photoactivated for 10 seconds, measured at each region of the restoration (central, mesial [4.5 mm away from the center], and distal [4.5 mm away from the center]), comparing the different LCUs and depths (analysis made comparing each region separately)*[a]

Depth	Mesial				Central	
	BP 20i	Celalux 3	Deep Cure	Valo Grand	BP 20i	Celalux 3
0.5	45.3 ± 4.3 Ba	39.0 ± 1.9 Ca	50.1 ± 0.8 Aa	50.4 ± 0.5 Aa	55.3 ± 1.4 Aa	53.6 ± 1.7 Aa
1.0	43.1 ± 3.8 Bab	38.2 ± 1.8 Ca	48.8 ± 1.3 Aab	49.4 ± 0.9 Aa	53.8 ± 0.9 Ab	52.5 ± 1.9 Ab
1.5	41.2 ± 3.2 Bbc	37.0 ± 1.4 Cab	47.4 ± 1.7 Abc	48.1 ± 1.3 Aab	52.1 ± 1.2 Ac	51.6 ± 1.6 Ac
2.0	39.7 ± 2.0 Bc	35.0 ± 1.6 Cb	45.7 ± 2.0 Acd	46.3 ± 0.8 Abc	51.6 ± 1.3 Ac	50.4 ± 2.2 Ad
2.5	35.5 ± 1.4 Bd	32.3 ± 2.2 Bc	43.3 ± 1.7 Ad	43.8 ± 1.4 Ac		
3.0	32.6 ± 1.5 Be	28.7 ± 3.2 Cd	40.2 ± 0.7 Ae	41.1 ± 1.7 Ad		
3.5	29.1 ± 2.2 Bf	26.5 ± 2.6 Bd	36.1 ± 1.1 Af	38.0 ± 1.2 Ae		
4.0	26.0 ± 2.0 Bg	22.9 ± 2.0 Be	31.5 ± 1.6 Ag	34.0 ± 0.6 Af		

[a] *Different uppercase letters indicate statistical differences within rows (light curing units); different lowercase letters indicate statistical differences within columns ($p < 0.05$). N = 5 repeats.*

Table 5: *Means ± Standard Deviations of the Knoop Microhardness Results for Filtek Bulk Fill Posterior photoactivated for 20 seconds, measured at each region of the restoration (central, mesial [4.5 mm away from the center], and distal [4.5 mm away from the center]), comparing the different LCUs and depths (analysis made comparing each region separately)*[a]

Depth	Mesial				Central	
	BP 20i	Celalux 3	Deep Cure	Valo Grand	BP 20i	Celalux 3
0.5	48.3 ± 0.7 Ba	48.2 ± 0.3 Ba	54.4 ± 1.3 Aa	55.5 ± 1.4 Aa	55.2 ± 1.1 Ba	55.4 ± 0.7 Ba
1.0	47.2 ± 0.7 Bab	47.5 ± 0.3 Ba	53.5 ± 1.3 Aab	54.5 ± 1.1 Aab	54.5 ± 0.9 Bb	54.6 ± 0.8 Bb
1.5	46.1 ± 0.7 Bbc	46.0 ± 0.4 Bb	52.9 ± 1.3 Ab	53.5 ± 1.1 Abc	53.6 ± 0.9 Bc	53.9 ± 0.8 Bc
2.0	44.9 ± 0.6 Bc	44.8 ± 1.0 Bb	52.4 ± 1.4 Abc	52.6 ± 1.0 Ac	52.7 ± 1.0 Bd	53.2 ± 0.7 Bd
2.5	43.2 ± 0.7 Bd	42.8 ± 1.0 Bc	51.5 ± 1.2 Ac	50.7 ± 1.7 Ad		
3.0	40.6 ± 0.8 Be	40.7 ± 1.1 Bd	50.0 ± 1.7 Ad	48.9 ± 1.7 Ae		
3.5	37.5 ± 0.3 Bf	38.0 ± 0.7 Be	47.7 ± 1.0 Ae	46.3 ± 1.3 Af		
4.0	34.1 ± 0.5 Bg	35.2 ± 1.3 Bf	45.1 ± 1.4 Af	43.5 ± 1.0 Ag		

[a] *Different uppercase letters indicate statistical differences within rows (light curing units); different lowercase letters indicate statistical differences within columns ($p < 0.05$). N = 5 repeats.*

Table 6: *Means ± Standard Deviations of the Knoop Microhardness Results for Tetric EvoCeram Bulk Fill photoactivated for 10 seconds, measured at each region of the restoration (central, mesial [4.5 mm away from the center], and distal [4.5 mm away from the center]), comparing the different LCUs and depths (analysis made comparing each region separately)*[a]

Depth	Mesial				Central	
	BP 20i	Celalux 3	Deep Cure	Valo Grand	BP 20i	Celalux 3
0.5	34.3 ± 3.1 Ba	26.7 ± 1.8 Ca	35.6 ± 0.8 Ba	43.6 ± 1.2 Aa	45.1 ± 1.0 Ba	40.9 ± 1.6 Ca
1.0	32.6 ± 1.9 Bab	25.3 ± 1.8 Cab	33.6 ± 0.7 Bb	42.3 ± 1.6 Aa	43.4 ± 0.8 Bb	39.5 ± 1.3 Ca
1.5	32.1 ± 1.1 Bb	24.1 ± 1.5 Cbc	32.3 ± 0.7 Bbc	40.4 ± 1.2 Ab	41.9 ± 1.3 Bc	37.8 ± 1.3 Cb
2.0	30.5 ± 1.5 Bc	22.8 ± 1.9 Ccd	30.7 ± 0.4 Bc	37.5 ± 1.4 Ac	39.7 ± 2.5 Bd	37.0 ± 0.9 Cc
2.5	27.9 ± 1.3 Bd	21.5 ± 1.7 Cd	28.5 ± 1.0 Bd	34.8 ± 2.1 Ad		
3.0	25.9 ± 1.0 Be	19.2 ± 0.7 Ce	26.5 ± 1.0 Be	31.9 ± 2.5 Ae		
3.5	24.0 ± 1.3 Bf	16.7 ± 0.6 Cf	24.6 ± 0.7 Bf	28.4 ± 1.1 Af		
4.0	20.6 ± 1.3 Bg	14.4 ± 0.5 Cg	21.9 ± 0.3 Bg	24.9 ± 1.2 Ag		

[a] *Different uppercase letters indicate statistical differences within rows (light curing units); different lowercase letters indicate statistical differences within columns ($p < 0.05$). N = 5 repeats.*

Table 4: *Means ± Standard Deviations of the Knoop Microhardness results for Filtek Bulk Fill Posterior photoactivated for 10 seconds, measured at each region of the restoration (central, mesial [4.5 mm away from the center], and distal [4.5 mm away from the center]), comparing the different LCUs and depths (analysis made comparing each region separately) (ext.)*

Depth	Central		Distal			
	Deep Cure	Valo Grand	BP 20i	Celalux 3	Deep Cure	Valo Grand
0.5	55.8 ± 1.2 Aa	54.1 ± 1.6 Aa	33.4 ± 1.8 Ca	32.6 ± 1.3 Ca	42.1 ± 1.3 Ba	47.1 ± 2.4 Aa
1.0	54.6 ± 0.8 Ab	53.1 ± 1.6 Ab	32.2 ± 1.8 Ca	31.4 ± 1.7 Cab	40.7 ± 1.2 Bab	45.4 ± 2.2 Aa
1.5	53.5 ± 0.8 Ac	51.9 ± 1.7 Ac	30.2 ± 2.3 Cb	30.1 ± 2.3 Cbc	38.9 ± 1.7 Bb	43.4 ± 1.9 Ab
2.0	52.6 ± 1.1 Ad	50.7 ± 1.6 Ad	28.6 ± 2.5 Cbc	28.4 ± 1.5 Cc	36.6 ± 1.7 Bc	41.5 ± 1.8 Ac
2.5			27.1 ± 2.4 Cc	26.3 ± 1.5 Cd	33.8 ± 1.6 Bd	39.2 ± 1.6 Ad
3.0			24.4 ± 1.6 Cd	23.8 ± 1.1 Ce	31.2 ± 1.7 Be	35.4 ± 1.7 Ae
3.5			21.3 ± 2.6 Ce	20.9 ± 1.9 Cf	27.8 ± 1.4 Bf	31.3 ± 1.4 Af
4.0			19.1 ± 2.9 Cf	17.5 ± 2.3 Cg	23.3 ± 0.9 Bg	26.9 ± 1.8 Ag

Table 5: *Means ± Standard Deviations of the Knoop Microhardness Results for Filtek Bulk Fill Posterior photoactivated for 20 seconds, measured at each region of the restoration (central, mesial [4.5 mm away from the center], and distal [4.5 mm away from the center]), comparing the different LCUs and depths (analysis made comparing each region separately) (ext.)*

Depth	Central		Distal			
	Deep Cure	Valo Grand	BP 20i	Celalux 3	Deep Cure	Valo Grand
0.5	57.9 ± 0.9 Aa	58.6 ± 0.7 Aa	46.5 ± 0.3 Ba	47.0 ± 1.0 Ba	52.2 ± 0.3 Aa	53.3 ± 1.3 Aa
1.0	56.9 ± 1.2 Ab	57.6 ± 0.9 Ab	45.6 ± 0.3 Bab	46.3 ± 1.1 Bab	51.1 ± 0.3 Aab	52.4 ± 1.2 Aab
1.5	56.0 ± 1.0 Ac	56.8 ± 1.0 Ac	44.5 ± 0.5 Bbc	45.3 ± 1.0 Bb	50.3 ± 0.8 Abc	51.6 ± 1.4 Ab
2.0	55.1 ± 1.2 Ad	56.2 ± 0.9 Ad	43.5 ± 0.7 Bc	43.5 ± 1.2 Bc	49.5 ± 0.8 Ac	50.9 ± 1.4 Abc
2.5			41.9 ± 0.9 Bd	41.6 ± 1.4 Bd	47.9 ± 1.1 Ad	49.7 ± 1.5 Ac
3.0			40.0 ± 1.1 Be	39.1 ± 1.5 Be	45.6 ± 1.1 Ae	47.2 ± 1.6 Ad
3.5			37.2 ± 1.2 Cf	36.0 ± 1.9 Cf	42.8 ± 1.4 Bf	45.6 ± 0.9 Ae
4.0			34.0 ± 1.0 Cg	33.3 ± 1.3 Cg	40.1 ± 1.3 Bg	42.9 ± 0.9 Af

Table 6: *Means ± Standard Deviations of the Knoop Microhardness Results for Tetric EvoCeram Bulk Fill photoactivated for 10 seconds, measured at each region of the restoration (central, mesial [4.5 mm away from the center], and distal [4.5 mm away from the center]), comparing the different LCUs and depths (analysis made comparing each region separately) (ext.)*

Depth	Central		Distal			
	Deep Cure	Valo Grand	BP 20i	Celalux 3	Deep Cure	Valo Grand
0.5	40.7 ± 0.9 Ca	47.9 ± 1.3 Aa	29.6 ± 3.2 Ba	22.7 ± 1.5 Ca	30.2 ± 0.3 Ba	41.3 ± 2.1 Aa
1.0	39.5 ± 0.8 Cab	46.7 ± 1.2 Aab	27.3 ± 2.8 Bb	21.3 ± 1.0 Cab	28.4 ± 0.5 Bab	39.1 ± 2.1 Aa
1.5	38.5 ± 0.8 Cbc	45.5 ± 1.7 Ab	25.7 ± 2.0 Bbc	19.9 ± 1.6 Cbc	26.7 ± 1.3 Bbc	35.5 ± 2.0 Ab
2.0	37.6 ± 0.8 BCc	43.5 ± 2.7 Ac	24.1 ± 1.2 Bc	17.9 ± 1.0 Ccd	24.9 ± 0.9 Bcd	31.8 ± 1.5 Ac
2.5			21.7 ± 0.9 Bd	16.5 ± 1.0 Cd	23.5 ± 1.1 Bd	29.7 ± 1.8 Ac
3.0			18.9 ± 2.1 Be	13.7 ± 1.1 Ce	21.2 ± 1.6 Be	25.1 ± 1.3 Ad
3.5			16.8 ± 1.7 Be	12.0 ± 0.6 Cef	20.1 ± 1.9 Ae	21.3 ± 0.9 Ae
4.0			14.1 ± 1.1 Bf	10.0 ± 0.6 Cf	17.8 ± 1.8 Af	18.7 ± 0.9 Af

Table 7: *Means ± Standard Deviations of the Knoop Microhardness Results for Tetric EvoCeram Bulk Fill photoactivated for 20 seconds, measured at each region of the restoration (central, mesial [4.5 mm away from the center], and distal [4.5 mm away from the center]), comparing the different LCUs and depths (analysis made comparing each region separately)*[a]

Depth	Mesial				Central	
	BP 20i	Celalux 3	Deep Cure	Valo Grand	BP 20i	Celalux 3
0.5	35.8 ± 1.9 Ca	33.1 ± 0.9 Da	42.1 ± 0.7 Ba	48.3 ± 0.3 Aa	47.0 ± 0.6 Ba	41.3 ± 0.6 Da
1.0	34.8 ± 1.6 Cab	32.4 ± 0.8 Dab	41.0 ± 0.6 Ba	46.9 ± 0.5 Ab	46.0 ± 0.6 Bb	40.6 ± 0.6 Db
1.5	33.8 ± 1.7 Cbc	31.4 ± 1.0 Db	39.5 ± 1.1 Bb	45.0 ± 0.7 Ac	45.1 ± 0.4 Bc	39.8 ± 0.6 Cc
2.0	32.5 ± 1.3 Cc	30.0 ± 1.2 Dc	38.4 ± 1.2 Bbc	42.0 ± 1.1 Ad	44.0 ± 0.5 Bd	39.2 ± 0.6 Cd
2.5	30.6 ± 1.7 Bd	28.6 ± 0.6 Cd	37.3 ± 1.1 Ac	38.8 ± 2.0 Ae		
3.0	28.7 ± 1.3 Be	25.8 ± 1.3 Ce	35.3 ± 0.9 Ad	36.0 ± 2.0 Af		
3.5	25.5 ± 0.9 Bf	24.1 ± 1.1 Bf	32.9 ± 1.4 Ae	32.7 ± 1.1 Ag		
4.0	23.4 ± 1.0 Bg	21.9 ± 0.9 Bg	31.0 ± 1.0 Af	30.2 ± 0.8 Ah		

[a] *Different uppercase letters indicate statistical differences within rows (light curing units); different lowercase letters indicate statistical differences within columns ($p < 0.05$). N = 5 repeats.*

the external tip diameters. This difference was as much as 3.4 mm for Valo Grand (Table 1) and may lead the user to erroneously believe that the whole restoration surface is being covered by light.

Radiant Exitance and Light Beam Profile

Another characteristic of LCUs that influences the polymerization of the RBCs is the irradiance beam profile of the light emitted from the LCU.[10,11] The light beam profile provides information about the distribution of the irradiance from the LCU.[9] It has already been shown that when very high irradiance values, above 1500 mW/cm^2, are received, this may lead to a lower degree of conversion the material.[21,22] Also, as the distance between the LCU tip and the RBC increases, the irradiance received by the RBC decreases.[23,24] In the present study, instead of light-curing at a 0-mm distance, the tip of the LCUs was fixed at a 2-mm distance because the cusp tips had been ground flat. Thus, this 2-mm distance represented the clinical distance between the cusp tip and the central fossa.

This study suggests that LCUs that have a wide tip diameter and deliver a more homogeneous light output should be used when photocuring large bulk-fill restorations since these LCUs will produce more uniform hardness values across the restoration.[10,11,19] Although smaller-diameter light tips may produce acceptable results when using a 4 mm diameter mold in the ISO 4049 test, the use of nonhomogeneous lights with narrow tip diameters will lead to inhomogeneous hardness results in MOD restorations in the tooth. This is illustrated by the nonuniform distribution of colors in the hardness maps in Figure 4. In addition to the discrepancy between the effective and the external tip dimensions, a nonuniform light beam profile may also lead to errors when trying to cover the restoration with the light adequately. Notably, the scaled irradiance color scheme in Figure 3 shows that, although the external tip diameter of the Celalux 3 is 8 mm, the effective tip diameter is 7.1 mm, and only the center 4-mm diameter produces a radiant exitance that is greater than 400 mW/cm^2. This can be observed by the increased amount of green, yellow, and red colors representing the higher irradiance values at the center of the LCU tip in Figure 3.

Emission Spectrum

Since it is known that the emission spectrum from the LCUs can influence the curing and microhardness of RBC restorations[25] the two different RBCs tested in this study were chosen because they use different photoinitiator systems. Filtek Bulk Fill Posterior uses only the type II initiator CQ, whereas Tetric EvoCeram Bulk Fill uses a combination of type II (CQ) and type I (Ivocerin) initiators. Although Ivocerin has its absorption peak close to 412 nm within the region of violet light, its absorption is different from other alternative type I initiators, such as Lucirin TPO, which absorb light mainly in the UV range, because Ivocerin is activated by wavelengths of blue light up to 460 nm.[14] In addition, since Ivocerin is a Type I photoinitiator and is a more efficient photoactivator compared to CQ[26], the curing profile of the two tested RBCs was anticipated to be different. Thus the fact that the multiple-peak LCUs (Bluephase 20i and Valo Grand) that both emitted violet light produced higher microhardness results than the use of the single-peak blue LCUs (Celalux 3 and Elipar DeepCure-S) was anticipated. However, this was only evident at

Table 7: *Means ± Standard Deviations of the Knoop Microhardness Results for Tetric EvoCeram Bulk Fill photoactivated for 20 seconds, measured at each region of the restoration (central, mesial [4.5 mm away from the center], and distal [4.5 mm away from the center]), comparing the different LCUs and depths (analysis made comparing each region separately) (ext.)*

Depth	Central		Distal			
	Deep Cure	Valo Grand	BP 20i	Celalux 3	Deep Cure	Valo Grand
0.5	45.5 ± 0.8 Ca	51.0 ± 1.0 Aa	34.3 ± 1.9 Ca	32.5 ± 0.8 Ca	38.4 ± 1.2 Ba	47.2 ± 1.3 Aa
1.0	44.8 ± 0.7 Cb	50.2 ± 0.9 Ab	33.3 ± 1.4 Cab	31.5 ± 0.6 Ca	37.3 ± 1.1 Ba	46.5 ± 1.1 Aab
1.5	44.0 ± 0.7 Bc	49.3 ± 0.6 Ac	31.9 ± 1.7 Cb	30.2 ± 0.7 Cb	35.8 ± 1.1 Bb	45.3 ± 1.3 Ab
2.0	43.2 ± 0.7 Bd	48.5 ± 0.6 Ad	30.4 ± 1.4 Cc	28.3 ± 0.8 Cc	34.7 ± 1.6 Bb	43.6 ± 1.0 Ac
2.5			28.4 ± 1.7 Cd	27.2 ± 0.9 Cc	33.3 ± 1.6 Bc	40.5 ± 1.4 Ad
3.0			26.7 ± 2.1 Ce	25.2 ± 1.0 Cd	31.2 ± 1.4 Bd	37.5 ± 0.8 Ae
3.5			24.8 ± 1.5 Cf	23.5 ± 1.1 Ce	29.2 ± 1.7 Be	34.2 ± 0.9 Af
4.0			21.9 ± 1.1 Cg	20.6 ± 1.0 Cf	27.4 ± 1.3 Bf	30.9 ± 0.5 Ag

the at the center of the Tetric EvoCeram Bulk Fill restorations where the RBC was 2 mm thick. At the proximal boxes, the violet light had no beneficial effect, and the tip diameter had a greater impact over microhardness results. Since the emission spectrum of the light emitted by the LCUs influenced the hardness results of one RBC, it is important to consider what wavelengths of light are effectively reaching the RBC at both the top and the bottom of the specimen. Thus, the beam profile of the violet light emitted at the tip of the LCUs and what light reaches the bottom of the RBC also becomes relevant.[27] Figure 3 shows that for the two multiple-peak lights used in this study, the beam profiles of the lights taken through the 400 nm filter show that violet light was emitted across the entire light tip, although at a much lower level than the blue light. As expected, since Filtek Bulk Fill Posterior does not require violet light, the microhardness results for Filtek Bulk Fill Posterior were not affected by the emission spectrum of the four different LCUs.

Exposure Time

To verify the effect of different exposure times on the curing profile of the restorations, both 10- and 20-second photoactivation times were used. A 10-second exposure was chosen according to the manufacturer's recommended time, but the specimens did not receive any exposures from the buccal and lingual surfaces.[28,29] When the exposure time was doubled to 20 seconds from the occlusal surface, the hardness results increased, and the curing profile became more homogeneous. This result was anticipated because it has been reported that the radiant exposure can be correlated to the degree of conversion of RBCs and that increasing the exposure time should result in increased photocuring, until a saturation point is reached.[25,30] This effect could be observed by the increase in the homogeneity of the hardness maps shown in Figure 4 independently of the LCU or the RBC used. This observation may raise doubts about the relevance of beam inhomogeneity on the photoactivation of RBCs since, when longer exposure times are used, the differences in the results of different materials photoactivated with different LCUs are reduced and may even disappear. However, any increase in exposure time beyond what is recommended by the manufacturer to improve the homogeneity of the curing profile of the composite resin should be done with caution because this longer exposure time will deliver more energy to the tooth. This may generate more heat in both the tissues adjacent to the restoration and the pulp.[26,31] Therefore, a short 5-second delay between multiple exposures is recommended to allow the tissues and tooth to cool.

Influence of the Mold

Overall, the microhardness values in the tooth were lower than anticipated, most notably at the bottom of the proximal boxes. The depth of cure of bulk-fill RBCs has already been well discussed,[4] but the width of cure, or curing profile in a tooth, has not.[5,19] However, a high methodological heterogeneity has been reported for the studies that have evaluated the depth of cure of bulk-fill RBCs[4], and it has been reported that the characteristics of the mold used can influence the results of RBC polymerization.[17,32,33] The material of which the mold is made can influence the light transmission and, consequently, the resin polymerization since

more opaque materials will transmit less light.[17] The present study used a mold made using a human tooth to simulate a large MOD restoration, because it has been shown that use of tooth mold may result in higher depth of cure than opaque molds.[34] The use of a molar tooth mold was important to determine the influence of tip diameter and light beam profile on the curing profile of bulk-fill RBC restorations in real teeth. Although a previous study[15] reported that there were no differences between LCUs with different light beam profiles, the specimens used in that study were only 6 mm wide, and a 20-second exposure time was used. The fact that similar results were found in the present study at the center of the 12-mm wide RBC specimens, but not at the proximal boxes, highlights the clinical importance of the mold material and diameter on the conclusions of the study. Considering the results of the present study, if the ISO 4049 test using a 4-mm-diameter metal mold had been used, the polymerization of the RBCs would have appeared to be much better than what actually occurs in the proximal boxes of a MOD restoration in the tooth. But since the 4-mm-diameter metal mold[35] cannot reproduce the photoactivation of the RBC in extensive restorations, the ISO 4049 method for the depth of cure evaluation may even produce conclusions that are not clinically relevant.[18]

The mold design used in this study allowed the microhardness measurements to be made on the transverse surface of the restorations without requiring the specimens to be cut or polished. This was done because although many previous studies have evaluated the polymerization after cutting or polishing the specimens,[5,36] the use of water or ethanol may cause some dissolution of the monomers in the RBC, and this might affect the results.[37]

Although the LCUs were positioned at the center of restorations, differences were observed between the hardness values measured at the mesial and distal box regions of the restorations. The light distribution over the restoration, seen in Figure 3, showed that both areas received light similarly; therefore, it would be expected that the hardness of the restorations should be uniform, and no differences should be found between mesial and distal boxes. Also, the specimens were always positioned in the same position under the LCUs, and the jig and light clamping fixture prevented any alignment changes during the light-curing of specimens. However, a VPS matrix was used to standardize the shape of the restorations and to simulate the original tooth contour. Similar to the metallic matrices commonly used in the restoration of class II cavities that do not allow any additional light transmission from the proximal surfaces, the VPS matrix was opaque. Consequently, it is likely that the small differences observed were probably caused by the differences in the natural anatomical contour of the mesial and distal surfaces of the human tooth and the restorations.

Effective Tip Size in Relation to Restoration Dimensions

The Knoop microhardness values were low at the bottom of the proximal boxes for all the LCUs tested, as illustrated by the greater number of blue regions in the curing profiles (Figure 4). Although LCUs with wide tips and homogeneous beam profile, such as Valo Grand and Elipar DeepCure-S, delivered better results in the proximal boxes than LCUs with narrow tips and an inhomogeneous beam profile, such as Bluephase 20i and Celalux 3, none of the LCUs produced hardness values that were acceptable (>80%)[38] at these regions. Instead, the hardness values at the bottom of the proximal boxes achieved by Celalux 3 used for 10 seconds were as low as 30% of the maximum hardness for Filtek Bulk Fill Posterior and only 20% of the maximum values achieved for Tetric EvoCeram Bulk Fill. The low hardness results at the bottom of the proximal boxes can be explained by the rather low amount of light that reached the bottom of the restoration (Figures 5 and 6). This occurred mainly when the LCUs with smaller tips were used. Because of the difficulty to access and see the restorations at the bottom of the proximal boxes and the low bond strength of poorly polymerized RBCs to the cervical area,[39] this region may be more susceptible to secondary caries,[40] increased solubility, and increased biofilm formation.[41]

The smaller-diameter area of light curing should not be an issue if an incremental filling and light-curing technique is used or even when considering the photoactivation of a restoration made with a bulk-fill RBC that is less than the effective diameter of the light tip. However, it becomes a problem when trying to bulk cure an extensive MOD restoration in a molar tooth. Instead of using a single light exposure at the center of the restoration, it is recommended that each proximal box be light-cured separately, even when larger-diameter light tips are used. By doing this, the clinician can ensure that all of the RBC they are trying to photocure is within the

region covered by the effective internal diameter of the light tip.

Limitations

This study was conducted under ideal conditions. The LCUs had been tested and were working within the manufacturer's specification, and the LCU was correctly positioned and stabilized above the restoration. These ideal circumstances may not always occur clinically. The low indentation load used for the microhardness test may be considered a limitation, but this low load was necessary to prevent damage to the specimens and was compensated for by increasing the objective magnification (10×) so that the image of the indent filled the imaging screen. Another limitation was that the curing lights were positioned only at the center of the restoration. However, exposure times of both 10 and 20 seconds were used because according to the manufacturer's instructions,[28] the exposure time for Filtek Bulk Fill Posterior used in the restoration of class II cavities should be 10 seconds at the occlusal surface and an extra 10 seconds at the buccal and lingual surfaces provided that the LCU delivers a radiant exitance above 1000 mW/cm^2. The manufacturer of Tetric EvoCeram Bulk Fill recommends that class II cavities be photoactivated for 10 seconds at the occlusal surface,[29] and the photoactivation should also be completed from the buccal and lingual surfaces, again provided that the LCU delivers a radiant exitance above 1000 mW/cm^2. Although the light transmission through teeth is low, and additional photoactivation from buccal and lingual surfaces should increase the polymerization of the RBCs, especially at greater depths,[42] the amount of light transmitted through the buccal and lingual surfaces the teeth is unpredictable. Further studies are necessary to verify the value of additional light exposure through the tooth on the polymerization of the RBC in the proximal boxes. For example, should the mesial and distal boxes of molar teeth be exposed separately from both the buccal and lingual surfaces as well as from the central occlusal surface, making a total of five exposures?

CONCLUSIONS

Within the limitations of the present study, that used a human molar with a 12-mm mesial-distal length, a 2.5-mm deep occlusal box, and two 4.5-mm deep proximal boxes, wider curing light tip diameters, a more homogeneous light beam profile, and longer exposure times were found to be preferable when photoactivating MOD restorations made in this molar tooth. The Valo Grand, followed by the Bluephase 20i, produced the highest hardness values ($p<0.05$) at the center of the 12-mm wide specimens of Tetric EvoCeram Bulk Fill. Since less light reaches the bottom of the proximal boxes and the microhardness in these regions was negatively affected, light-curing from more than one location is recommended.

Acknowledgements

The authors wish to acknowledge the manufacturers who kindly donated the resin composites and the curing lights for this study.

Regulatory Statement

This study was conducted in accordance with all the provisions of the local human subjects oversight committee guidelines and policies of the Dalhousie University. The approval code issued for this study is: 2015-3632.

Conflict of Interest

The authors of this manuscript certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

(Accepted 1 August 2019)

REFERENCES

1. Van Ende A, De Munck J, Lise DP, & Van Meerbeek B (2017) Bulk-fill composites: A review of the current literature *Journal of Adhesive Dentistry* **19(2)** 95-109, 10.3290/j.jad.a38141.
2. Ilie N & Stark K (2014) Curing behaviour of high-viscosity bulk-fill composites *Journal of Dentistry* **42(8)** 977-985, 10.1016/j.jdent.2014.05.012.
3. Fronza BM, Rueggeberg FA, Braga RR, Mogilevych B, Soares LE, Martin AA, Ambrosano G, & Giannini M (2015) Monomer conversion, microhardness, internal marginal adaptation, and shrinkage stress of bulk-fill resin composites *Dental Materials* **31(12)** 1542-1551, 10.1016/j.dental.2015.10.001.
4. Lima RBW, Troconis CCM, Moreno MBP, Murillo-Gomez F, & De Goes MF (2018) Depth of cure of bulk fill resin composites: A systematic review *Journal of Esthetic and Restorative Dentistry* **30(6)** 492-501, 10.1111/jerd.12394.
5. Li X, Pongprueksa P, Van Meerbeek B, & De Munck J (2015) Curing profile of bulk-fill resin-based composites *Journal of Dentistry* **43(6)** 664-672, 10.1016/j.jdent.2015.01.002.
6. van Dijken JWV & Pallesen U (2017) Bulk-filled posterior resin restorations based on stress-decreasing resin technology: A randomized, controlled 6-year evaluation *European Journal of Oral Sciences* **125(4)** 303-309, 10.1111/eos.12351.
7. Shimokawa CA, Turbino ML, Harlow JE, Price HL, & Price RB (2016) Light output from six battery operated dental curing lights *Material Science and Engineering C-*

Materials for Biological Applications **69** 1036-1042, 10.1016/j.msec.2016.07.033.

8. Soares CJ, Braganca GF, Pereira R, Rodrigues MP, Braga SSL, Oliveira LRS, Giannini M, & Price RB (2018) Irradiance and radiant exposures delivered by LED light-curing units used by a left and right-handed operator *Brazilian Dental Journal* **29(3)** 282-289, 10.1590/0103-6440201802127.
9. Price RB, Ferracane JL, & Shortall AC (2015) Light-curing units: A review of what we need to know *Journal of Dental Research* **94(9)** 1179-1186, 10.1177/0022034515594786.
10. Magalhaes Filho TR, Weig KM, Costa MF, Werneck MM, Barthem RB, & Costa Neto CA (2016) Effect of LED-LCU light irradiance distribution on mechanical properties of resin based materials *Material Science and Engineering C-Materials for Biological Applications* **63** 301-307, 10.1016/j.msec.2016.02.060.
11. Price RB, Labrie D, Rueggeberg FA, Sullivan B, Kostylev, I & Fahey J (2014) Correlation between the beam profile from a curing light and the microhardness of four resins *Dental Materials* **30(12)** 1345-1357, 10.1016/j.dental.2014.10.001.
12. Zorzin J, Maier E, Harre S, Fey T, Belli R, Lohbauer U, Petschelt A, & Taschner M (2015) Bulk-fill resin composites: Polymerization properties and extended light curing *Dental Materials* **31(3)** 293-301, 10.1016/j.dental.2014.12.010.
13. Palin WM, Leprince JG, & Hadis MA (2018) Shining a light on high volume photocurable materials *Dental Materials* **34(5)** 695-710, 10.1016/j.dental.2018.02.009.
14. Burtscher P (2013) Ivocerin® in comparison to camphorquinone *Report—Research and development, Schaan, Liechtenstein: Ivoclar Vivadent* **19** 11-15.
15. Rocha MG, de Oliveira D, Correa IC, Correr-Sobrinho L, Sinhoreti M, Ferracane JL, & Correr AB (2017) Light-emitting diode beam profile and spectral output influence on the degree of conversion of bulk fill composites *Operative Dentistry* **42(4)** 418-427, 10.2341/16-164-L.
16. Price RB, Rueggeberg FA, Harlow J, & Sullivan B (2016) Effect of mold type, diameter, and uncured composite removal method on depth of cure *Clinical Oral Investigations* **20(7)** 1699-1707, 10.1007/s00784-015-1672-4.
17. AlShaafi MM, AlQussier A, AlQahtani MQ, & Price RB (2018) Effect of mold type and diameter on the depth of cure of three resin-based composites *Operative Dentistry* **43(5)** 520-529, 10.2341/17-122-L.
18. Flury S, Hayoz S, Peutzfeldt A, Husler J, & Lussi A (2012) Depth of cure of resin composites: Is the ISO 4049 method suitable for bulk fill materials? *Dental Materials* **28(5)** 521-528, 10.1016/j.dental.2012.02.002.
19. Shimokawa CAK, Turbino ML, Giannini M, Braga RR, & Price RB (2018) Effect of light curing units on the polymerization of bulk fill resin-based composites *Dental Materials* **34(8)** 1211-1221, 10.1016/j.dental.2018.05.002.
20. Ophir-Spiricon (2018) BeamGage®—User guide *North Logan, UT: Ophir-Spiricon*.
21. Selig D, Haenel T, Hausnerová B, Moeginger B, Labrie D, Sullivan B, & Price RB (2015) Examining exposure reciprocity in a resin based composite using high irradiance levels and real-time degree of conversion values *Dental Materials* **31(5)** 583-93, 10.1016/j.dental.2015.02.010.
22. Feng L, Carvalho R, & Suh BI (2009) Insufficient cure under the condition of high irradiance and short irradiation time *Dental Materials* **25(3)** 283-289, 10.1016/j.dental.2008.07.007.
23. Price RB, Labrie D, Whalen JM, & Felix CM (2011) Effect of distance on irradiance and beam homogeneity from 4 light-emitting diode curing units *Journal of the Canadian Dental Association* **77** b9.
24. Corciolani G, Vichi A, Davidson CL, & Ferrari M (2008) The influence of tip geometry and distance on light-curing efficacy *Operative Dentistry* **33(3)** 325-331, 10.2341/07-94.
25. Shimokawa C, Sullivan B, Turbino ML, Soares CJ, & Price RB (2017) Influence of emission spectrum and irradiance on light curing of resin-based composites *Operative Dentistry* **42(5)** 537-547, 10.2341/16-349-L.
26. Rueggeberg FA, Giannini M, Arrais CAG, & Price RBT (2017) Light curing in dentistry and clinical implications: A literature review *Brazilian Oral Research* **31(Supplement 1)** e61, 10.1590/1807-3107BOR-2017.vol31.0061.
27. Issa Y, Watts DC, Boyd D, & Price RB (2016) Effect of curing light emission spectrum on the nanohardness and elastic modulus of two bulk-fill resin composites *Dental Materials* **32(4)** 535-550, 10.1016/j.dental.2015.12.017.
28. 3M Oral Care (2016) Filtek Bulk Fill Posterior Restorative—Instructions for use *St Paul, MN: 3M Oral Care*.
29. Ivoclar Vivadent (2017) Tetric EvoCeram Bulk Fill—Instructions for use *Schaan, Liechtenstein: Ivoclar Vivadent*.
30. Erickson RL, Barkmeier WW, & Halvorson RH (2014) Curing characteristics of a composite. Part 1: Cure depth relationship to conversion, hardness and radiant exposure *Dental Materials* **30(6)** e125-133, 10.1016/j.dental.2014.02.012.
31. Mouhat M, Mercer J, Stangvaltaite L, & Ortengren U (2017) Light-curing units used in dentistry: Factors associated with heat development-potential risk for patients *Clinical Oral Investigations* **21(5)** 1687-1696, 10.1007/s00784-016-1962-5.
32. Erickson RL & Barkmeier WW (2014) Curing characteristics of a composite. Part 2: The effect of curing configuration on depth and distribution of cure *Dental Materials* **30(6)** e134-145, 10.1016/j.dental.2014.02.013.
33. Harrington E & Wilson HJ (1993) Depth of cure of radiation-activated materials—Effect of mould material and cavity size *Journal of Dentistry* **21(5)** 305-311.
34. Church BW, Tantbirojn D, Do T, Wells MH, & Versluis A (2017) Depth-of-cure of bulk-fill composites cured in tooth or opaque substrate *International Journal of Experimental Dental Science* **6(2)** 68-73.
35. ISO-Standards (2019) ISO 4049 Dentistry—Polymer based restorative materials *Geneve: International Organization for Standardization*.
36. Eshmawi YT, Al-Zain AO, Eckert GJ, & Platt JA (2018) Variation in composite degree of conversion and micro-

flexural strength for different curing lights and surface locations *Journal of the American Dental Association* **149(10)** 893-902, 10.1016/j.adaj.2018.06.004.

37. Sunbul HA, Silikas N, & Watts DC (2016) Surface and bulk properties of dental resin- composites after solvent storage *Dental Materials* **32(8)** 987-997, 10.1016/j.dental.2016.05.007.
38. Watts DC, Amer O, & Combe EC (1984) Characteristics of visible-light-activated composite systems *British Dental Journal* **156(6)** 209-215.
39. Xu X, Sandras DA, & Burgess JO (2006) Shear bond strength with increasing light-guide distance from dentin *Journal of Esthetic and Restorative Dentistry* **18(1)** 19-27 discussion 28.
40. Brouwer F, Askar H, Paris S, & Schwendicke F (2016) Detecting secondary caries lesions: A systematic review and meta-analysis *Journal of Dental Research* **95(2)** 143-151, 10.1177/0022034515611041.
41. Maktabi H, Ibrahim M, Alkhubaizi Q, Weir M, Xu H, Strassler H, Fugolin APP, Pfeifer CS, & Melo MAS (2019) Underperforming light curing procedures trigger detrimental irradiance-dependent biofilm response on incrementally placed dental composites *Journal of Dentistry* **88(Sep)** 103110, doi:10.1016/j.jdent.2019.04.003.
42. Hamlin NJ, Bailey C, Motyka NC, & Vandewalle KS (2016) Effect of tooth-structure thickness on light attenuation and depth of cure *Operative Dentistry* **41(2)** 200-207, 10.2341/15-067-L.

©Operative Dentistry, 2020, **45-3,** E156-E166

Wear Properties of Different Additive Restorative Materials Used for Onlay/Overlay Posterior Restorations

F De Angelis • C D'Arcangelo • N Malíšková • L Vanini • M Vadini

Clinical Relevance

Recently introduced indirect resin composites and dental ceramics show a wear behavior similar to traditional gold alloys. The present laboratory findings support a successful use of such new materials on load-bearing occlusal surfaces of posterior teeth, even for extensive occlusal rehabilitations.

SUMMARY

The purpose of this laboratory study was to compare the two-body wear resistance of different restorative materials commonly used for the indirect restoration of posterior teeth. The tested materials, based on ceramic (Imagine Press X, IPS e.max CAD, Milled Celtra Duo, Glaze-Fired Celtra Duo, Vita Mark II) and composite (Enamel Plus HRi, Enamel Plus HRi Bio-Function, Filtek Supreme XTE, Lava Ultimate), were compared with the wear properties of a type III gold alloy (Aurocast 8). Flat samples were prepared with a 6-mm thickness (n=10). Composite samples were tested after a heat polymerization cycle. All samples were exposed to a two-body wear test in a dual axis chewing simulator performing over 120,000 loading cycles. The opposing abrader cusps were fabricated from yttria-stabilized tetragonal zirconia polycrystal. The vertical substance loss (mm) and the volume loss (mm^3) were recorded, as was the wear of the antagonist cusp (mm). Mean values were analyzed by one-way analysis of variance. Significant differences among materials were detected. The heat-cured resin-based composite material Enamel Plus Bio-Function and the type III gold

*Francesco De Angelis, PhD, DDS, assistant professor, Department of Medical, Oral and Biotechnological Science, Unit of Restorative Dentistry and Endodontics, "G. D'Annunzio" University of Chieti-Pescara, Chieti, Italy

Camillo D'Arcangelo, DDS, full professor, Department of Medical, Oral and Biotechnological Science, Unit of Restorative Dentistry and Endodontics, "G. D'Annunzio" University of Chieti-Pescara, Chieti, Italy

Nela Malíšková, DDS, resident, Department of Medical, Oral and Biotechnological Science, Unit of Restorative Dentistry and Endodontics, "G. D'Annunzio" University of Chieti-Pescara, Chieti, Italy

Lorenzo Vanini, DDS, private practitioner, Chiasso, Switzerland

Mirco Vadini, PhD, DDS, research fellow, Department of Medical, Oral and Biotechnological Science, Unit of Restorative Dentistry and Endodontics, "G. D'Annunzio" University of Chieti-Pescara, Chieti, Italy

*Corresponding author: Via dei Vestini, 31, Chieti 66100, Italy; e-mail: fda580@gmail.com

https://doi.org/10.2341/19-115-L

alloy demonstrated similar mean values for wear depth and volumetric loss.

INTRODUCTION

The evolution of esthetics and adhesion has strongly modified the approach to restorative dentistry, raising the necessity to find the most suitable biomaterials. In recent years, ceramics and resin composites have become the most commonly used restorative materials. Adhesive dental ceramics and resin-based composites have proven to guarantee optimal esthetic results alongside satisfactory mechanical properties. Due to these qualities, today they are considered the first-choice restorative materials both for minimal restorations and for the reconstruction of severely compromised teeth. Gold alloy reconstructions preferred in the past, especially for their optimal wear properties, have been progressively substituted by these new technologies.

Loss of hard tooth substance is a natural process taking place during mastication. The rate of wear depends on many individually resulting factors that interact all at the same time.[1] The wear can be caused by abrasiveness of the food (so-called three-body wear) in case of normal masticatory function or by attrition in the case of parafunctional oral habits[2] (such as bruxism or grinding) that lead to direct contact of the occlusal surfaces. Other possible participating factors are muscular strength of the temporomandibular apparatus, the quality of enamel,[3,4] and salivary composition and acidity. The effect of these circumstances naturally changes the surface anatomy of the tooth, the cusps of the posterior teeth become flatter, and the incisal edges of anterior teeth reduce their length and volume of the mamelon area.[5]

Increased wear is a common reason of failure for restorations exposed to masticatory forces. Excessive wear may be responsible for numerous problems, such as hypersensitivity, loss of occlusal contact, defects of the periodontium, reduction of masticatory efficiency, tooth migration and wrong tooth relations, weakness of masticatory muscles, and changes in the vertical and horizontal jaw relations, which may cause functional and esthetic impairments.[6-10]

An optimal restorative material should provide similar characteristics to natural dental tissues. The physiological wear of enamel and dentin should represent the reference for a reasonable wear pattern of restorative materials, which typically wear out through different mechanisms, such as microplowing, microcutting, microcracking, and microfatigue.[11,12]

Previous studies[13,14] have documented that the wear behavior of type III gold alloy (Aurocast 8) is very similar to that of human enamel. Over previous decades, gold restorations were considered an appropriate solution, especially for the occlusal surface of teeth, participating in the functional contact with the opposing enamel or other prosthetic materials.[15,16] Because of the wear similarity to natural enamel, gold restorations lead to minimal wear of the antagonist tooth surface.[17] In addition, gold restorations show no correlation with the onset of pathologies related to the musculoskeletal system and occlusal disharmony.[18] The accuracy of the marginal fit is another favorable feature of gold-based restorations.[19,20] In contrast, the metallic aspect is considered its main shortcoming, as it leads to reduced esthetics and translucency. This feature has contributed to a more limited use in practice today.

Dental ceramics generally provide optimal optical qualities, color stability, and biocompatibility,[21-23] as well as clinically acceptable flexural strength and hardness.[24-29] On the other hand, their main disadvantage is that they can be used just for indirect restorations (which typically leads to higher prices and a higher number of patient sessions), there is no chance for intraoral microrepairs, and they seem to lead to enhanced wear of the opposing occlusal material.[30-33]

Resin composite indirect restorations[25,34] (onlays and overlays) represent a valid alternative for an adhesive and conservative approach.[35-37] Moreover, resin composites can also be used following a direct technique,[38] making them suitable as a minimally invasive treatment.[39-41] These key characteristics make them ideal materials to be used in the treatment of extended occlusal rehabilitations and full mouth rehabilitations and in patients with parafunctions and occlusal disorders. Other advantages include easy handling properties and a relatively low cost. Furthermore, they allow easy intraoral adjustments for proper occlusion and effective surface polishing, according to actual clinical needs, which may reduce patient chair time.

The fact that the manufacturers tend to improve the mechanical behavior of their products leads to the progressive offer of new composites and ceramics for daily practice. Assessment of their wear behavior and comparison through detailed tests become necessary at this point.

The purpose of this study was to investigate and compare the wear behavior of different additive materials frequently used for indirect restorative

Table 1: *List of Materials Tested and Their Composition as Provided by the Respective Manufacturers*

Commercial Name	Manufacturer	Material Description
Imagine Press X	Wieland Dental Ceramics (Pforzheim, Germany)	Heat-pressed silicon oxide (SiO)–based glass ceramic
IPS e.max CAD	Ivoclar Vivadent AG (Schaan, Liechtenstein)	Milled lithium disilicate glass ceramic block Filler content: approx. 70% wt Lithium disilicate crystals ($Li_2Si_2O_5$), glassy matrix Composition (W/W): SiO_2 = 57%-80%, Li_2O = 11%-19%, K_2O = 0%-13%, P_2O_5 = 0%-11%, ZrO_2 = 0%-8%, ZnO = 0%-8%, other oxides and ceramic pigments = 0%-10%
Celtra Duo	Dentsply DeTrey GmbH (Konstanz, Germany)	Zirconia-reinforced lithium silicate ceramic block Fine-grained lithium silicate, with high glass content, 10% zirconium oxide Glass with completely dissolved zirconia Lithium silicate crystallites: 500-700 nm
Vita Mark II	Vita Zahnfabrik (Bad Säckingen, Germany)	Milled feldspathic porcelain block Fine feldspathic crystalline particles embedded in a glassy matrix: vol % $\approx$ 30 Density (g/cm^3): 2.44 $\pm$ 0.01, small Particle size: average 4 μm
Lava Ultimate	3M ESPE (Neuss, Germany)	Milled resin composite block Filler content: almost 80% Silica nanomers: 20 nm; zirconia nanomers: 4-11 nm; silica-zirconia nanoclusters: 0.6-10 μm Highly cross-linked polymeric matrix: Bis-GMA, Bis-EMA, UDMA, TEGDMA
Enamel Plus HRi Bio-Function	Micerium (Avegno, Italy)	Resin composite Filler content: 74% wt (60% in volume) Dimension of particles of silicon dioxide: 0.005-0.05 μm Dimension of glassy particles: 0.2-3.0 μm
Enamel Plus HRi	Micerium (Avegno, Italy)	Resin composite Filler content: 80% wt (63% volume) Composition: 12% zirconium-oxide fillers, 68% innovative proprietary glass-based filler Mean particle size: 1 μm
Filtek Supreme XTE	3M ESPE (Seefeld, Germany)	Resin composite Filler content: 78% wt fillers (combination of nonagglomerated/nonaggregated 20-nm silica filler, nonagglomerated/nonaggregated 4- to 11-nm zirconia filler, and aggregated zirconia/silica cluster filler)
Aurocast 8	Nobil-Metal (Villafranca d'Asti, Italy)	Type III high-gold dental alloy Composition (W/W): Au = 85.4%, Ag = 9.0%, Cu = 5.0%, Pd < 1.0%, Ir < 1.0%

purposes in posterior sectors following a simulated laboratory two-body wear test. All materials included in this protocol were exposed to 120,000 chewing simulation cycles, and the measured results of wear depth, volume loss, and antagonist wear were compared to the wear properties of a traditional gold-based dental alloy.

The null hypothesis was that there are no significant differences between the gold alloy and the evaluated materials concerning laboratory wear properties.

METHODS AND MATERIALS

The different dental materials included in this protocol are summarized in Table 1.

Specimen Preparation

Proceeding with the conventional lost-wax technique, 10 specimens were made out of Imagine Press X pressable ceramic. Plexiglass discs (Plexiglas, Evonik Rohm GmbH, Darmstadt, Germany) were prepared (with dimensions of 7 mm in diameter and 6 mm in thickness) and then invested and burned out by heat. The pressable ceramic was brought in to replace the empty space and pressed at a temperature of 930°C for 20 minutes.

In order to produce specimens for computer-aided design/computer-aided manufacturing (CAD/CAM), the blocks of each material (IPS e.max CAD, Milled Celtra Duo, Glaze-Fired Celtra Duo, Vita Mark II, Lava Ultimate) were milled into the desired shape of 6-mm-thick slices.

Afterward, the lithium disilicate specimens (n=10) were crystallized in a ceramic oven (Programat EP 5000, Ivoclar Vivadent, Schaan, Liechtenstein) at 840°C to 850°C. The glaze-firing protocol for zirconia lithium silicate specimens of the Glaze-Fired Celtra Duo material was conducted in accordance with the manufacturer's instructions. The Milled Celtra Duo

samples, together with the feldspathic ceramic Vita Mark II, were not exposed to any firing after milling.

In order to create composite specimens (Enamel Plus HRi Bio-Function, Enamel Plus HRi, Filtek Supreme XTE), silicon molds were used, with an inner diameter of 7 mm and a height of 6 mm. Each mold was put on a glass surface. The composite resin material was stratified in three layers of about 2 mm and light cured for 40 seconds each (L.E. Demetron I with a 1200 mW/cm^2 output, Sybron/ Kerr, Orange, CA, USA), placing the curing unit tip as close as possible to the mold. After light curing, all specimens underwent a heat curing procedure in a composite oven (LaborLux, Micerium, Avegno, Italy) for 10 minutes at 80°C. The top surface of each composite sample was treated with 600-grit silicon carbide (SiC) paper under running water for 30 seconds, finished using diamond pastes (Shiny A, 3 μm, and Shiny B, 1 μm, Micerium), and finally polished with aluminum oxide paste (Shiny C, Micerium) delivered with a specific brush (Goat Brush Shiny S-HP and Felt Shiny F-HP, Micerium).

To fabricate 10 type III gold alloy samples (Aurocast 8), the traditional lost-wax technique was used following the manufacturer's guidelines.

Antagonist cusps were fabricated from yttria-stabilized tetragonal zirconia polycrystalline blocks (Katana Zirconia ML, Kuraray Noritake Dental Inc, Tokyo, Japan) with the use of a computer-aided milling machine (Dental CAD/CAM GN-1, GC, Tokyo, Japan), shaped like a blunt conus with a round 3-mm-wide tip, and then sintered at 1500°C for two hours. The polishing procedures were carried out with 6-μm diamond pastes.

All specimens were stored in distilled water for 24 hours at 37°C before wear simulation.

Wear Testing and Scanning Electron Microscope Analysis

All specimens were fixed in a dual axis chewing simulator (CS-4.2, SD Mechatronik GmbH, Feldkirchen-Westerham, Germany) specimen holder and subsequently exposed to the two-body wear test against zirconia cusps.

In this study, following the Ivoclar method for laboratory wear testing,[42-44] the masticatory cycle involved three stages: contact with a vertical force of 5 kg, horizontal sliding of 0.7 mm, and separation of the specimen and its antagonistic cusp. A total number of 120,000 masticatory cycles were performed at a frequency of 1.6 Hz in wet condition under distilled water.[42-44] The parameter set for the masticatory simulation is shown in Table 2.

Table 2: *Settings of Parameters for the Wear Resistance Protocol*

Parameter	Value
Number of cycles	120,000
Force	49 N
Height	3 mm
Lateral movement	−0.7 mm
Descendent speed	60 mm/s
Lifting speed	60 mm/s
Feed speed	40 mm/s
Return speed	40 mm/s
Frequency	1.6 Hz

Afterward, a quantitative surface analysis was performed on all samples. Using a CAD/CAM three-dimensional contact scanner (Renishaw Dental Scanner, Renishaw, Wotton-under-Edge, UK), a three-dimensional mesh was acquired from every sample (Figure 1). Subsequently, the wear depth (mm) and the volume loss (mm^3) were measured employing CAD software (AutoCAD 2009, Autodesk Inc, San Rafael, CA, USA). The height of each zirconia cusp was registered before and after the test procedure using a digital caliper with an accuracy of 1 μm. The difference was calculated and considered as antagonist wear (mm).

The wear facets of some representative samples from each experimental group were also subjected to a qualitative surface evaluation using a scanning electron microscope (SEM) (EVO 50 XVP LaB6, Carl Zeiss SMT Ltd, Cambridge, UK) at 60× magnification (Figure 2). The microstructure of the resin composite materials underwent a more detailed SEM analysis, up to 5000× magnification, using both secondary and back-scattered electrons (Figure 3).

Statistical Analysis

Achieved data of wear depth, volume loss, and antagonist wear were analyzed through SigmaStat for Windows 3.0.1 (Systat Software Inc, San Jose, CA, USA) statistical software. Mean values and standard deviations were calculated in each group. After having confirmed the homogeneity of the variances (Levene test) and the normal distribution of the data set (Kolmogorov-Smirnov test with the Lilliefors correction), three different one-way analysis of variance tests, followed by Tukey multiple comparison tests, were performed to assess the significance of mean differences (α=0.05).

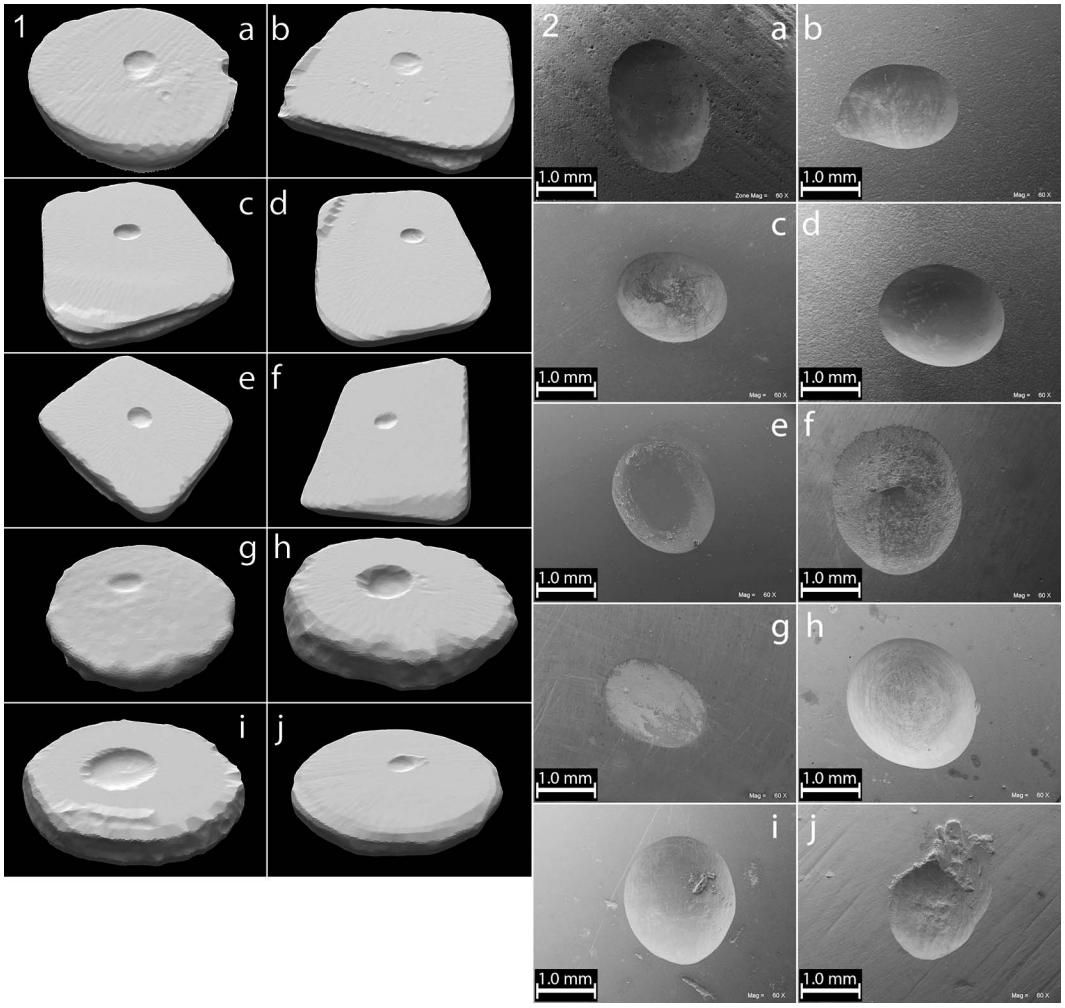


Figure 1. *Three-dimensional meshes of representative wear facets from the experimental groups. (a): Wieland Imagine Press X. (b): IPS e.max CAD. (c): Milled Celtra Duo. (d): Glaze-Fired Celtra Duo. (e): Vita Mark II. (f): Lava Ultimate. (g): HRi Bio-Function heat cured. (h): Enamel Plus HRi heat cured. (i): Filtek heat cured. (j): Aurocast 8 gold alloy.*

Figure 2. *Scanning electron microphotographs (original magnification 60×) of representative wear facets from the experimental groups. (a): Wieland Imagine Press X. (b): IPS e.max CAD. (c): Milled Celtra Duo. (d): Glaze-Fired Celtra Duo. (e): Vita Mark II. (f): Lava Ultimate. (g): HRi Bio-Function heat cured. (h): Enamel Plus HRi heat cured. (i): Filtek heat cured. (j): Aurocast 8 gold alloy.*

RESULTS

Table 3 summarizes the mean values of the wear depth and volume loss recorded for every material after 120,000 chewing simulation cycles against the antagonist cusp, whose wear is also shown.

The one-way analysis of variance confirmed statistically significant differences among the mean values for wear depth (F=23.310; p<0.001) and volume loss (F=69.026; p<0.001).

Glaze-Fired Celta Duo exhibited mean values for wear depth and volume loss statistically similar to those of gold alloy (p>0.05), while, when used soon after grinding, Milled Celtra Duo was significantly less wear resistant (p<0.05). The results of other tested dental ceramics were not statistically different from values of the gold alloy (p>0.05).

Wear depth and volume loss mean values recorded for the heat-cured Enamel Plus HRi Bio-Function resin composite, compared to the other investigated composites and ceramics, were the closest to the mean values achieved on gold alloy samples. The highest wear values were recorded in the Enamel Plus HRi and Filtek Supreme XTE groups, with no statistically significant differences between one another but with significant differences compared to other studied materials (p<0.05).

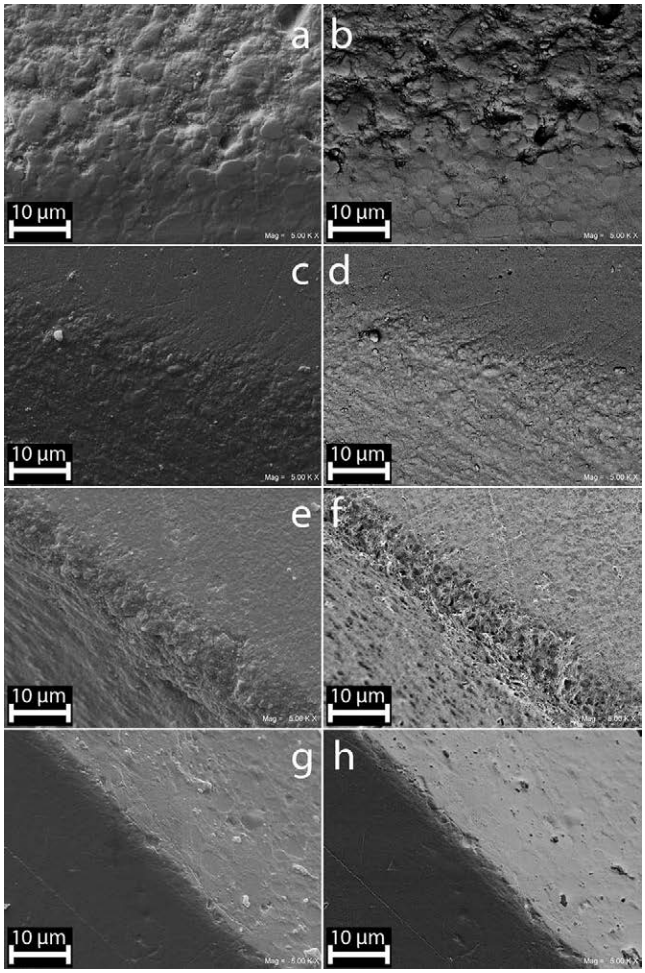


Figure 3. *Secondary (left row) and back-scattered (right row) electron microphotographs of the following resin composite materials, which were examined at higher magnification (5000×) in order to analyze their microstructure. (a, b): Lava Ultimate. (c, d): HRi Bio-Function heat cured. (e, f): Enamel Plus HRi heat cured. (g, h): Filtek heat cured. Back-scattered electrons help one better appreciate the differences in filler particle sizes and morphologies.*

DISCUSSION

The wear behavior of dental materials and dental tissues during mastication is an important factor that should be carefully evaluated when planning dental treatments. An optimal material that replaces missing enamel and opposes to natural enamel should have a wear behavior as similar to the natural dental tissue as possible.[12] It should be sufficiently wear resistant while presenting at the same time a minimal abrasiveness toward the opposing surface. Such material should provide optimal adaptation and response to the masticatory action. Optimal wear behavior is a central aspect to be considered, especially in the treatment of parafunctional patients with occlusal imbalance.

The null hypothesis tested in the present study, which assumed no difference in terms of laboratory wear properties among the several restoratives, must be rejected.

As already documented, the type III gold alloy (Aurocast 8) presents wear behavior very similar to that of human enamel, which shows great hardness, although is still subjected to wear when in contact with other restorative materials.[13,14,17] This characteristic has made gold alloy the preferred material for occlusal restorations over the past years due to its excellent adaption to the physiological occlusal needs of the patient.[15,16] Therefore, considering such a characteristic, it is supposed to minimize risk of occlusal disharmony and functional pathologies.[18]

According to the observed results, both ceramic- and resin-based composite indirect materials may show a satisfactory wear behavior compared to the gold alloy reference.

SiO-based pressable glass ceramics are among the most frequently used materials for metal-free fixed restorations. The present results demonstrated their wear resistance as satisfactory since their wear depth and volume loss mean values were very close to the mean values recorded for type III gold alloy. In the present study, we focused also on testing the wear behavior of a CAD/CAM feldspathic porcelain. This highly esthetic material is composed mainly of a glass phase, with a reduced crystalline phase, which is the reason for its excellent translucency and its optimal esthetics. The limited amount of crystalline phase, however, can affect its mechanical properties.[45] From the obtained results, the CAD/CAM feldspathic porcelain also did not differ from gold alloy and from other ceramic materials in terms of wear properties.

Glass ceramic and feldspathic porcelain hardness results in major abrasive power compared to composite materials in general. Although their behavior in terms of wear resistance is physiologically valuable, abrasiveness is still higher than composite materials.[46-48] Even if some enhanced ceramics may present improved flexural strength, feldspathic porcelains are typically more brittle than resin composites, which can increase the risk of fracture while milling extremely thin CAD/CAM restorations.[46,49,50] It is also true that glass ceramic restorations ensure a very high esthetic outcome, but any eventual intraoral occlusal correction or any new finishing/polishing procedure is certainly more problematic compared to what is allowed by resin composite materials.

Table 3: *Mean Values (and Standard Deviations) for Wear Depth and Volume Loss Achieved in the Experimental Groups.*[a]

Material	Wear Depth (mm)		Volume Loss (mm^3)		Antagonist Wear (mm)	
Imagine Press X	0.301 B	(0.058)	0.536 B	(0.107)	0.005 A	(0.001)
IPS e.max CAD	0.254 BC	(0.054)	0.351 CD	(0.091)	0.005 A	(0.002)
Milled Celtra Duo	0.320 B	(0.063)	0.555 B	(0.093)	0.004 A	(0.001)
Glaze-Fired Celtra Duo	0.280 BC	(0.051)	0.375 CD	(0.090)	0.005 A	(0.002)
Vita Mark II	0.282 BC	(0.057)	0.475 BC	(0.110)	0.005 A	(0.003)
Lava Ultimate	0.281 BC	(0.078)	0.456 BCD	(0.099)	0.005 A	(0.002)
Enamel Plus HRi Bio-Function	0.213 C	(0.052)	0.375 CD	(0.052)	0.005 A	(0.002)
Enamel Plus HRi	0.458 A	(0.057)	1.002 A	(0.121)	0.004 A	(0.002)
Filtek Supreme	0.456 A	(0.029)	1.026 A	(0.115)	0.006 A	(0.001)
Aurocast 8	0.216 C	(0.056)	0.327 D	(0.082)	0.004 A	(0.002)

[a] *Same letters indicate no statistically significant differences ($p>0.05$).*

In the present study, a CAD/CAM lithium disilicate ceramic (IPS e.max CAD) was investigated. Lithium disilicate is a material of unique composition, containing 70% small interlocking and randomly oriented crystals that provide extraordinary flexural strength. In this study, the CAD/CAM lithium disilicate demonstrated very similar wear properties to the gold alloy ($p>0.05$).

The zirconia-reinforced lithium silicate (ZLS) ceramic (Celtra Duo) was treated following two different finalization protocols in this study: milled and glaze fired. According to the manufacturer's instructions, the milled version provides the great advantage of saving time due to the possibility of skipping the firing procedure and directly polishing after grinding. This could be favorable for the chairside manufacture of adhesively luted indirect restorations. However, the glaze firing cycle, even if not required, is recommended, as it improves esthetic and flexural strength properties.[51] The wear properties of the ZLS material were examined both soon after grinding and after the optional glaze firing procedure. The wear depth and volume loss of the ground ZLS demonstrated statistically significant differences compared to gold alloy ($p<0.05$). Conversely, the differences found for the glaze-fired ZLS samples, albeit present, were not statistically significant ($p>0.05$). These results point to the glaze firing cycle as an important advanced procedure that may improve the wear resistance of ZLS-based ceramic.

The investigated CAD/CAM resin composite (LAVA Ultimate) demonstrated satisfying results of wear properties similar to gold alloy. According to the information presented by the manufacturer, this material presents enhanced strength, allowing the fabrication of indirect restorations with a minimal thickness and thus the preparation of the tooth with a maximally conservative approach. For restorations with a minimal thickness, an optimal wear resistance seems required, and, according to the collected data, Lava Ultimate may also guarantee a satisfactory behavior from this point of view.

Generally, the composite materials are considered advantageous because of many favorable aspects, such as the ease of handling, workability, low cost, and the possibility to easily carry out any required intraoral adjustment. Three types of frequently used composite materials were tested in this protocol.

Enamel Plus HRi and Filtek Supreme XTE, which are traditional composite restorative materials, displayed significant differences in the wear behavior compared to gold alloy. Excessively high wear depth and volumetric loss mean values may cause undesirable effects from the clinical point of view, such as loss of the occlusal contact, compromised function and esthetics, impaired occlusion, and possible musculoskeletal disequilibrium.[6-10] These aspects should be carefully considered, especially when treating parafunctional patients.

Different from the other samples, the novel composite material Enamel Plus HRi Bio-Function demonstrated the most statistically similar behavior in terms of wear depth, volume loss, and antagonist wear to the type III gold alloy group when submitted to the tests. Such similarity makes this material very promising, especially in terms of low interference with other materials. As stated by the manufacturer, the novel material is free of cytotoxic monomers (eg, 2-hydroxyethyl methacrylate and bis glycidyl methacrylate), which, if released during incomplete polymerization, may be harmful to dental tissue cells and increase the risk of pulp pathologies.[52,53] The absence of these components promises the material's biocompatibility. Thus, Enamel Plus HRi Bio-Function seems to unify the advantageous

handling of composites, satisfying wear properties (such as some ceramics) and high biocompatibility. Due to these features, such a material may be adequate for clinical use, especially for complex treatments of parafunctional patients presenting a compromised occlusal balance.

Among the factors influencing the wear properties of composite materials, the percentage of filler content and the filler particle size/quality[54] have been extensively discussed.[55-58] Earlier laboratory studies have reported that the higher loading of filler particles into the resin matrix plays a particularly important role in the wear resistance of conventional composites,[59] as it increases the coefficients of friction between filler particles and the matrix and thus the rate of wear loss.[55,60] In recently introduced nano-filled resin composites, with reduced size of particles, the mechanical and esthetic properties seem to be improved with respect to conventional resin composites.[61] Such materials are highly filled with nano-filler particles that are distributed homogeneously in the resin matrix while creating larger interface area between fillers and resin matrix.[61] It was documented that smaller particles for a fixed-volume fraction of filler and decreased interparticle spacing are factors reducing the wear loss of nano-resin composites.[62-65] Nevertheless, there are also other factors that significantly affect the wear resistance of the material,[55] such as the type of resin matrix and the initiators for polymerization of resin composite[66] and the bonding between fillers and resin matrix.[67] The effect of all these factors, which are also influenced by loading details, makes the whole system of wear resistance complex.[55]

In this study, all resin composites investigated had comparable filler loads, ranging between 74% and 80% (Table 1). The filler particle sizes/qualities claimed by the manufacturer for Lava Ultimate and Filtek Supreme XTE appeared also similar (Table 1). Moreover, both Enamel HRi Bio-Function and Enamel plus HRi do contain both nano-scaled and non–nano-scaled particles (Table 1). Despite those microstructural similarities (Figure 3), a significantly increased wear resistance was detected for Lava Ultimate and Enamel Plus HRi Bio-Function when they were compared, respectively, with Filtek Supreme XTE and Enamel Plus HRi. As a consequence, without neglecting the previously mentioned correlation between filler particle size/quality, filler load, and mechanical properties, it seems clear that additional factors may play a paramount role in the determination of the ultimate wear resistance of resin-based materials, such as the degree of conversion of the resin matrix (that is inherently enhanced for an industrially polymerized CAD/CAM resin block) or an effective bond between the inorganic filler particles and the organic matrix (which has been claimed as enhanced in the recently introduced Enamel Plus HRi Bio-Function).

The clinical methods for the evaluation of dental material wear properties have been reported as hardly standardizable, time consuming, and subjected to many patient-related variable factors.[43,68-70] Therefore, different laboratory methods and simulation devices have been developed in order to provide a standard asset for the wear evaluation, and different studies have been reported with the aim to demonstrate their validity and the clinical correlation between clinical and laboratory tests.[43,71,72]

In the present study, based on the methodology already used in previous research,[1,42-44,73] the Ivoclar two-body wear test method was used, which is based on the simulation of 120,000 chewing cycles. Some studies state that in clinical conditions, approximately 330,000 chewing cycles are registered in one year of mastication.[44] This would mean that the quantity of 120,000 may be correlated to 132.7 days (approximately four months) of clinical chewing strokes.

However, as there are many variable factors influencing clinical wear (such as masticatory force, direction of the mastication, quality of meal, composition of saliva, and so on), the possibility of such a direct and strict correlation between laboratory and clinical data does not seem so strong for almost all different laboratory chewing simulation methods available, as reported by Heintze and others[44] in a recent review.

As far as the abraders used for laboratory testing are concerned, the preparation of antagonist samples made of human enamel is subjected to many conditions that may cause variability of its quality. These conditions include the eventual manipulation errors in order to prepare equal abraders introduced in the steps of the protocol and variability in the degree of mineralization and thickness of the enamel from the individual donors. In order to obtain a standardized shape of antagonist cusps,[74] zirconia ceramic spheres were used in the present protocol. They retained their shape during the entire testing period, avoiding any influence of the abrader surface shape on the process.[75,76] In this way, it was possible to obtain standardized experimental conditions in order to reach results not influenced by these variable factors.

CONCLUSIONS

The present protocol showed that distinct materials have a statistically different behavior in terms of wear resistance when exposed to simulated chewing cycles.

Among the heat cured resin composites tested in this study, only one (Enamel Plus HRi Bio-Function) showed vertical wear and volumetric loss results statistically similar to the traditional type III gold alloys. Because of the additional advantage of biocompatibility, it is considered that this material could be a promising alternative for reconstructions of posterior sectors also in the treatment of parafunctional patients. Both Enamel Plus HRi and Filtek Supreme XTE showed insufficient wear resistance and unfavorable results.

The milled Celtra Duo demonstrated a shallow but considerably augmented wear depth compared to Aurocast 8 gold alloy. Results of wear depth and volumetric loss for Celtra Duo subjected to a fire glazing cycle have been recorded and did not appear to be statistically different when compared to gold alloy.

Conflict of Interest

The authors of this article certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

(Accepted 20 September 2019)

REFERENCES

1. Heintze SD, Zellweger G, Cavalleri A, & Ferracane J (2006) Influence of the antagonist material on the wear of different composites using two different wear simulation methods *Dental Materials* **22(2)** 166-175, http://dx.doi.org/10.1016/j.dental.2005.04.012.
2. Okeson JP (2008) Tooth wear In: Pendill J, Dolan J (eds) *Management of Temporomandibular Disorders and Occlusion* Mosby, St Louis, MO 245-247.
3. Murphy T (1959) The changing pattern of dentine exposure in human tooth attrition *American Journal of Physical Anthropology* **17** 167-178.
4. Lavelle C (1970) Analysis of attrition in adult human molars *Journal of Dental Research* **49(4)** 822-828.
5. Oh WS, Delong R, & Anusavice KJ (2002) Factors affecting enamel and ceramic wear: A literature review *Journal of Prosthetic Dentistry* **87(4)** 451-459.
6. Ramp MH, Suzuki S, Cox CF, Lacefield WR, & Koth DL (1997) Evaluation of wear: Enamel opposing three ceramic materials and a gold alloy *Journal of Prosthetic Dentistry* **77(5)** 523-530.
7. Yip KH, Smales RJ, & Kaidonis JA (2004) Differential wear of teeth and restorative materials: Clinical implications *International Journal of Prosthodontics* **17(3)** 350-356.
8. Zeng J, Sato Y, Ohkubo C, & Hosoi T (2005) In vitro wear resistance of three types of composite resin denture teeth *Journal of Prosthetic Dentistry* **94(5)** 453-457, http://dx.doi.org/10.1016/j.prosdent.2005.08.010.
9. Ogle RE & Davis EL (1998) Clinical wear study of three commercially available artificial tooth materials: Thirty-six month results *Journal of Prosthetic Dentistry* **79(2)** 145-151.
10. Dahl BL & Oilo G (1994) In vivo wear ranking of some restorative materials *Quintessence International* **25(8)** 561-565.
11. Lambrechts P, Braem M, Vuylsteke-Wauters M, & Vanherle G (1989) Quantitative in vivo wear of human enamel *Journal of Dental Research* **68(12)** 1752-1754, http://dx.doi.org/10.1177/00220345890680120601.
12. Seghi RR, Rosenstiel SF, & Bauer P (1991) Abrasion of human enamel by different dental ceramics in vitro *Journal of Dental Research* **70(3)** 221-225, http://dx.doi.org/10.1177/00220345910700031301.
13. D'Arcangelo C, Vanini L, Rondoni GD, & De Angelis F (2016) Wear properties of dental ceramics and porcelains compared with human enamel *Journal of Prosthetic Dentistry* **115(3)** 350-355, http://dx.doi.org/10.1016/j.prosdent.2015.09.010.
14. D'Arcangelo C, Vanini L, Rondoni GD, Pirani M, Vadini M, Gattone M, & De Angelis F (2014) Wear properties of a novel resin composite compared to human enamel and other restorative materials *Operative Dentistry* **39(6)** 612-618, http://dx.doi.org/10.2341/13-108-L.
15. Elkins WE (1973) Gold occlusal surfaces and organic occlusion in denture construction *Journal of Prosthetic Dentistry* **30(1)** 94-98.
16. Kumar S, Arora A, & Yadav R (2012) An alternative treatment of occlusal wear: Cast metal occlusal surface *Indian Journal of Dental Research* **23(2)** 279-282, http://dx.doi.org/10.4103/0970-9290.100441.
17. Barco MT Jr & Synnott SA (1989) Precision metal occlusal surfaces for removable partial dentures *International Journal of Prosthodontics* **2(4)** 365-367.
18. Elmaria A, Goldstein G, Vijayaraghavan T, Legeros RZ, & Hittelman EL (2006) An evaluation of wear when enamel is opposed by various ceramic materials and gold *Journal of Prosthetic Dentistry* **96(5)** 345-353, http://dx.doi.org/10.1016/j.prosdent.2006.09.002.
19. Park JM, Hong YS, Park EJ, Heo SJ, & Oh N (2016) Clinical evaluations of cast gold alloy, machinable zirconia, and semiprecious alloy crowns: A multicenter study *Journal of Prosthetic Dentistry* **115(6)** 684-691, http://dx.doi.org/10.1016/j.prosdent.2015.10.018.
20. Johnson R, Verrett R, Haney S, Mansueto M, & Challa S (2017) Marginal gap of milled versus cast gold restorations *Journal of Prosthodontics* **26(1)** 56-63, http://dx.doi.org/10.1111/jopr.12432.
21. Rosenblum MA & Schulman A (1997) A review of all-ceramic restorations *Journal of the American Dental Association* **128(3)** 297-307.

22. McLean JW (2001) Evolution of dental ceramics in the twentieth century *Journal of Prosthetic Dentistry* **85(1)** 61-66, http://dx.doi.org/10.1067/mpr.2001.112545.

23. Kelly JR & Benetti P (2011) Ceramic materials in dentistry: Historical evolution and current practice *Australian Dental Journal* **56(Supplement 1)** 84-96, http://dx.doi.org/10.1111/j.1834-7819.2010.01299.x.

24. Ghazal M & Kern M (2009) Wear of human enamel and nano-filled composite resin denture teeth under different loading forces *Journal of Oral Rehabilitation* **36(1)** 58-64, http://dx.doi.org/10.1111/j.1365-2842.2008.01904.x.

25. D'Arcangelo C, De Angelis F, D'Amario M, Zazzeroni S, Ciampoli C, & Caputi S (2009) The influence of luting systems on the microtensile bond strength of dentin to indirect resin-based composite and ceramic restorations *Operative Dentistry* **34(3)** 328-336, http://dx.doi.org/10.2341/08-101.

26. Burke FJ, Fleming GJ, Nathanson D, & Marquis PM (2002) Are adhesive technologies needed to support ceramics? An assessment of the current evidence *Journal of Adhesive Dentistry* **4(1)** 7-22.

27. Rosenstiel SF, Gupta PK, Van der Sluys RA, & Zimmerman MH (1993) Strength of a dental glass-ceramic after surface coating *Dental Materials* **9(4)** 274-279.

28. Malament KA & Socransky SS (1999) Survival of Dicor glass-ceramic dental restorations over 14 years: Part I. Survival of Dicor complete coverage restorations and effect of internal surface acid etching, tooth position, gender, and age *Journal of Prosthetic Dentistry* **81(1)** 23-32.

29. D'Arcangelo C, De Angelis F, Vadini M, D'Amario M & Caputi S (2010) Fracture resistance and deflection of pulpless anterior teeth restored with composite or porcelain veneers *Journal of Endodontics* **36(1)** 153-156, http://dx.doi.org/10.1016/j.joen.2009.09.036.

30. Mahalick JA, Knap FJ, & Weiter EJ (1971) Occusal wear in prosthodontics *Journal of the American Dental Association* **82(1)** 154-159.

31. Hudson JD, Goldstein GR, & Georgescu M (1995) Enamel wear caused by three different restorative materials *Journal of Prosthetic Dentistry* **74(6)** 647-654.

32. Jagger DC & Harrison A (1995) An in vitro investigation into the wear effects of selected restorative materials on dentine *Journal of Oral Rehabilitation* **22(5)** 349-354.

33. Fisher RM, Moore BK, Swartz ML, & Dykema RW (1983) The effects of enamel wear on the metal-porcelain interface *Journal of Prosthetic Dentistry* **50(5)** 627-631.

34. D'Arcangelo C & Vanini L (2007) Effect of three surface treatments on the adhesive properties of indirect composite restorations *Journal of Adhesive Dentistry* **9(3)** 319-326.

35. Manhart J, Chen H, Hamm G, & Hickel R (2004) Buonocore Memorial Lecture. Review of the clinical survival of direct and indirect restorations in posterior teeth of the permanent dentition *Operative Dentistry* **29(5)** 481-508.

36. Barone A, Derchi G, Rossi A, Marconcini S, & Covani U (2008) Longitudinal clinical evaluation of bonded composite inlays: A 3-year study *Quintessence International* **39(1)** 65-71.

37. Jongsma LA, Kleverlaan CJ, & Feilzer AJ (2012) Clinical success and survival of indirect resin composite crowns: Results of a 3-year prospective study *Dental Materials* **28(9)** 952-960, http://dx.doi.org/10.1016/j.dental.2012.04.007.

38. Ruse ND & Sadoun MJ (2014) Resin-composite blocks for dental CAD/CAM applications *Journal of Dental Research* **93(12)** 1232-1234, http://dx.doi.org/10.1177/0022034514553976.

39. Ryder MI & Armitage GC (2016) Minimally invasive periodontal therapy for general practitioners *Periodontology 2000* **71(1)** 7-9, http://dx.doi.org/10.1111/prd.12132.

40. D'Amario M, Baldi M, Petricca R, De Angelis F, El Abed R, & D'Arcangelo C (2013) Evaluation of a new nickel-titanium system to create the glide path in root canal preparation of curved canals *Journal of Endodontics* **39(12)** 1581-1584, http://dx.doi.org/10.1016/j.joen.2013.06.037.

41. Opal S, Garg S, Dhindsa A, & Taluja T (2014) Minimally invasive clinical approach in indirect pulp therapy and healing of deep carious lesions *Journal of Clinical Pediatric Dentistry* **38(3)** 185-192.

42. Heintze SD (2006) How to qualify and validate wear simulation devices and methods *Dental Materials* **22(8)** 712-734, http://dx.doi.org/10.1016/j.dental.2006.02.002.

43. Heintze SD, Faouzi M, Rousson V, & Ozcan M (2012) Correlation of wear in vivo and six laboratory wear methods *Dental Materials* **28(9)** 961-973, http://dx.doi.org/10.1016/j.dental.2012.04.006.

44. Heintze SD, Reichl FX, & Hickel R (2019) Wear of dental materials: Clinical significance and laboratory wear simulation methods—A review *Dental Materials Journal* **38(3)** 343-353, http://dx.doi.org/10.4012/dmj.2018-140.

45. Helvey GA (2014) Classifying dental ceramics: Numerous materials and formulations available for indirect restorations *Compendium of Continuing Education in Dentistry* **35(1)** 38-43.

46. Stawarczyk B, Ender A, Trottmann A, Ozcan M, Fischer J, & Hammerle CH (2012) Load-bearing capacity of CAD/CAM milled polymeric three-unit fixed dental prostheses: Effect of aging regimens *Clinical Oral Investigations* **16(6)** 1669-1677, http://dx.doi.org/10.1007/s00784-011-0670-4.

47. Kramer N, Kunzelmann KH, Taschner M, Mehl A, Garcia-Godoy F, & Frankenberger R (2006) Antagonist enamel wears more than ceramic inlays *Journal of Dental Research* **85(12)** 1097-1100, http://dx.doi.org/10.1177/154405910608501206.

48. Giordano R (2006) Materials for chairside CAD/CAM-produced restorations *Journal of the American Dental Association* **137(Supplement)** 14S-21S.

49. Rocca GT, Bonnafous F, Rizcalla N, & Krejci I (2010) A technique to improve the esthetic aspects of CAD/CAM composite resin restorations *Journal of Prosthetic Dentistry* **104(4)** 273-275, http://dx.doi.org/10.1016/S0022-3913(10)60138-2.

50. Lin CL, Chang YH, & Liu PR (2008) Multi-factorial analysis of a cusp-replacing adhesive premolar restoration: A finite element study *Journal of Dentistry* **36(3)** 194-203, http://dx.doi.org/10.1016/j.jdent.2007.11.016.
51. D'Arcangelo C, Vanini L, Rondoni GD, Vadini M, & De Angelis F (2018) Wear evaluation of prosthetic materials opposing themselves *Operative Dentistry* **43(1)** 38-50, http://dx.doi.org/10.2341/16-212-L.
52. Trubiani O, Caputi S, Di Iorio D, D'Amario M, Paludi M, Giancola R, Di Nardo Di Maio F, De Angelis F, & D'Arcangelo C (2010) The cytotoxic effects of resin-based sealers on dental pulp stem cells *International Endodontic Journal* **43(8)** 646-653, http://dx.doi.org/10.1111/j.1365-2591.2010.01720.x.
53. Trubiani O, Cataldi A, De Angelis F, D'Arcangelo C, & Caputi S (2012) Overexpression of interleukin-6 and -8, cell growth inhibition and morphological changes in 2-hydroxyethyl methacrylate-treated human dental pulp mesenchymal stem cells *International Endodontic Journal* **45(1)** 19-25, http://dx.doi.org/10.1111/j.1365-2591.2011.01942.x.
54. Ferracane JL (2011) Resin composite—State of the art *Dental Materials* **27(1)** 29-38, http://dx.doi.org/10.1016/j.dental.2010.10.020.
55. Tsujimoto A, Barkmeier WW, Fischer NG, Nojiri K, Nagura Y, Takamizawa T, Latta MA, & Miazaki M (2018) Wear of resin composites: Current insights into underlying mechanisms, evaluation methods and influential factors *Japanese Dental Science Review* **54(2)** 76-87, http://dx.doi.org/10.1016/j.jdsr.2017.11.002.
56. Jaarda MJ, Wang RF, & Lang BR (1997) A regression analysis of filler particle content to predict composite wear *Journal of Prosthetic Dentistry* **77(1)** 57-67, http://dx.doi.org/10.1016/s0022-3913(97)70208-7.
57. Shinkai K, Taira Y, Suzuki S, Kawashima S, & Suzuki M (2018) Effect of filler size and filler loading on wear of experimental flowable resin composites *Journal of Applied Oral Science* **26** e20160652, http://dx.doi.org/10.1590/1678-7757-2016-0652.
58. Lang BR, Jaarda M, & Wang RF (1992) Filler particle size and composite resin classification systems *Journal of Oral Rehabilitation* **19(6)** 569-584.
59. Clelland NL, Pagnotto MP, Kerby RE, & Seghi RR (2005) Relative wear of flowable and highly filled composite *Journal of Prosthetic Dentistry* **93(2)** 153-157, http://dx.doi.org/10.1016/j.prosdent.2004.11.006.
60. Hu X, Marquis PM, & Shortall AC (2003) Influence of filler loading on the two-body wear of a dental composite *Journal of Oral Rehabilitation* **30(7)** 729-737.
61. Ilie N, Rencz A, & Hickel R (2013) Investigations towards nano-hybrid resin-based composites *Clinical Oral Investigations* **17(1)** 185-193, http://dx.doi.org/10.1007/s00784-012-0689-1.
62. Suzuki S, Leinfelder KF, Kawai K, & Tsuchitani Y (1995) Effect of particle variation on wear rates of posterior composites *American Journal of Dentistry* **8(4)** 173-178.
63. Suzuki S (2004) In vitro wear of nano-composite denture teeth *Journal of Prosthodontics* **13(4)** 238-243, http://dx.doi.org/10.1111/j.1532-849X.2004.04043.x.
64. Bayne SC, Taylor DF, & Heymann HO (1992) Protection hypothesis for composite wear *Dental Materials* **8(5)** 305-309.
65. Soderholm KJ & Richards ND (1998) Wear resistance of composites: A solved problem? *General Dentistry* **46(3)** 256-263; quiz 264-255.
66. Turssi CP, Ferracane JL, & Vogel K (2005) Filler features and their effects on wear and degree of conversion of particulate dental resin composites *Biomaterials* **26(24)** 4932-4937, http://dx.doi.org/10.1016/j.biomaterials.2005.01.026.
67. Nihei T, Dabanoglu A, Teranaka T, Kurata S, Ohashi K, Kondo Y, Yoshino N, Hickel R, & Kunzelmann KH (2008) Three-body-wear resistance of the experimental composites containing filler treated with hydrophobic silane coupling agents *Dental Materials* **24(6)** 760-764, http://dx.doi.org/10.1016/j.dental.2007.09.001.
68. Stober T, Geiger A, Rues S, Dreyhaupt J, Rammelsberg P, & Ohlmann B (2012) Factors affecting wear of composite resin denture teeth—24-month results from a clinical study *Clinical Oral Investigations* **16(2)** 413-420, http://dx.doi.org/10.1007/s00784-011-0534-y.
69. Heintze SD, Rousson V, & Stober T (2015) Patient- and therapy-related factors on the wear of denture teeth—Results of a clinical trial *Dental Materials* **31(3)** 302-307, http://dx.doi.org/10.1016/j.dental.2014.12.009.
70. Wetselaar P & Lobbezoo F (2016) The tooth wear evaluation system: A modular clinical guideline for the diagnosis and management planning of worn dentitions *Journal of Oral Rehabilitation* **43(1)** 69-80, http://dx.doi.org/10.1111/joor.12340.
71. Ilie N, Hilton TJ, Heintze SD, Hickel R, Watts DC, Silikas N, Stansbury JW, Cadenaro M, & Ferracane JL (2017) Academy of Dental Materials guidance—Resin composites: Part I—Mechanical properties *Dental Materials* **33(8)** 880-894, http://dx.doi.org/10.1016/j.dental.2017.04.013.
72. Krejci I & Lutz F (1990) In-vitro test results of the evaluation of dental restoration systems. Correlation with in-vivo results *Schweizer Monatsschrift für Zahnmedizin* **100(12)** 1445-1449.
73. Hu X, Zhang Q, Ning J, Wu W, & Li C (2018) Study of two-body wear performance of dental materials *Journal of the National Medical Association* **110(3)** 250-255, http://dx.doi.org/10.1016/j.jnma.2017.05.009.
74. Heintze SD, Cavalleri A, Forjanic M, Zellweger G, & Rousson V (2008) Wear of ceramic and antagonist—A systematic evaluation of influencing factors in vitro *Dental Materials* **24(4)** 433-449, http://dx.doi.org/10.1016/j.dental.2007.06.016.
75. Faria ACL, de Oliveira AA, Alves Gomes E, Silveira Rodrigues RC, & Faria Ribeiro R (2014) Wear resistance of a pressable low-fusing ceramic opposed by dental alloys *Journal of the Mechanical Behavior of Biomedical Materials* **32** 46-51, http://dx.doi.org/10.1016/j.jmbbm.2013.12.018.
76. Condon JR & Ferracane JL (1997) In vitro wear of composite with varied cure, filler level, and filler treatment *Journal of Dental Research* **76(7)** 1405-1411, http://dx.doi.org/10.1177/00220345970760071101.

OPERATIVE DENTISTRY

CORPORATE SPONSORS

These Dental Manufacturers have joined Operative Dentistry in our commitment to publish quality dental literature in a timely manner. We thank them for their support.

OPERATIVE DENTISTRY

Volume 45 / Number 3
May/June 2020

www.jopdent.org
229–340

CLINICAL TECHNIQUE/CASE REPORT

CLINICAL RESEARCH

LITERATURE REVIEW

LABORATORY RESEARCH

DEPARTMENTS

ONLINE ONLY ARTICLES