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Flight over the Black Sea, Foros, Ukraine. Photo provided by Kevin Matis of Indianapolis, Indiana, USA. Photo taken with a Nikon D70, 85mm f/11 1/500 sec. © Operative Dentistry, Inc..

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Case Reports of Enamel Microabrasion Associated with At-home Dental Bleaching After Orthodontic Bracket Removal

CC Pavani • LR Vieira • TC Schott • D Sundfeld
NIP Pini • APM Bertoz • RR Pacheco • RH Sundfeld

Clinical Relevance

Enamel microabrasion is a successful technique that can be employed for enamel surface regularization/polishing after orthodontic bracket removal.

SUMMARY

Adequate removal of residual bonded materials from the enamel surface after orthodontic bracket debonding is critical, since any remaining composite may compromise enamel surface morphology and esthetics. The following clinical

case reports present the association of at-home dental bleaching using 10% carbamide peroxide and the removal of residual bonded material using a super fine, tapered diamond bur followed by the use of an enamel microabrasion product after orthodontic bracket debonding. The proposed treatment considerably improved the esthetics and

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successfully removed the grooves created during the removal of the bonding composite, resulting in a smooth enamel surface.

INTRODUCTION

Resin-based materials are typically used to bond orthodontic brackets to dental enamel surfaces, following adhesive protocols that are well-established in the dental literature.¹ However, thorough removal of adhesive materials is often necessary after orthodontic bracket debonding due to the high bond strength of resin-based materials to enamel surfaces. Several protocols for the removal of these bonding materials have been described to include the use of bracket-removing pliers, tungsten and/or titanium carbide burs, fine/super-fine/ultra-fine burs, aluminum oxide discs, diamond burs, erbium-doped yttrium aluminium garnet laser, ultrasonic tools, “Arkansas” stones, green stones, steel burs, enamel chisels, fiberglass burs, and air-abrasion with bioactive glass.²⁻¹⁸ However, there is no standardized protocol regarding their effectiveness. Thus, many professionals tend to neglect the important orthodontic treatment step.

The inadequate removal of resin-based materials can result in iatrogenic enamel harm, producing enamel surface morphological alterations that may compromise esthetics and increase biofilm accumulation.^{3,19} Although superficial enamel alterations appear to be inevitable during adhesive removal, the damage can be reduced to a negligible level if the proper technique is selected.^{4,15-17} It is worth mentioning that the enamel surface should receive a polishing treatment after residue removal, regardless of the technique used. The inclusion of a polishing treatment improves the texture and surface smoothness of the enamel surface, approximating normal clinical conditions.^{17,20}

An appropriate clinical technique for the esthetic removal of orthodontic bracket adhesive could include the use of a super-fine diamond bur, followed by the application of a microabrasive paste, and at-home vital-tooth bleaching procedures.^{14,15,17,21} A survey²² of 267 orthodontists showed a high variability in methods used for bracket removal, residue removal, and polishing protocols. Thus, it is important to discuss clinical techniques for the adequate removal of resin-based materials that would “restore” the enamel surface to its pretreatment condition, that is, a technique that reduces the iatrogenic effects to the enamel surface to an insignificant level.^{2,23}

The present clinical case series aims to describe the association of at-home dental bleaching with enamel microabrasion for removing grooves created during composite removal. The use of different clinical techniques for the removal of resin-based remnants has also been discussed.

CASE REPORTS

Case Report #1 (At-home Dental Bleaching Followed by Microabrasion)

A 25-year-old female patient presented to the Restorative Dentistry Clinic at the School of Dentistry with a chief complaint of “darkened teeth” one month after orthodontic bracket debonding and the removal of residual bonded material from the buccal surfaces of maxillary incisors, canines, and premolars. The orthodontic treatment was performed for 6 months to correct an open bite in the maxillary anterior teeth region. The patient’s teeth presented residual bonded material on the buccal enamel, with morphological surface alterations caused by the adhesive removal procedures, represented by the presence of superficial irregularities and grooves (Figure 1). The proposed

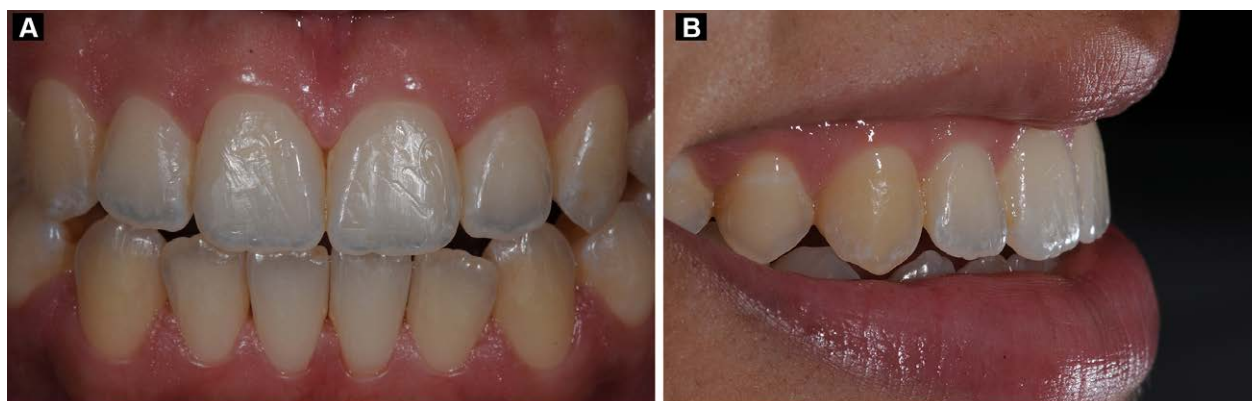


Figure 1. A 25-year-old patient presenting with residual bonded material and morphological surface alterations in the buccal enamel of maxillary teeth after orthodontic bracket debonding. (A): Intraoral view of anterior teeth. (B): Extra-oral photo of the patient's smile.

treatment plan was dental bleaching followed by enamel microabrasion. The patient was informed of the negligible and harmless removal of enamel when utilizing the microabrasion technique. The patient was informed on the quality and longevity of the achieved superficial smoothness from enamel microabrasion by a clinician with 30 years of clinical experience.

Initially, at-home dental bleaching was performed in both arches using 10% carbamide peroxide gel (Opalescence 10%; Ultradent Products Inc, South Jordan, UT, USA). The initial shade of the maxillary central incisors was recorded as A2 using a shade guide (Vitapan Classical Shade Guide; Vita Zahnfabrik, Bad Säckingen, Germany) (Figure 2). Maxillary and mandibular acetate trays were fabricated from casts made of the patient's dental arches. During the bleaching treatment, the patient was instructed to place a drop of 10% carbamide peroxide into each tooth section of the acetate trays and to use both trays at the same time for 6–8 hours each day. Three syringes (1.2 mL each) of dental bleaching product were used over 21 days of bleaching treatment. The final shade was recorded as B1 (Figure 3) upon completion of the bleaching treatment. Neither gingival irritation nor dental sensitivity were observed during treatment.



Figure 2. Initial shade match of maxillary central incisors as A2 (Vitapan Classical Shade Guide; Vita Zahnfabrik).



Figure 3. Final shade match of maxillary central incisors as B1 (Vitapan Classical Shade Guide; Vita Zahnfabrik).

One week after dental bleaching, the residual bonded material was removed from the maxillary teeth using a super-fine tapered diamond bur (15 μ m, #3195 FF; KG Sorensen, Barueri, Brazil) in a high-speed handpiece (KaVo 505C Extratorque; KaVo do Brasil Ind) under water-cooling (macroabrasion) (Figure 4A). The enamel surface was verified under reflector light and with tactile assessment using a #5 dental explorer to ensure complete removal of residual resin. Enamel microabrasion was then performed under rubber dam isolation using a microabrasive product (Opalustre; Ultradent Products Inc) to finalize the enamel surface. The microabrasive product was applied using a specific rubber cup (OpalCups; Ultradent Products Inc) in a low-speed handpiece (KaVo MicroMotor; KaVo do Brasil Ind, Joinville, SC, Brazil) and at a slow rotation speed, to prevent splattering of the product (Figure 4B). Three applications of 60 seconds each were performed on each of 4 teeth, with the teeth being rinsed with water/air spray between each application. The enamel surfaces were polished using a fluoride-containing paste (Herjos; Vigodent SA Indústria e Comércio, Rio de Janeiro, Brazil) (Figure 4C), water-rinsed and air-dried, and immediately received a topical application of 2% neutral-pH sodium fluoride gel for 4 minutes

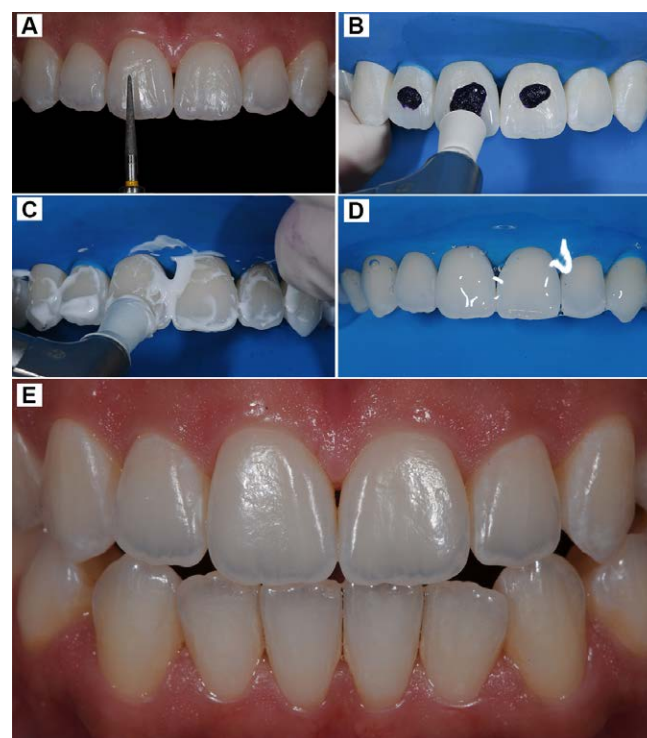


Figure 4. (A): Removal of bonded material using a fine-tapered diamond bur. (B): Application of enamel microabrasive product. (C): Polishing of enamel surfaces with fluoride paste. (D): Topical application of 2% neutral-pH sodium fluoride gel. (E): 14-day follow-up.

(Figure 4D). A 14-day follow-up was performed, and excellent clinical results were observed for the enamel surface (Figure 4E).

Impressions of the upper and lower central incisors were taken before and after the clinical procedures using polyvinyl siloxane impression material (Express XT Putty and Light Body; 3M Oral Care, St Paul, MN, USA) in order to fabricate epoxy resin (Epo-thin resin; Buehler, Düsseldorf, Germany) replicas to evaluate the enamel surface under a stereo-microscope (SteREO Discovery.V20; Carl Zeiss Microscopy GmbH, Jena, Germany) under 7.5x and 30x magnifications (Figures 5, 6, and 7). The middle-thirds of the buccal surfaces of all teeth demonstrated that the application of the

microabrasive product, after the use of a diamond bur for the removal of residual resin material, was effective for creating a uniform and smooth enamel surface.

Case Report #2 (Microabrasion Followed by At-home Dental Bleaching)

An 18-year-old female patient presented to the Restorative Dentistry Clinic at the School of Dentistry, with residual

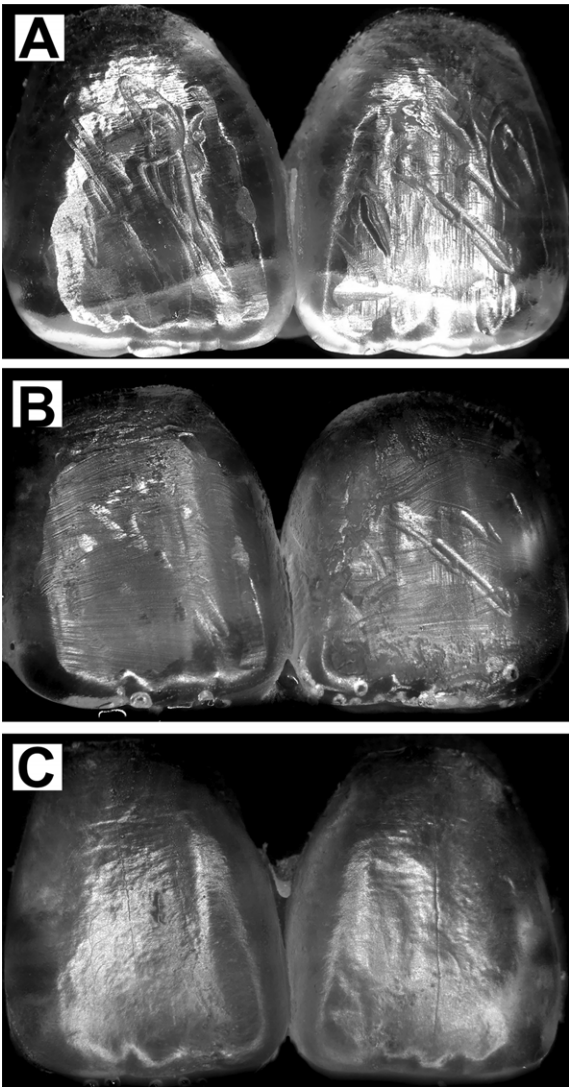


Figure 5. Microscopic images of buccal surface of maxillary central incisors. (A): Initial. (B): After macroabrasion for removal of residual bonded material with application of a diamond fine-tapered bur. (C): After application of enamel microabrasive, at 7.5x magnification.

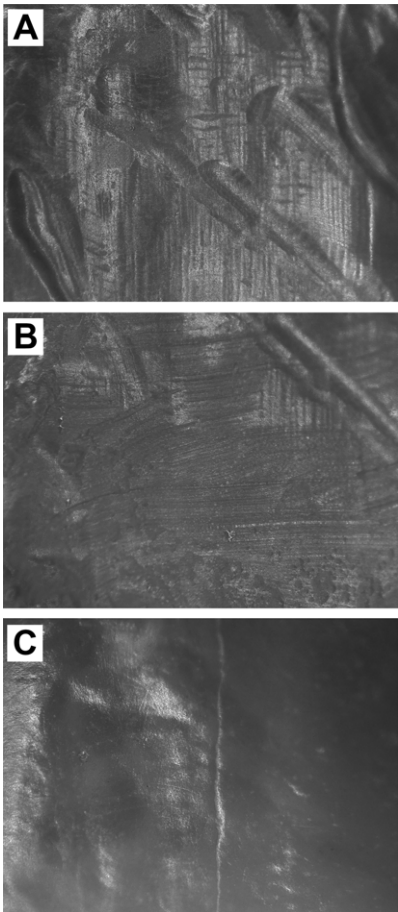


Figure 6. Microscopic images of buccal surface of maxillary central incisors. (A): Initial. (B): After macroabrasion for removal of residual bonded material with application of a diamond fine-tapered bur. (C): After application of enamel microabrasive, at 30x magnification.

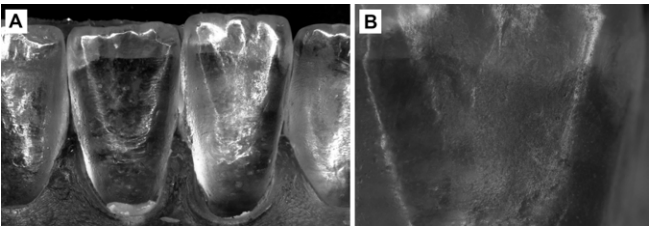


Figure 7. Microscopic images of buccal surfaces of mandibular central incisor teeth. (A): At 7.5x magnification. (B): At 30x magnification.



Figure 8. Initial view after bracket debonding (A), depicting scratched enamel surfaces due to improper removal of resin cement (B and C).

bonded material and morphological alterations on the buccal surfaces of her maxillary and mandibular incisors, canines, and premolars (Figures 8 and 9). The orthodontic treatment was performed to correct an open bite in the maxillary anterior teeth region. The proposed treatment plan was dental bleaching followed by enamel microabrasion. The patient was informed of the negligible and harmless removal of enamel when utilizing the microabrasion technique. The patient was informed on the quality and longevity of the achieved superficial smoothness from enamel microabrasion by a clinician with 30 years of clinical experience.

The protocol used for removing the residual bonded material and enamel grooves/irregularities started with a super-fine diamond bur (15 μ m, #3195 FF; KG Sorensen) (Figure 10), followed by microabrasion of the enamel under rubber dam isolation, with 3 applications of the microabrasive product (Opalustre; Ultradent Products Inc), using a specified rubber cup (Figure 11). The enamel surfaces were polished using a fluoride paste (Herjos; Vigodent SA Indústria e Comércio) (Figure 12A), water-rinsed and air-dried, followed by the immediate topical application of 2% neutral-pH sodium fluoride gel for 4 minutes (Figure 12B). Effective regularization and adequate smoothness of the enamel surface was obtained.

After one week, at-home dental bleaching using a 10% carbamide peroxide (Opalescence; Ultradent Products

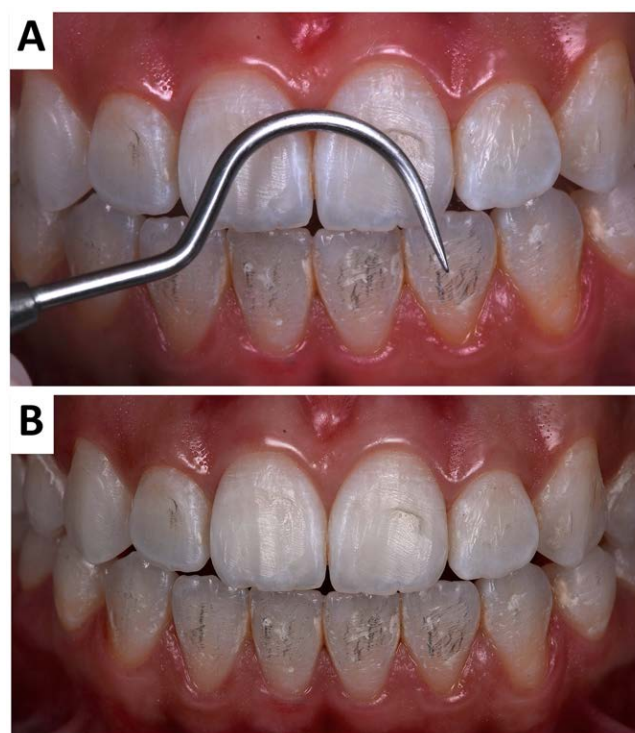


Figure 9. Resin cement highlighted with an exploratory probe (A and B).

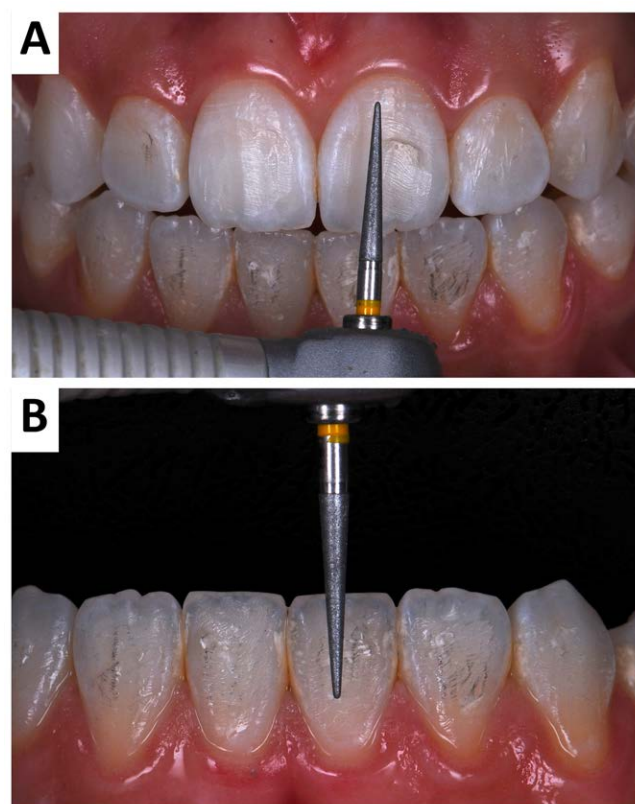


Figure 10. Residual resin cement removal using a fine-tapered diamond bur (A and B).

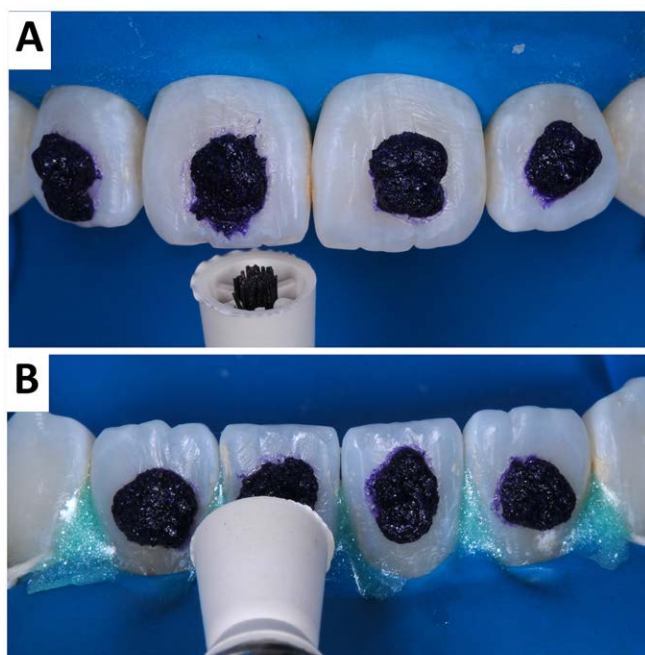


Figure 11. Application of the microabrasive product (Opalustre; Ultradent Inc) on the facial surface using a specific rubber cup (OpalCups; Ultradent Inc) (A and B).



Figure 12. Application of a prophylaxis paste (A) followed by 2% neutral-pH sodium fluoride gel (B).

Inc) for 2 weeks was prescribed. The initial and final shades of the maxillary central incisors were recorded as A1 and B1, respectively, using a shade guide (Vitapan Classical Shade Guide; Vita Zahnfabrik) (Figure 13).

DISCUSSION

Removal of bonded orthodontic brackets involves the risk of damaging the enamel surface and altering



Figure 13. Final aspect after home-dental bleaching using carbamide peroxide, depicting a smooth, clean, and healthy upper (A) and lower (B) enamel surface.

its morphology. Restoring the enamel to its original morphology, to include surface regularity and texture, is an even bigger challenge. The bonding procedures of orthodontic brackets to the tooth structure involves acid etching of the enamel surface and resin-based materials (adhesive systems, resin composites, resin cements). Upon completion of orthodontic treatment, and subsequent bracket removal/debonding, the enamel surfaces must be carefully treated so that the residual bonded material is properly removed in order to prevent surface alterations. All these steps involve the risk of damaging the enamel surface and changing its original morphology.¹⁸ Improper residue removal can lead to discoloration and increased biofilm accumulation.^{3,19} The present clinical case series describes the use of an enamel microabrasion technique after orthodontic bracket removal in order to produce a smooth enamel surface, after the use of a super-fine diamond bur for the removal of bonded resin-based materials.

Although *in vitro* studies describe different residue removal methods after bracket debonding, there is no consensus on which technique is most suitable for addressing the damage caused to the enamel. A systematic review⁵ reported that the most popular technique for residue removal was the use of tungsten carbide burs, which was deemed a faster and more effective technique when compared with the use of aluminum oxide discs, ultrasonic tools, hand instruments, rubber points, and/or diamond composite burs. However, the use of tungsten carbide burs may not be enough to completely remove the residual bonded material.²⁴⁻²⁶ Furthermore, when these burs are used in association with high-speed handpieces, the enamel surface roughness can increase, similar to the roughness caused by an ultra-fine diamond bur.⁴

The use of diamond burs leads to the formation of grooves on the enamel surface that are proportional to the abrasives present in these burs¹⁷ (Figure 1). Similarly, the use of aluminum oxide discs can also create grooves/scratches on the enamel surface,⁶ which also require a polishing protocol to minimize damage to the enamel surface. Another study²⁷ reported that the association of a fine diamond bur with twelve 20-fluted carbide burs after bracket debonding yielded a rougher enamel surface than a sound enamel surface. Based on multiple reports, it is possible to conclude that proper residue removal from the enamel surface without damage to the enamel is difficult to achieve.³

Another protocol has been suggested⁶ by using a 30-blade tungsten carbide bur at high-speed, followed by abrasive-containing rubber tips (Enhance; Dentsply Sirona, Inc, York, PA, USA) and a final polishing with aluminum oxide paste. This procedure seems to produce less harm to the enamel surface and requires less chair-side time. Polishing with a pumice paste has been shown to be inadequate for providing adequate enamel surface roughness after residue removal using 12 (fine), 16 (super-fine), and 20 (ultra-fine) blade titanium carbide burs.^{7,13} A split-mouth design clinical study²⁰ observed that the use of either aluminum oxide discs or a microabrasive product were efficient methods for smoothing the surface of dental enamel. However, the application of the microabrasive product more consistently regularized the dental enamel surfaces independently of the number and/or magnitude of grooves, while the aluminum oxide discs were not efficient for surfaces with deeper grooves and irregularities. This fact could be observed in the images of Case Report #1, which were made with the stereo microscope under 7.5x and 30x magnification (Figures 5 and 6).

The microabrasion technique is commonly employed to remove intrinsic stains or smooth enamel, resulting in an increased glossiness.^{17,28,29} In addition, an enamel surface with reduced roughness is more resistant to colonization by *Streptococcus mutans*.³⁰ This “abrasion effect” is created by the compaction of minerals from the product’s abrasive acid action on the dental enamel.^{31,32} The microabrasion technique removes 25 μm of dental enamel for each 1-minute application (10 applications would remove 200 μm), on average.¹⁵ It is worth mentioning that only 3 applications of the microabrasive product were used for each of the presented case reports, suggesting minimal enamel loss when compared with the amount of remaining enamel. Therefore, enamel microabrasion can be considered a minimally invasive approach that may be safely used for this purpose. A microscopic analysis was conducted for Case Report #1 (Figures 5 and 6) in order to assess if the

acid/abrasive action reached the deeper regions of the superficial enamel grooves, leaving them considerably regular and polished. This was evident by comparing the buccal surface of the maxillary central incisors to the buccal surfaces of the mandibular central incisors, which were and were not submitted to orthodontic treatment, respectively (Figure 7).

Both clinical cases in the present report resulted in desirable shade alteration without sensitivity during and/or after the treatment. The recommendation of when the bleaching procedures should be conducted (prior to or after residue removal) did not affect shade alteration. The action of the bleaching product occurs intrinsically by diffusion of their by-products through the entire dental substrate and is not affected by the presence of a small amount of resin-bonded material.¹⁴ It should be noted that for Case Report #1 both dental arches required the same 21 days of bleaching treatment for a satisfactory result, even with the mandibular arch having no residual bonded material, since it did not receive orthodontic treatment.

The presence of residual bonding material and superficial grooves in both clinical cases were clearly visible on the buccal surfaces after bracket debonding, justifying the application of a diamond bur followed by enamel microabrasion, a technique commonly employed.¹⁴⁻¹⁷ The enamel microabrasion technique allowed for adequate removal of the residual bonding material and regularization of the enamel surface through the acid/abrasive action of the microabrasive product. Removing the adhesive remnants with a super-fine diamond bur (macroabrasion) did not lead to substantial enamel loss, but it promoted complete removal of the adhesive materials, as seen in Figures 5 and 6. Enamel microabrasion achieved a highly polished/smooth enamel surface; consequently, glossy and natural-looking enamel can be verified in Figures 4E and 13.

CONCLUSIONS

The association of at-home dental bleaching with enamel microabrasion was effective for obtaining satisfactory shade alteration associated with a smooth and regular enamel surface after orthodontic bracket debonding, highly contributing to improved dental esthetics.

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.

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Single-Tooth Rehabilitation Combining Root Displacement and Crown Lengthening Two-Year Follow-Up: A Case Report

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Clinical Relevance

Combined techniques to expose circumferential tooth structure associated with subsequent restoration may represent a valid option in many situations. This case provides an example of the successful management of the anterior tooth rehabilitation combining root displacement and crown lengthening.

SUMMARY

Rehabilitation of an extensively compromised single anterior tooth represents an intriguing challenge for dentists, particularly when the rehabilitation involves esthetic, psychosocial, and functional requirements. The success in rehabilitating a patient with a conservative approach depends on a critical evaluation of the remaining structures, precise treatment plan, systematic treatment strategies, and patient compliance. In this case,

the patient's chief complaint was the undesirable appearance of the maxillary right lateral, caused by the displacement of the post and crown. Clinical examination revealed a remaining tooth with coronal fracture, severe loss of tissue due to caries, and absence of ferrule effect. Radiographic examination revealed that the fracture margin was located subgingival. This case report describes a single-tooth rehabilitation involving a combination of root displacement via orthodontic extrusion and crown lengthening. The rehabilitation was followed

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by post-and-core restoration using a prefabricated glass fiber post associated with a disilicate lithium crown. The clinical decision making and combined effect of both treatment strategies are explained in this report. The treatment required three months, including recovery times after surgery and the placement of the provisional crown. The patient was esthetically and functionally satisfied with the restoration. Patient follow-up examination was performed 24 months after the treatment. This clinical report contributes to the clinical practice and exemplifies the possibility of rehabilitating the natural tooth using combined techniques, which may offer particular advantages regarding prognosis and invested efforts.

INTRODUCTION

Failures of post-restored and endodontically treated teeth often occur in anterior due to trauma, secondary caries, or post-and-core displacement.¹ The rehabilitation of teeth with extensive loss of coronal tooth structure represents one of the most challenging scenarios for dentists.² Typical treatment options including implant-supported single crowns or fixed partial dentures have evolved as the primary choice of therapy for these cases.³ Still, whenever possible, conservative procedures that preserve existing structure should be included in the treatment plan.

The preservation of tooth structure is utmost in maintaining the balance among biological, mechanical, functional, and esthetic parameters.⁴ The clinician must be able to assess the dimensions of the remaining tooth structure as well as the influences of biological and occlusal factors. The decision to treat a tooth endodontically should be based on prosthetic restoration of the tooth, bone quality, esthetic demands, cost-benefit ratio, systematic factors, potential adverse effects, and patient preferences.⁵ The assessment of these critical factors allows the clinician to make clinical decisions based on the best evidence and is in the patient's best interest.⁶ The periodontal ligament absorbs the occlusal loads and provides a better transfer of force at the root interface level.⁷ Furthermore, implant placement may be subsequently performed in the event of failure of conservative structure-preserving approaches.⁸

When performing restoration of endodontically treated teeth with extensive loss of coronal tooth structure, the presence of ferrule is highly relevant for the expected mechanical behavior of restored teeth.⁹ The clinician should use available tissue to provide a ferrule whenever possible.¹⁰ Prosthetic and periodontal

factors should be taken into account to ensure a ferrule with the desired height and circumferential area.¹¹ Ferrule height values from 1 to 2 mm have been shown to provide improved survival of extensively damaged endodontically treated existing structures.⁹

Another critical factor to take into account is the crown-to-root ratio. Different techniques can be performed to reestablish the ferrule before beginning the restoration. Surgical crown-lengthening procedure refers to osteotomy procedures followed by an apical flap repositioning to the reinstatement of biologic width.¹² However, this conventional surgical approach may compromise the crown-to-root ratio and lead to an unpleasing gingival alignment and extremely long clinical crowns.¹³ Slow root displacement by orthodontic extrusion is a less invasive and viable alternative for reinstatement of biologic width, with the advantage of allowing the gingival papilla to keep surrounding the teeth.¹⁴ The intended orthodontic movement of the tooth often results in the displacement of the gingival margin by approximately 80% of the total amount of extrusion.¹⁵ In this approach, the crown-to-root ratio of the erupted tooth slightly increases, thus improving the long-term periodontal prognosis and esthetic appearance facilitating the subsequent prosthetic rehabilitation.

This case report documents successful conservative structure-preserving treatment with the use of the combined techniques described above: root displacement by orthodontic extrusion and minimally invasive crown lengthening for the rehabilitation of anterior tooth with extensive loss of coronal tooth structure.

CLINICAL CASE REPORT

A healthy 38-year-old man presented for comprehensive evaluation complaining about the undesirable appearance of the maxillary right lateral, caused by the displacement of the post and crown. Clinical examination revealed a coronal fracture, destruction due to caries, and absence of ferrule effect (Figure 1). The following equipment was used to photograph the patient: camera Nikon D7000; macro lens micro-NIKKOR 105 mm, Nikon; Flash, Nikon R1C1 wireless close-up Speedlight; Light softboxes 30 x 20 cm (Nikon Corp, Tokyo, Japan). The radiographic examination revealed a subgingival fracture margin extended almost to the alveolar crest level on the facial surface (Figure 1). A multidisciplinary treatment was discussed, and informed consent was obtained by the patient. The decision was made to perform crown lengthening with orthodontic extrusion and periodontal surgery and subsequent restorative treatment with a fiber post and crown treatment.

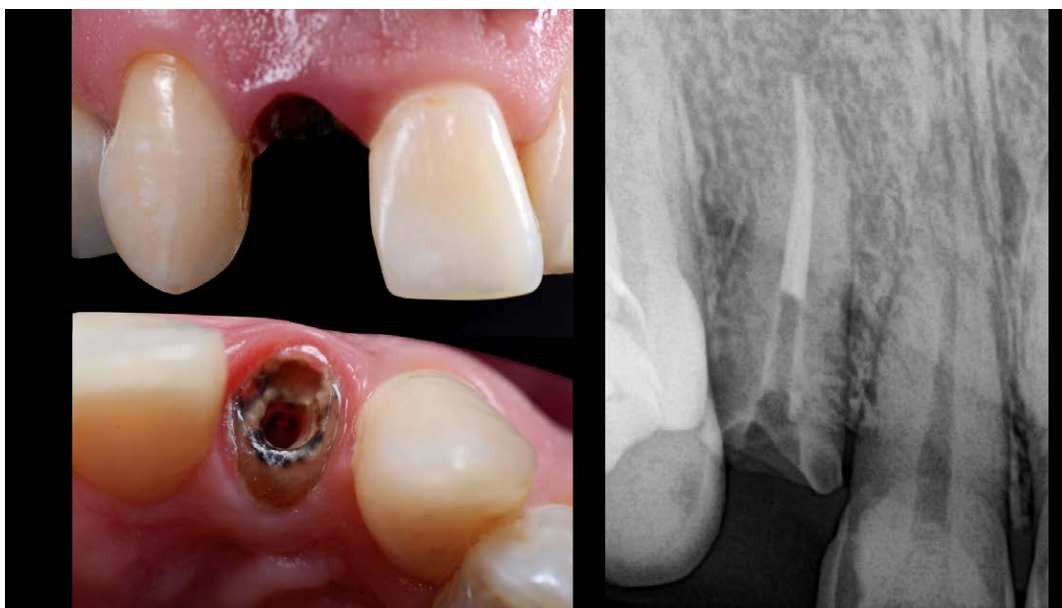


Figure 1. Preoperative labial and occlusal views of coronal fracture on tooth 7 with invasive margins evident in the vicinity of the alveolar ridge. Initial radiograph examination.

Since the endodontic treatment was acceptable, the orthodontic extrusion was initiated. The orthodontically guided extrusion made use of the patient's existing post and crown. A provisional crown was relined with self-cure temporary resin (Alike, GC, Alsip, IL, USA) to reach the internal fit. The temporary restoration was cemented with glass ionomer (GC Fuji Temp LT, GC, Tokyo, Japan). Afterward, passive sectional 0.022 inches x 0.028 inches Edgewise standard brackets were bonded cement (Morelli, Sorocaba, SP, Brazil) using an orthodontic bonding (Orthocem, FGM, Joinville, SC, Brazil) on maxillary teeth (tooth 6 and tooth 8). The maxillary right lateral bracket was positioned toward the cervical third. After, a stainless steel archwire (0.017 inches x 0.025 inches) was placed passively in teeth (tooth 6 and tooth 8). For the maxillary right lateral incisor, the wire was not inserted into the bracket but subjected to active extrusion force promoted by two elastomeric rings (Figure 2).

The incisal and lingual portions of the provisional restoration were reduced to prevent occlusal interference during extrusive movement. A simple orthodontic assembly was used to apply force along the long axis of the tooth root. Extrusion of 2-3 mm was obtained in three weeks (Figure 2). Following extrusion, it is essential to establish a healing time, allowing the mineralization of the bone and maturation of the tissues around the extruded teeth, for approximately two to three months.

Periodontal surgery was performed to level the soft tissues after reaching the planned orthodontic extrusion

(Figure 3). The provisional crown was removed with the aid of ultrasonic instrumentation, and the surgical procedure was conducted. Local anesthesia with 2% lidocaine and epinephrine was applied. An intrasulcular incision was made using a #15C surgical blade (Swann-Morton, Sheffield, England), and it was extended to each side of the adjacent tooth. Full-thickness mucoperiosteal flaps were raised both labially and lingually with Molt periosteal elevator (Hu-Friedy, Chicago, IL, USA; Figure 3). Granulation tissue was thoroughly removed with Gracey periodontal curettes (Hu-Friedy; Figure 3).

Furthermore, bone architecture recontouring was performed using Ochsenbein periodontal chisels (Hu-Friedy; Figure 3). At this time, it should be highlighted that dentists must take care to remove all interproximal bone to prevent inadvertent trauma to the teeth. The distance from the tooth fracture margin to the crest of the alveolar bone was measured with a probe (Hu-Friedy; Figure 3).

Next, an intraoperative tooth preparation was carried out (diamond bur, 8850F, Kommet, Lemgo, Germany) after osteotomy and osteoplasty, positioning the margins at a distance of at least 1 mm from the gingival level. This step facilitates the elimination of undercuts, root proximity correction, and smoothing and cleansing of root surfaces by removing calculus and cement remnants.¹⁶ The flap was closed (Nylon 6:0, Shalon Medical, Goiânia, GO, Brazil) with vertical mattress sutures anchored to the periosteum with the rationale of obtaining a greater closure strength and a

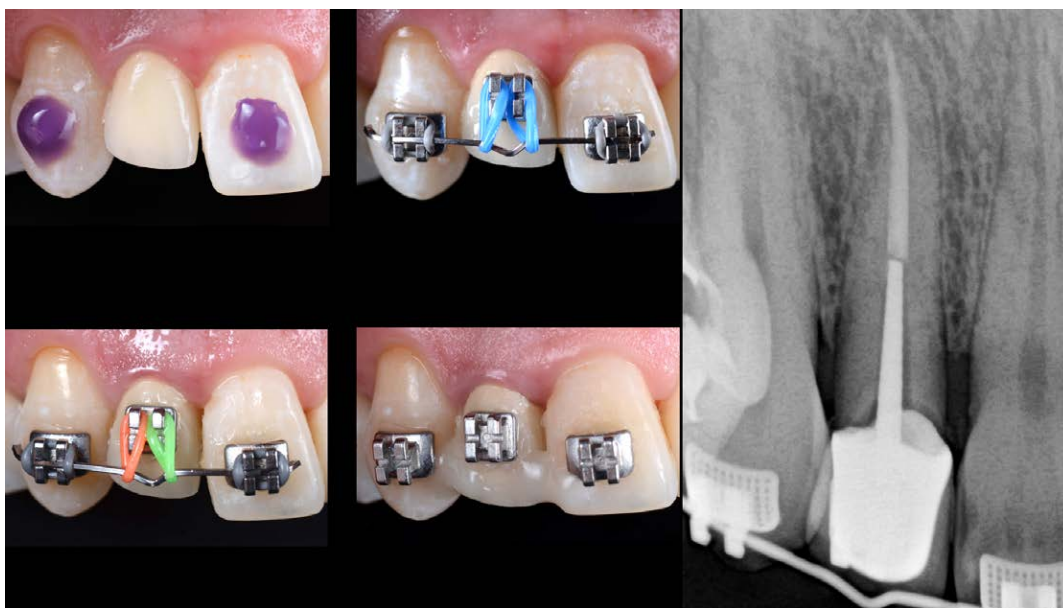


Figure 2. Phases of the orthodontic extrusion of the maxillary, right lateral incisor. Note the elastic thread was exerting force against the rectangular wire and the coronal migration of the gingival tissue. After three weeks, the extrusion was deemed sufficient and then splinted to the adjacent teeth. Post extrusion radiograph.



Figure 3. Close-up views of the clinical sequence of surgical crown lengthening performed on the maxillary right lateral incisor

better distribution of tension in the underlying tissues at the desired apical position (Figure 3). Finally, the patient was instructed to rinse the area twice a day with a 0.12% chlorhexidine solution (PerioAid, Dentaïd, Barcelona, Spain) during the following week. The suture was removed after 14 days.

In the follow-up appointment, the gutta-percha in the root canal was partially removed using #2 Largo Peeso

and #2 Peeso reamer post drills (Figure 4). After this step, a periapical radiograph was employed to check the preparation and to select the fiber post size, according to the anatomical dimensions of the root canal (Figure 4). The chosen fiber post (Whitepost-DC-E #2, FGM, SC, Joinville, Brazil) was demarcated and cleaned with ethyl alcohol blended 70%. Then, phosphoric acid at 37% (Gel Etchant, SDS Kerr, Brea, CA, USA)



Figure 4. Root canal preparation by post drill #2. Bonding procedures. Periapical radiograph to check the adaptation of the fiber post. Temporary restoration.

was applied for 30 seconds, followed by water rinsing and light air-drying. An organosilane (Prosil, FGM) and an etch-and-rinse adhesive system (Ambar, FGM) were applied following the manufacturer instructions. Light-curing was performed for 20 seconds with a light-emitting diode (LED) curing unit (Valo, Ultradent, South Jordan, UT, USA) with 1000 mW/cm².

At the same time, the root canal was etched with 37% phosphoric acid for 15 seconds, followed by water rinsing and light air-drying and then carefully dried with absorbent paper before the bonding procedure. An adhesive system was applied to the root canal walls with a microbrush (Figure 4). The adhesive excess was removed with absorbent paper points. Light-curing of the adhesive was performed for 24 seconds with a LED light source in high power mode at 1400 mW/cm². The dual-curing resin cement (Allcem Core, FGM) was directly applied into the canal and onto the fiber post surface, and the fiber post was placed into the final position and stabilized (Figure 4). It was light-cured for 40 seconds with a LED light source at 1000 mW/cm².

Next, the tooth was prepared, and a provisional restoration was performed (Figure 4). The early tooth preparation offers the following advantages¹⁷: less aggressive abutment preparation; no interference from the temporary phase with the reestablishment of the biologic width; easy supragingival preparation using the healed soft-tissue margin as a guide; easy supragingival relining of the provisional restoration; conditioning of the soft tissues during the maximal regrowth period;

and no need for retraction cords during abutment preparation and relining of the temporary restoration (necessary in the case of delayed tooth preparation and provisional relining) (Figure 4).

After 60 days of surgical follow-up, the soft tissue displayed stability, and the final restoration was planned. The crown preparation was finished using an 8850F diamond bur and H375R carbide bur (Kommet) on a 1:5 increaser contra-angle (TI Max X95, NSK, Tochigi, Japan) to enhance the preparation before impression. The prepared areas were then polished using silicone points (Jiffy, Ultradent, South Jordan, UT, USA). A two-step impression was performed with heavy-body followed by light-body addition silicones (President, Coltene, Altstätten, Switzerland). All information, including a set of photographs and impressions, was sent to the laboratory.

A bilaminar lithium disilicate crown (IPS e.max Press and Ceram, Ivoclar Vivadent, Schaan, Liechtenstein) was prepared in the laboratory. Shape, color, and contact points of the restoration were checked during a try-in appointment. The final ceramic crown had the internal surface acid treated using 10% hydrofluoric acid for 20 seconds (Dentsply, Petrópolis, RJ, Brazil). The restoration was cleaned with 37.5% phosphoric acid for 10 seconds, followed by a water rinsing. The ceramic crown was placed in an ultrasonic bath with distilled water for 4 minutes to remove residual acid and then dried. An organosilane (Prosil, FGM) was applied for one minute and lightly air-dried. An adhesive system (Ambar APS, FGM) was used

following the manufacturer guidelines. The tooth preparation was cleaned with pumice stone and water, rinsed thoroughly with water, and surface dried.

Modified dental dam isolation (Nictone, Zapopan, Jal, Mexico) and a retraction cord 000 (Ultrapack-Ultradent) were placed before the bonding procedures. The surfaces of the adjacent teeth were protected with Teflon tape during etching for 15 seconds. An adhesive system (Ambar, FGM) was applied and light-cured for 20 seconds. Before the light cure of adhesive internally applied in the restoration, a luting cement (All Cem, FGM) was loaded into the crown. The crown was then placed over the prepared tooth for correct fitting and alignment. The excess cement was removed using a silicone point polishing tip (KG Sorensen, Cotia, SP, Brazil) and dental floss (Superfloss, Oral B, Ireland). The restoration was light-cured for three seconds, and a thin coat of glycerin was applied to block the air. The curing was then completed with light activation for 40 seconds on each side. The remaining cured cement was removed using a #12 surgical blade. The rubber dam was removed, and the patient was asked first to perform closure without force and then centric, protrusive, and lateral excursions.

A follow-up examination was performed 24 months after the treatment. Clinical and radiographic images taken during the follow-up examination demonstrate that the bone levels, gingival architecture, and esthetic appearance remained stable, as shown in Figures 5 and 6.

DISCUSSION

Evidence supports that the use of implant-supported single crowns results in reliable long-term outcomes with a five-year survival rate reaching 96.8% (95% confidence interval [CI]: 95.9-97.6).¹⁸ It would be reasonable to suggest that dentists adopt implant-supported single crowns as a treatment for this case. Nevertheless, biological and technical complications such as peri-implantitis bone loss and soft tissue complications occurred adjacent to 9.7% of the single crowns after five years. Additionally, when a tooth is removed from its alveolar socket, the blood to the facial bone is interrupted.¹⁹ Even with expected healing after tooth extraction, the alveolar defect will only become partially restored. The highest amount of bone loss is in the horizontal dimension and occurs mainly on the facial aspect of the ridge, which may compromise the esthetic outcomes.²⁰

In this case report,²¹ we demonstrated the combined effect of root displacement and minimally invasive crown lengthening for the rehabilitation of an anterior tooth with extensive loss of coronal tooth structure. The

case report presented “current integrated management approaches”²² to solve the patient’s issues, which were practical and demonstrated stability after 24 months, supporting mechanical and biological needs. The ultimate healing and symmetrical alignment of the periodontal soft tissues were prime concerns to the crown-lengthening approach. The reduced osteotomy promoted by the combination with orthodontic extrusion seems to confirm that the supplementary orthodontic approach improves the short- and long-term outcomes.²³

Orthodontic extrusion and crown lengthening is the best approach for the conservative establishment of biological width. Slow orthodontic teeth extrusion has also been investigated to enhance hard and soft periodontal tissue quality before implant positioning in the esthetic area.²⁰ In the last several years, surgical extrusion, or intra-alveolar transplantation, has also been proposed in the literature as a third option to reposition the tooth into a more coronal position to allow restoration.²⁴

Although predictable, adopting the crown lengthening alone would compromise the esthetic outcomes but would reduce cost and time of treatment. Orthodontic extrusion is highly suitable for a dentist to restore otherwise hopeless teeth and maintain the biologic distance between the apical portion of the junctional epithelium and the alveolar crest.²⁵ The foremost limitation of forced orthodontic extrusion is the long duration of the treatment stabilization period.²⁶ It is also contraindicated in a small crown-to-root ratio, lack of occlusal clearance for the required amount of eruption, and periodontal complications.²⁷

Van Venrooy and Yukna²⁸ first studied the amount of vertical bone deposition, and they reported a mean of 2.00 mm of crestal bone deposition after three weeks of orthodontic extrusion. There is no high quality of evidence on the efficacy of orthodontic strategies aimed at tooth extrusion.²⁹ The consensus in the literature is that orthodontic extrusion success relies on stable anchorage for the extrusion. The anchoring elements will act as support for the discharge of the forces applied to cause tooth movement.³⁰ Fixed orthodontic appliances or mini-implant screws can be used for the anchorage.¹⁴ In the present case, we also used brackets and provisional posts for better discharge of the forces at the root level.

In our case, planning the decision-making process included clinical, biological, and patient preferences in support of our evidence-based approach. The root-to-crown ratio, the amount of expected forced orthodontic extraction to allow a ferrule design, and the desire to reduce the side effects of individual approaches have



Figure 5. Clinical and radiographic controls of tooth 7 after the multidisciplinary treatment.



Figure 6. Treatment 24-months postoperative. Note the favorable clinical and radiographic outcomes.

led to the selection of a plan that combines treatments to establish biological width.

Concerning the restorative aspect of this case, adhesive core build-up with fiber post was chosen. The entire system comprised of post cementation and core build-up works in harmony toward reinforcing the tooth.³¹ Fiber-reinforced posts have been used mainly for their biomechanical properties similar to those of dentin.³² The documented long-term clinical use of fiber posts consistently indicate a conservative failure that leaves the root intact when compared to metal post

use.³³ In a previous meta-analysis, the survival rate for fiber posts considering repairable failures was 83.9% in studies from five to 10 years of follow-up.³⁴ It is worth mentioning that if fiber post failure occurs, the fiber post can be replaced while keeping the existing root structure intact.

Full-ceramic crowns have become a standard procedure in the treatment of anterior teeth.³⁵ Lithium disilicate crowns are a reliable and long-lasting treatment option to restore the anterior zone to fulfill esthetic and functional demands.³⁶ The most common

technical complication reported was the fracture of the core framework, followed by porcelain chipping and debonding of the restoration from the tooth.³⁷ Nevertheless, several studies reported an encouraging survival rate for lithium disilicate single crowns ranging from 100% after two years to 96%-98% after five years and 94%-96% up to 10 years.^{37,38} The crown made in the above case was esthetically integrated, considering the patient's facial harmony and symmetry with its lateral incisor counterpart. From the patient perspective,²² he was fully satisfied with the resulting appearance and functional aspects of the tooth. The patient continually maintained the hygiene of the restored area, and no post, core, or crown complications were observed at the 24-month follow-up. Future studies on long-term clinical outcomes and predictors for the combined approach of root displacement and minimally invasive crown lengthening restored with fiber post merit consideration.

CONCLUSION

A severely compromised tooth was recovered with combined management of root displacement and minimally invasive crown lengthening. This approach, in concert with modern restorative dentistry, led to successful results and patient satisfaction. These results were documented during an examination 24 months after treatment.

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Conflicts 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.

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Post-retained Restorations: A Cost-minimization Analysis Nested in a Randomized Clinical Trial

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Clinical Relevance

Although the clinical performance of restorations was similar, the combination of glass fiber post and direct composite presented superior outcomes for cost versus other restorative possibilities for endodontically treated teeth.

SUMMARY

Objectives: The aim of this study was to assess four post-retained restorative strategies for endodontically treated teeth using cost-minimization analysis. **Methods and Materials:** The cost-minimization analysis was based on primary data from a randomized clinical trial and followed the Consolidated Health Economic Evaluation Reporting Standards (CHEERS) guidelines. Two hundred twenty-five teeth (141

patients) restored using four strategies—teeth with ferrules+ restored with either glass fiber posts or direct composite or crowns, and teeth without ferrules- restored with either glass fiber or cast metal posts with crowns—were evaluated annually between 2009 and 2018. Initial costs and incremental costs per year were calculated. Survival curves were created using the Kaplan-Meier method and log-rank test. Kruskal-Wallis analysis was followed by Dunn's test, which was used to compare restorative treatments, with a significance level of 5%. **Results:** Initial costs were greater for cast metal posts without crowns (US\$153.14). Glass fiber posts with composite (US\$27.11) were least costly; the most failures occurred in this group, but they were primarily repairable restoration fractures. The number of extractions, and thus cost, was greater for glass fiber posts with crowns. The mean annual cost was significantly lower for teeth restored with composite ($p < 0.001$). Ferrule presence did not significantly impact annual costs. **Conclusions:** The use of glass fiber posts and direct composite incurred significantly lower annual costs than did other alternatives involving crowns or metal posts.

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INTRODUCTION

To achieve efficiency in the provision of health services, economic evaluations are necessary for decision making and improved allocation of resources. Economic health assessments aid in the organization of information in an understandable and simplified way; they can be defined as the comparison intervention options with the consideration of costs and consequences. Different types of economic analysis are used to represent health problems analytically without changing their essential attributes.^{1,2}

Cost-minimization analysis enables the evaluation of health intervention results and is imperative to inform and aid health policy decision making.²⁻⁴ It involves the performance of a prospective economic evaluation nested in a clinical trial that has revealed no significant difference in the primary clinical outcome,¹ thereby enabling identification of the intervention with the lowest cost.

When considering endodontically treated teeth and treatment choices, there is still a low body of evidence suggesting that cast metal posts have higher survival rates for teeth without ferrules⁵; however, all posts perform similarly when at least one remaining wall or a ferrule effect is present.^{6,7} Thus, in the presence of one or more remaining coronal walls, other parameters, especially the intervention cost, must be considered. The use of glass fiber posts (GFPs) is common and less expensive than the use of cast metal posts, which can influence clinical decision making. Glass fiber posts use less-expensive restorative materials and operative techniques, as adhesive approaches such as those for direct composite resin restoration reduce the amount of tooth structure removed and can extend the lifetimes of restored teeth, thereby avoiding more complex and expensive treatments.⁸ Also, as minor repairs of restorations are often required, economic evaluation in these cases can be critical to support clinical practice.

Given the amount of evidence regarding this type of analysis in dentistry and considering primary data from a randomized clinical trial (RCT), this study was conducted to economically assess four post-retained restorative strategies for endodontically treated teeth using cost-minimization analysis. The hypothesis tested was that glass fiber-retained direct composite resin restorations would be less expensive than restorations retained with cast post and core (CPC) or glass fiber posts with metal-ceramic crowns.

METHODS AND MATERIALS

This health economic evaluation was based on primary data from a parallel-arm RCT comparing success and

survival for four restorative strategies for endodontically treated teeth with and without ferrule use (ClinicalTrials.gov NCT01461239). The RCT was approved by the local research ethics committee (protocol 122/2009). The reporting of this study followed the Consolidated Health Economic Evaluation Reporting Standards (CHEERS).⁹

Target Population and Setting

The RCT was conducted at a dental school; 25 undergraduate students performed all clinical procedures under the researchers' supervision. One-hundred and forty-one participants were included, and 225 teeth were restored.

The inclusion criteria were good oral health (no active carious lesion or periodontal disease), the presence of one or more endodontically treated anterior or posterior teeth with or without ferrules (2 mm or 0-0.5 mm) requiring intraradicular retention, and the presence of bilateral posterior occlusal contact. Exclusion criteria were the presence of one or more endodontically treated teeth with periodontal or occlusal problem and the presence of a large prosthesis (Kennedy class I or II) in the opposing arch of the tooth or teeth to be restored.^{6,10}

Comparators and Sample Size

Randomization took the tooth type (anterior, molar, or premolar) into account to minimize bias due to anatomical variation. Briefly, when no ferrule was present, teeth were randomized according to the type of post (GFP, $n=71$; CPC, $n=79$) and all teeth received single metal-ceramic crowns. When a 2-mm ferrule was present, a GFP was luted, followed by a second randomization (metal-ceramic crown, $n=36$; direct composite resin restoration, $n=39$). Crowns were made with CoCr alloy^{6,10} and luted with self-adhesive resin cement (RelyX U100/U200; 3M ESPE, St Paul, MN, USA). The posts were luted with regular or self-adhesive dual resin cement (RelyX ARC or RelyX U100/U200; 3M ESPE). The randomization sequence was generated using computerized random number tables. A third party not involved in the study performed allocation concealment with the use of sealed opaque envelopes.

Under the assumption of no difference between treatments, 64 participants were required to achieve 90% confidence that the limits of a two-sided 90% confidence interval (CI) would exclude a difference $>18\%$ between the treatment groups.^{6,10} Considering the sample size for the GFP + CR⁺ and GFP + MC⁺ groups, an alpha level of 0.05, and success rates of 97.14% and 74.63%, respectively, this study had 90% power to detect incidence rate ratios ≥ 1.3 .

Follow-up

Overall, 225 teeth in 141 patients were evaluated annually between 2009 and 2018, with an average follow-up duration of 4.5 years (95% CI, 4.2-4.8).

Cost Estimation

The perspective of the Brazilian Public Health System (PHS) was adopted, considering total treatment coverage, as cost estimates accrue from primary and secondary care provided free of charge to patients. Costs were converted to US dollars (US\$1:R\$3.866). Prices were obtained in November 2018. An annual discount rate of 6.5% was applied to account for time preference.¹¹

The PHS procedure codes and national price lists were used to estimate direct medical costs, including initial treatment and maintenance (incremental) costs. Initial costs comprised those of all materials, consumables, dental technicians' work, and appointments required for the completion of a treatment. Incremental costs accrued from new interventions performed on teeth presenting repairable or irreparable failures. Material and consumable costs were accrued from the quantities (weights or amounts) of materials and their purchase costs, based on Brazilian PHS catalogs. Dental technician costs were in agreement with national standards for private practice. Incremental costs were calculated by summing the procedures required to repair a failure and/or replace a missing tooth. Non-medical costs (eg, structural costs, productive input) and indirect (opportunity) costs were assumed to be similar among treatments and were not considered.

Health Outcomes and Effectiveness

The primary health outcome was tooth extraction due to caries, root fracture, or endodontic complication. Associated costs included the extraction of the tooth and the insertion of an implant followed by a metal-ceramic implant-supported crown. The choice of this treatment was based on the inclusion criteria, justifying the replacement of the extracted tooth with a single implant in all cases of failure requiring tooth extraction. Secondary outcomes included the costs of repair, re-cementation, retreatment or apical surgery, and post/crown replacement. When restorative treatment or removal/replacement of the crown/restoration was performed at another dental practice (by another dentist) for no reconstructable reason, the affected tooth was censored and data from the last clinical assessment were considered.

Analysis

The analysis was performed using Excel 2016 MSO (Microsoft Corporation, Redmond, WA, USA) and

Stata 12.0 (StataCorp, College Station, TX, USA) software. Descriptive analysis was used to characterize the patients (teeth) included in the study and the reasons for failure. Survival curves were created using the Kaplan-Meier method, followed by the log-rank test. As cost estimates were distributed asymmetrically ($p < 0.05$, Shapiro-Wilk normality test), non-parametric tests (the Kruskal-Wallis test, followed by Dunn's test) were used to compare restorative treatments. A 5% α error level was adopted.

RESULTS

The treatment distribution among restorative strategies and between maxillary/mandibular locations was homogeneous (Table 1); in contrast, we observed a larger number of cast metal posts with crowns used in anterior teeth due to the larger number of patients requiring anterior rehabilitation. Kaplan-Meier survival curves showed no significant difference in tooth longevity during the follow-up period according to the restorative approach (Figure 1).

The cost of dental extraction and tooth replacement with dental implants was highest (US\$363.92), followed by the use of cast metal posts with crowns (US\$153.14). Restoration repair (US\$16.47) and re-cementation (US\$6.11) were the least expensive treatments (Table 2).

Table 3 shows initial, incremental, and average annual costs by restorative strategy (itemized prices are provided in Supplementary Table 1). Initial costs were lowest for GFP + CR⁺ (US\$27.11) and highest for CMP + MC⁺ (US\$153.14). The most failures occurred in the GFP + CR⁺ group, but they were primarily restoration fractures that were repaired. In contrast, the largest number of teeth lost, incurring high costs, was in the GFP + MC⁺ group. Overall, the mean annual cost was significantly lower in the GFP + CR⁺ group than in the other groups ($p < 0.001$), with no significant difference among the other groups or according to ferrule presence.

DISCUSSION

The rehabilitation of endodontically treated teeth is discussed widely in the literature, with several dental material options and indications for restorative procedures, considering ferrule, tooth location, and esthetics. Survival was similar among restorative strategies examined in this study, corroborating previous findings^{6,7,10,12} and justifying a cost-minimization approach for economic evaluation. Although cost-minimization analysis can be used to identify the least costly option among treatments with equivalent outcomes, the economic factor alone should not be

Table 1: Descriptive Analysis of Patients and Teeth Included in the Study						
		Glass Fiber Post with Crown ⁻ n=79 (SD)	Cast Metal Post with Crown ⁻ n=71 (SD)	Glass Fiber Post with Crown ⁺ n=36 (SD)	Glass Fiber Post and Composite Resin ⁺ n=39 (SD)	Total N=225 (SD)
Follow-up, y		4.6 ± 2.2 (4.1-5.1)	5.0 ± 2.0 (4.5-5.5)	4.9 ± 1.8 (4.3-5.5)	3.3 ± 1.6 (2.8-3.8)	4.5 ± 2.1 (4.2-4.8)
Age, y		46.1 ± 9.5 (43.9-48.2)	43.9 ± 13.5 (40.7-47.1)	47.1 ± 10.8 (43.4-50.8)	42.1 ± 13.2 (37.8-46.4)	44.8 ± 11.9 (43.2-46.4)
Location	Upper	60 (75.95%)	55 (77.46%)	27 (75%)	24 (61.54%)	166 (65.10%)
	Lower	19 (24.05%)	16 (22.54%)	9 (25%)	15 (38.46%)	59 (34.9%)
Tooth type	Incisor	39 (49.37%)	44 (61.97%)	9 (25%)	6 (15.39%)	98 (50.2%)
	Premolar	32 (40.5%)	15 (21.12%)	15 (41.67%)	13 (33.33%)	75 (29.41%)
	Molar	8 (10.13%)	12 (16.91%)	12 (33.33%)	20 (51.28%)	52 (20.39%)
Abbreviations: CI, confidence interval; SD, standard deviation; y, years. +: with ferrule; -: without ferrule; mean ± SD are given for follow-up and age (95% confidence interval), while sample size is given for location and tooth type.						

extrapolated for clinical decision making, especially as factors such as the tooth type, remaining tooth structure, quality of endodontic treatment, parafunctional habits, and caries risk could act as confounders for outcomes and in clinical practice. However, the economic factor

is among the main aspects that directly influence the choice of dental restorative material. Although differences between public and private clinical practices exist, both need to satisfy the needs of policymakers and patients.

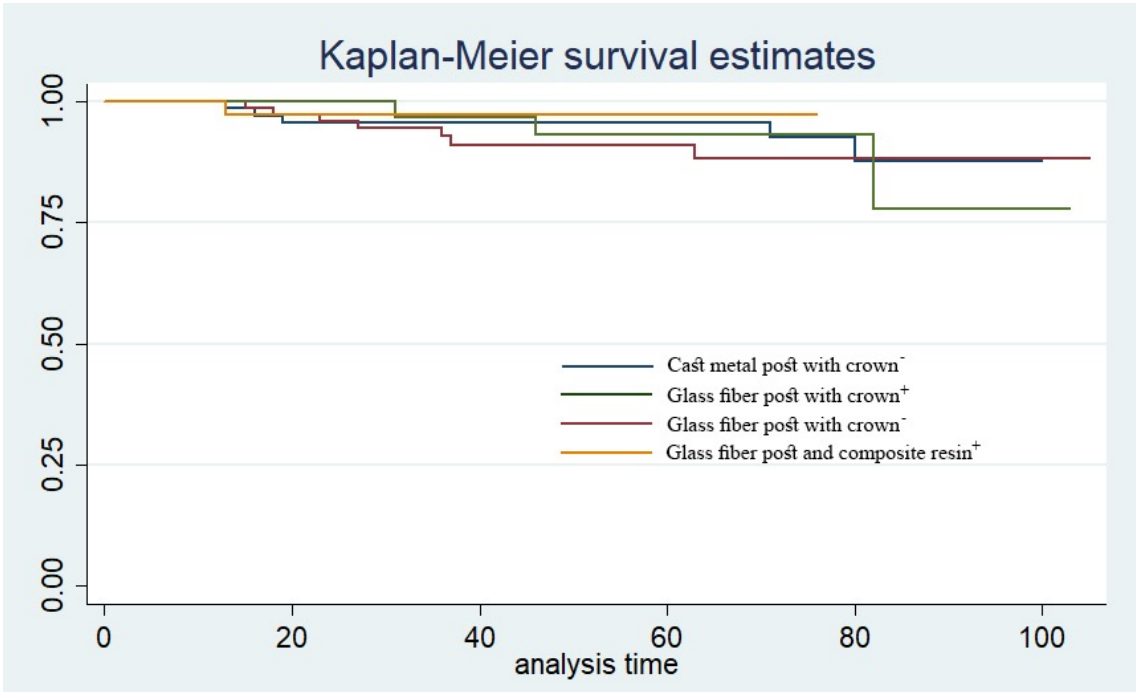


Figure 1. Kaplan-Meier curves according to the groups investigated (p=0.864; + with ferrule; - without ferrule).

Table 2: <i>Estimated Cost of Treatments^a</i>	
Treatment	Costs (US\$)
Cast metal post with crown	153.14
Glass fiber post with crown	121.75
Glass fiber post and composite resin	27.11
Tooth removal, implant placement and crown	363.92
New crown	114.78
Endodontic retreatment	56.97
Apical surgery	52.14
Restoration repair	16.47
Recementation of a crown	6.11
^a More details are presented in Supplement Table 1.	

The most common health economic analysis in the dental literature is cost-effectiveness analysis, which, together with other analyses, is based on an assumed difference among treatments examined. Cost-minimization analysis was used in the present study due to the lack of a significant difference among treatments. This finding is corroborated by systematic reviews being unable to reliably rank the different treatment options,^{13,14} which could be due to the lack of statistical power, given the limited availability of clinical data, rather than to the true absence of such a difference.

Glass fiber posts with direct composite resin restorations had the lowest annual costs over the follow-up period in this study, as direct composite resin is initially less costly and limited costs were generated during follow-up, in part because the main type of reintervention performed was repair. Thus, this approach was least costly in the long term, compensating all reinterventions. Reintervention was possible because the failures were not catastrophic, corroborating results from a cost-effectiveness analysis reported in the literature, which revealed more debonding-related failures among glass fiber post

Table 3: *Costs of the Different Restorative Strategies (US\$, mean $\pm$ SD)^a*

	Glass Fiber Post and Composite Resin⁺ n=39	Glass Fiber Post and Crown⁺ n=36	Glass Fiber Post and Crown⁻ n=79	Cast Metal Post and Crown⁻ n=71	p-value^b
Initial cost	27.11	121.75	121.75	153.14	
Incremental costs (maintenance costs)	17.35 $\pm$ 58.78 A	38.16 $\pm$ 104.76 B	33.85 $\pm$ 104.38 B	25.80 $\pm$ 93.73 B	0.025
Mean annual costs (initial + maintenance costs per year)	23.83 $\pm$ 56.71 A	39.73 $\pm$ 35.62 B	51.46 $\pm$ 65.59 B	53.27 $\pm$ 77.87 B	<0.001
Total costs over follow-up	1,734.14	5,756.90	12,292.69	12,704.76	

Abbreviation: SD, standard deviation

+: with ferrule; -: without ferrule

^aGroups with different lowercase letters represent statistically significant differences in each row ($p < 0.05$).

^bKruskal-Wallis followed by Dunn's test.

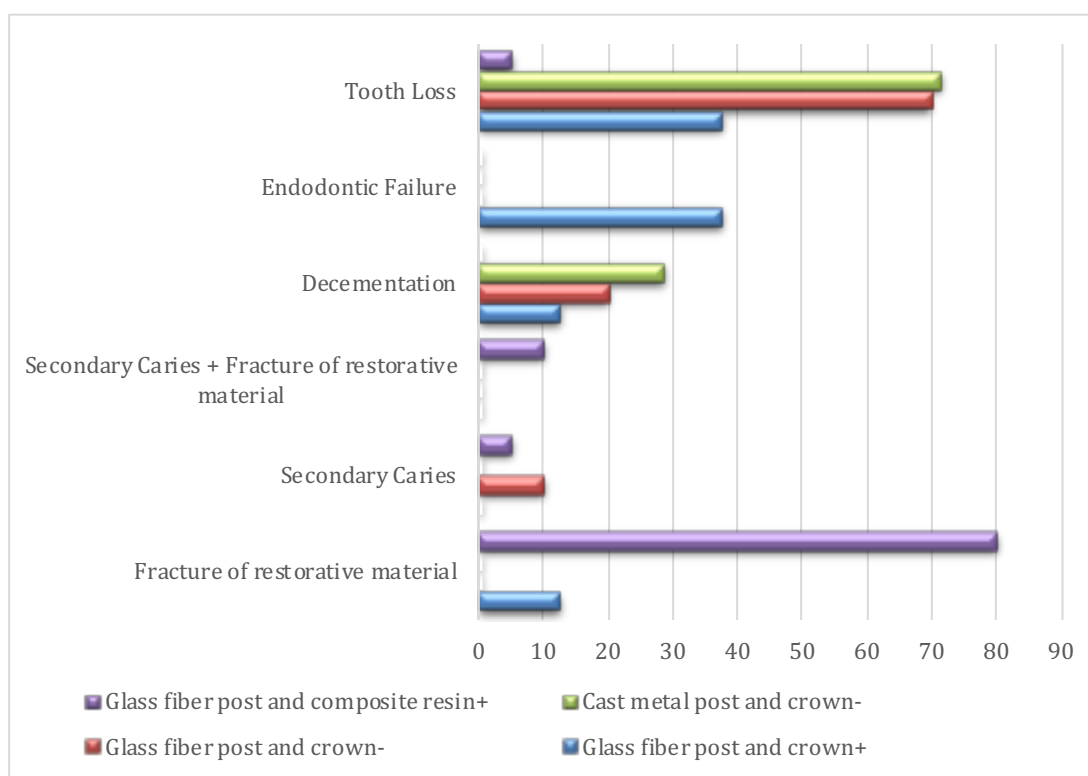


Figure 2. Distribution and types of failure in the groups investigated (in %; + with ferrule; - without ferrule).

restorations, making them more cost effective than cast metal posts.⁸ Although survival did not differ among treatments in the present study, major complications in the GFP + MC⁻ group necessitated reinterventions requiring laboratory work, making them more expensive. A meta-analysis revealed no significant difference in the incidence of root fractures between cast metal posts and fiber posts, but no economic analysis was performed.¹⁵ Our findings emphasize that the maintenance of fallback options and avoidance of tooth loss, even by accepting a higher rate of reintervention, is economically advisable given the high cost of tooth removal and replacement.

Our results are in line with those of recent studies evaluating other oral health outcomes and emphasize that less-invasive treatments are often less expensive.¹⁶⁻¹⁸ For example, the cost of removing all molars predicted to be at risk of extraction during supportive periodontal therapy was found to be greater than that of removing only molars with furcation involvement.¹⁶ Similarly, less-invasive caries removal (selective excavation) was shown to be more effective and less costly than stepwise complete excavation.¹⁹ These observations reinforce the importance of considering the economic analysis. Based on our findings, and considering differences in cost and all possible intercurrents, glass fiber post with direct composite resin can be less invasive and less

expensive, while achieving clinical success similar to that achieved with other restorative strategies.

Ferrule presence has been associated with increased survival rates of endodontically treated teeth in clinical studies, as it promotes better biomechanical performance.²⁰ However, due to the extensive dental destruction present in patients treated in the present study, the inclusion of teeth with ferrules was challenging. For this reason, the four groups contained different numbers of teeth, especially teeth rehabilitated with direct composite resin and metal-ceramic crowns with glass fiber posts and ferrules.

The literature contains no high-quality evidence for the best treatment strategy for endodontically treated teeth.^{21,22} There seems to be weak evidence suggesting that the best option for teeth with no ferrule is the use of cast metal posts;⁵ however, in the presence of at least one remaining coronal wall, all posts have similar longevity.^{6,7} Nevertheless, few studies of teeth treated with different rehabilitation strategies have involved long follow-up periods, and few studies have evaluated post-retained direct composite resin restorations. Even considering that teeth with and without ferrules perform differently, this comparison shows that the maintenance of a dentinal wall instead of greater tooth preparation not only preserves tissue, which is desired, but also decreases costs for patients

and clinicians. The removal of existing dentinal walls in metal-ceramic crown preparation should be discussed with patients, as it is more expensive and tooth survival could be extended by avoiding more invasive treatments.

The paucity of RCTs with long follow-up periods in dentistry has led to the absence of answers to critical clinical issues—such as the identification of the best restorative strategy for endodontically treated teeth—and even fewer trials have been designed to support health economic analyses. When the clinical outcomes of rehabilitative treatments do not differ significantly or differ only subtly, the economic evaluation of interventions is imperative for decision making.¹

As limitations of this study, we note the smaller number of teeth included in the ferrule cluster, which had an extended run-in, leading also to shorter follow-up times for these cases. Although the mean follow-up duration for teeth without ferrules (4.5 years) was somewhat longer than in many published trials,²³⁻²⁵ it may not have been sufficient to capture later complications. In addition, the calculations did not include fixed and variable expenses and costs, such as structural costs (eg, of the physical space, natural equipment wear, maintenance, cleaning, and conservation), productive inputs (eg, water and energy), chair-side time, and transportation, which would increase overall costs. Moreover, the study design did not include the present health economic evaluation. However, the detailed information extracted from the patients' files was sufficient for the analysis to be performed. The PHS codes were adopted for this study, and prices were fixed. A dentist in a private clinical practice could charge more for their services, such as the technically demanding direct build-up of a crown (especially an anterior crown) using direct composite resin; such potential differences were not taken into account in this study.

CONCLUSION

Within the limitations of this cost-minimization analysis, rehabilitation with glass fiber posts and direct composite resin had significantly lower annual costs than did other alternatives involving crowns and metal posts. The presence of a ferrule effect did not significantly affect costs. Additional factors, such as applicability and dentists' expertise and individual wishes, should be considered in clinical decision making.

Acknowledgement

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Regulatory Statement

This study was conducted in accordance with all the provisions of the human subjects oversight committee guidelines and policies of the Local Research Ethics Committee of the Federal University of Pelotas. The approval code issued for this study is Protocol 122/2009.

Conflict of Interest

The authors have no financial interest in any of the companies or products mentioned in this article.

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Longevity of Crown Margin Repairs Using Glass Ionomer Cement: A Retrospective Study

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TP Thyvalikakath • NB Cook

Clinical Relevance

Repairing defective crown margins can extend the functional life of existing crowns.

SUMMARY

Objective: The objective of this study was to determine the survival time of crown margin repairs (CMRs) with glass ionomer and resin-modified glass ionomer cements on permanent teeth using electronic dental record (EDR) data.

Methods: We queried a database of EDR (axiUm; Exan Group, Coquitlam, BC, Canada) in the

Indiana University School of Dentistry (IUSD), Indianapolis, IN, USA, for records of patients who underwent CMRs of permanent teeth at the Graduate Operative Dentistry Clinic. Two examiners developed guidelines for reviewing the records and manually reviewed the clinical notes of patient records to confirm for CMRs. Only records that were confirmed with the presence of CMRs were retained in the final dataset for survival

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analysis. Survival time was calculated by Kaplan-Meier statistics, and a Cox proportional hazards model was performed to assess the influence of age, gender, and tooth type on survival time ($\alpha < 0.05$).

Results: A total of 214 teeth (115 patients) with CMR were evaluated. Patient average age was 69.4 ± 11.7 years old. Posterior teeth accounted for 78.5% ($n=168$) of teeth treated. CMRs using glass ionomer cements had a 5-year survival rate of 62.9% and an annual failure rate (AFR) of 8.9%. Cox proportional-hazards model revealed that none of the factors examined (age, gender, tooth type) affected time to failure.

Conclusion: The results indicate the potential of CMRs for extending the functional life of crowns with defective margins, thus reducing provider and patient burden of replacing an indirect restoration. We recommend future studies with a larger population who received CMR to extend the generalizability of our findings and to determine the influence of factors such as caries risk and severity of defects on survival time.

INTRODUCTION

Numerous studies have investigated the efficacy of repairing direct restorations.¹⁻⁶ These studies reported that repairing restorations increased the longevity of the defective direct restorations. However, no studies investigating survival rates of indirect restoration margin repairs due to caries are found in the dental literature.

A crown margin repair (CMR) can be described as a procedure that is performed to remove caries or other defects at the margin of an indirect restoration where the lesion or defect is accessible. Ideally, removal of the caries lesion is performed at the expense of the crown rather than removing excessive sound tooth structure to access the lesion. In vitro studies have investigated margin adaptation and microleakage of margin repairs of indirect restorations (Figures 1-4). These studies showed that glass ionomer cements, direct gold and amalgam may be suitable materials to restore these defective margins.^{7,8}

Restoration replacement is more time consuming and expensive, and potentially more traumatic to the tooth, than repair. Therefore, extending the longevity of a restoration seems to be the most reasonable plan to preserve tooth health, if it can be done efficiently and reliably.⁹ Major U.S. insurance companies will reimburse replacing a crown between 5 and 10 years,



Figure 1. Tooth 13: Preoperative defective carious PFM margin. Abbreviation: PFM, porcelain fused to metal.



Figure 2. Isolated defective carious PFM margin. PFM, porcelain fused to metal.

depending on the specific plan.^{10,11} Moreover, recent studies indicate a rising population of adults ages 65 years and older who have natural teeth and less tooth loss.^{12,13} However, this population may have limited dental insurance coverage since Medicare does not offer coverage for dental expenses and obtaining additional dental insurance could be expensive, especially for people who are retired.¹⁴ The crown margin repair (CMR) concept makes logical sense but lacks supporting data to consider it evidenced-based dentistry.

Glass ionomer CMRs have been performed in the Indiana University School of Dentistry (IUSD) Graduate Operative Dentistry Clinic for many years. Glass ionomer cements are contraindicated in restorations that are subject to occlusal loading; however, this is not a concern when repairing crown margins. A 5-year survival rate of up to 80% was demonstrated when using glass ionomer cements to restore cervical lesions at a dental hospital in the United Kingdom.¹⁵ There are no studies found in the dental literature in which the longevity of glass ionomer CMRs has been investigated.



Figure 3. Carious lesion removed at expense of crown to ensure complete excavation of lesion and minimize excess loss of sound tooth structure.

Therefore, the objective of this study was to determine the longevity of glass ionomer CMRs completed in the Graduate Operative Dentistry Clinic between 2006 and 2018. The results of this study will inform the viability of CMRs as a cost-effective treatment for defective crown margins, especially among adults ages 65 years and older and patients whose crown replacement may not be eligible for insurance coverage.

METHODS AND MATERIALS

This was a retrospective study of CMRs completed on patients seen in the Graduate Operative Dentistry Clinic, IUSD, Indianapolis, IN, USA, between January 1, 2006, and January 1, 2018. One cannot do a simple query in axiUm (Exan Group, Coquitlam, BC, Canada) for CMRs using glass ionomer cements, as both resin composite and glass ionomer cement share the same Code on Dental Procedures and Nomenclature (CDT codes).¹⁶ Also, there is no code for a CMR procedure.

In this study, the inclusion criteria included patients 18 years and older who underwent CMR on permanent teeth in the IUSD Graduate Operative Dentistry

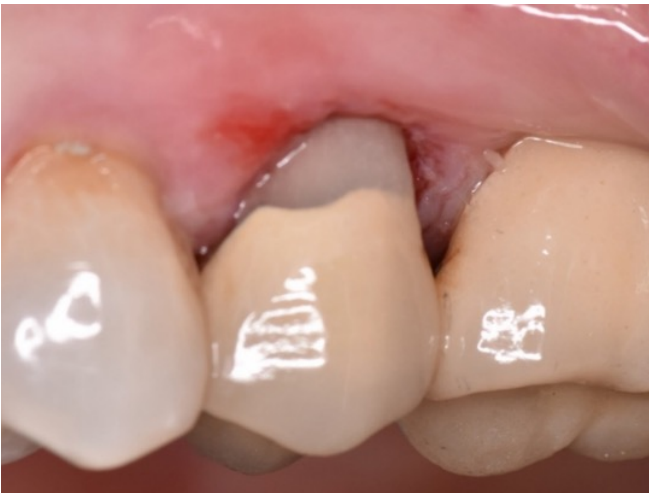


Figure 4. Completed crown margin repair with resin-modified glass ionomer.

Clinic. Queried CDT codes for anterior and posterior resin/GI restorations (Table 1). A list of keywords and phrases was developed after a review of 100 randomly selected records (Table 2). Any restoration that included an occlusal surface was excluded. Failure variables included extraction, new crown and re-repair. Failure variables were identified by reviewing treatment notes after a failure variable was identified.

The data set included patient demographics such as patient ID, age, gender, dates of treatments, procedure codes in the form of CDT codes, tooth type, tooth surface, existing findings such as conditions and treatment received elsewhere, and treatment notes. This data set was placed in an Indiana University-approved secure folder, and server that complies with the federal regulations for privacy and security (<https://www.hhs.gov/hipaa/for-professionals/privacy/index.html>), and with the Indiana University Office of Information Security policies.

Two reviewers who are dentists manually reviewed all patient records to confirm that the clinical treatment notes contained a treatment history for CMR. The reviewers developed a guideline to determine the words

Table 1: Inclusion and Exclusion Criteria	
Inclusion Criteria	Exclusion Criteria
- At least 18 years old - Anterior resin composite (02330, 02331, 02332, 02335) - Posterior resin composite (02391, 02393, 02393, 02394) - Manual review confirmed GI or RMGI use - Manual review confirmed existing crown	- Manual review did not confirm GI or RMGI use - Manual review did not confirm existing crown
Abbreviations: GI, glass ionomer; RMGI, resin modified glass ionomer.	

Table 2: Initial Search Words and Span of Text	
Initial Search Words, Phrases, or Span of Text	
• Glass ionomer • GI • Resin modified glass ionomer • RMGI • Crown • Repair	• Crown margin • Margin • Defective margin • Recurrent caries • Recurrent decay • Secondary caries
Abbreviations: GI, glass ionomer; RMGI, resin modified glass ionomer.	

and span of text that indicate the presence of CMRs in the clinical notes (see Supplementary Table 1). They reviewed a random set of 100 patient records and calculated an inter-rater reliability score of 82.3% using Cohen’s kappa statistic for agreement. The reviewers then individually reviewed the remaining records. Consensus was reached on any disagreements through discussion. Only records confirmed with the presence of CMR by the two reviewers were retained in the final dataset for survival analysis.

Data Analysis

Kaplan-Meier survival curves, including 95% confidence intervals, were used to estimate the survival time for CMRs. The mean annual failure rate (AFR) of the investigated CMRs was calculated according to the formula: $(1-y)^z = (1-x)$.¹⁷ Factors that may affect crown margin repair survival were evaluated using Cox proportional hazards models. Factors examined included age, gender, and type of tooth treated. The Cox model also included a frailty term to account for correlation among multiple teeth within a patient. A 5% significance level was used for all tests.

RESULTS

Our query of IUSD electronic dental record (EDR) database (axiUm for CDT codes) indicating resin restorations initially identified 2324 restorations. Words, phrases, and span of texts that indicated CMRs were recorded from the manual review of treatment notes (Figure 5). The manual review of treatment notes eliminated 2110 restorations. After a final review, 214 teeth in 115 patients were included in the analysis. The mean age of the patients was 69.4 years with a standard deviation of 11.7 and a range from 32.3-98.9 years. The sample consisted of 48.7% males (n=56) and 51.3% females (n=59).

Of the 214 CMRs, anterior teeth accounted for 21% (n=46) (upper and lower anterior teeth were combined due to the small number of lower anterior teeth; Table 3). Lower posterior teeth accounted for 38% (n=81), while upper posterior teeth accounted for 41% (n=87) (Table 3).

The results revealed 62.9% 5-year survival, with a 95% confidence interval, using the Kaplan-Meier survival curve (Figure 6). This can be restated as an 8.9% AFR. Only 29.4% (n=63) were observed with a failure (Table 4). The average time to an observed failure was 2.7 years (Table 4). The remaining CMRs were censored at the last follow-up visit. The average follow-up time before censoring was 3.1 years (Table 4). Lower posterior teeth had the longest time to failure or follow-up time (3.4 years) and also the longest censoring time (3.3 years) (Table 3). For anterior teeth that were treated as censored, the average follow-up time was 3 years (Table 3), and for anterior teeth that were treated as failures, the average time was 2.5 years (Table 3).

Cox proportional-hazards model was performed to examine if age, gender, or tooth type affected time to failure; in addition, a frailty term was included in the model to account for correlation among multiple teeth within a patient in the study. The results showed none of the factors affected time to failure ($p>0.05$ for all).

Table 3: Average Time (Years) to Failure or Follow-up Time (Years) by Teeth Type ^a									
Failure	Tooth Type	N	Mean	Standard Deviation	Minimum	Q1	Median	Q3	Maximum
No	Anterior	30	3.01	3.94	0.00	0.40	0.72	5.85	13.07
No	Lower posterior	60	3.44	3.50	0.00	0.54	2.25	5.23	12.55
No	Upper posterior	61	2.70	2.74	0.00	0.60	1.61	3.80	9.18
Yes	Anterior	16	2.48	2.07	0.00	1.02	1.14	5.07	5.73
Yes	Lower posterior	21	3.34	2.31	0.44	1.69	3.18	3.96	9.42
Yes	Upper posterior	26	2.31	1.90	0.02	0.96	1.62	3.55	6.45
^a For anterior teeth that were treated as censoring, the average follow-up time was 3.01 years; for anterior teeth that were treated as failure, the average time to failure was 2.48 years. Abbreviations: Q1, quartile 1; Q3, quartile 3.									

Table 4: Average Time (Years) to Failure or Follow-up Time (Years) by Teeth Type^a

Failure	N	Mean	Standard Deviation	Minimum	Q1	Median	Q3	Maximum
No	151	3.06	3.31	0.00	0.52	1.61	4.52	13.07
Yes	63	2.70	2.11	0.00	1.02	2.10	3.91	9.42

^aFor teeth that were treated as censored, the average follow-up time was 3.06 years; for teeth that were treated as failure, the average time to failure was 2.70 years. Failure included extracted, new crown, and re-repair. Abbreviations: Q1, quartile 1; Q3, quartile 3.

DISCUSSION

To the authors' knowledge, this study is the first to investigate the longevity of indirect restoration margin repairs. Major findings of this study demonstrated that CMRs had a 62.9% 5-year survival rate, with no significant differences on which tooth the repair occurred. Due to these findings, treating defective crown margins by repairing with glass ionomer cement should be considered as a potential treatment option. CMRs may extend the survival of the crown and ultimately the tooth. Another significant outcome of this study was the manual review of the records identified words, phrases, and group of words that confirmed the

existence of CMRs. This manual review of 2324 possible CMR restorations revealed important keywords such as "margin repair," "repair margin," and "crown margin" that indicated a CMR (Table 4). Numerous combinations and variations of crown, margin, and/or repair were used in conjunction with CDT codes and previous treatment notes to confirm that a CMR was completed. This list of keywords and phrases is a rich resource to identify CMRs using EDR data.

Of the 2324 restorations that were identified in the initial data query, only 214 CMRs were confirmed. There are several reasons that may explain the low number. First, accurate or standardized dictation of treatment notes varied in describing CMR procedures.

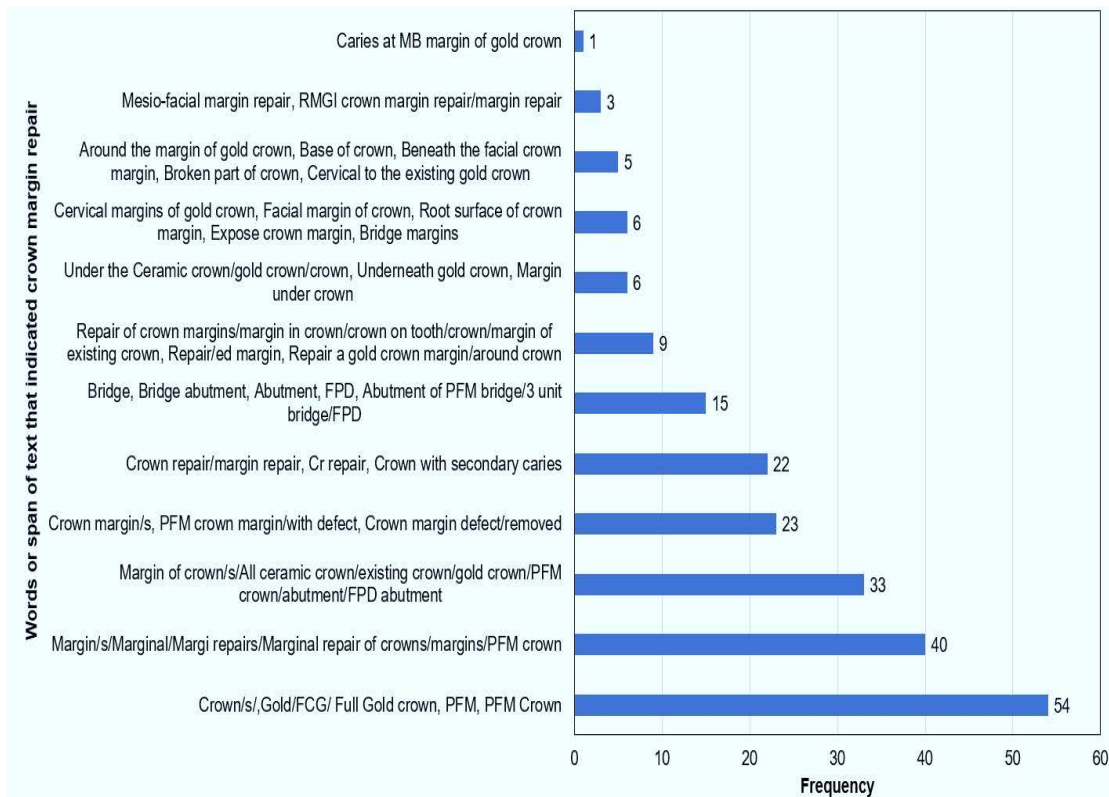


Figure 5. Crown margin repair keywords from manual note review. Abbreviations: Cr, crown; FCG, full gold crown; FPD, fixed partial denture; MB, mesial buccal; PFM, porcelain fused to metal; RMGI, resin modified glass ionomer.

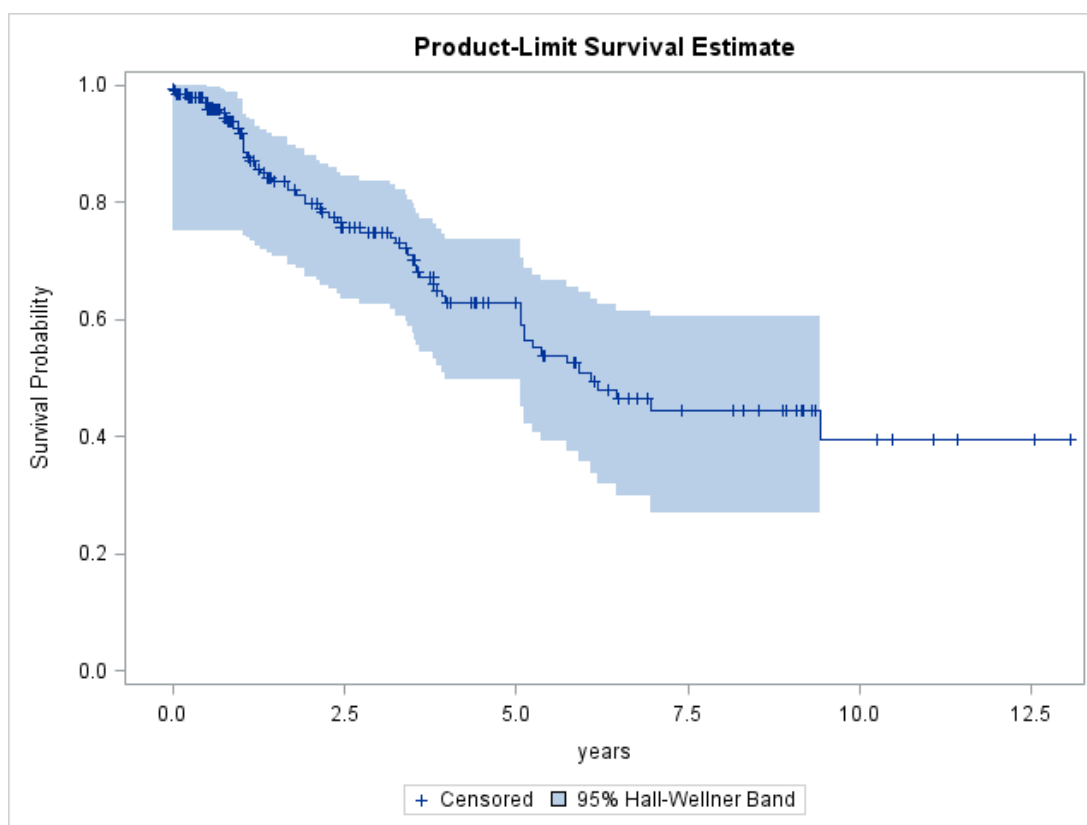


FIGURE 6. Kaplan Meier survival curve with confidence intervals The survival rate with crown margin repairs using glass ionomer at 5 years was 62.9% with 95% confidence interval (54.2%, 71.6%).

As CDT codes evolve, it may be beneficial to have codes that identify the repair of restorations versus initial placement or replacement of restored surfaces. In addition, glass ionomer cements should not be considered resin-based restorations, but should have their own coding index as amalgam, gold, resin composite, and ceramic do. More CMR repairs may have also been identified if patients' radiographs were used adjunctively with the treatment notes to confirm the presence of an existing crown for the of lack of detail in describing the clinical procedure in the treatment note.

The reported survival rate could have been affected by factors not investigated in this study. First, failure and success were not assessed by an actual clinical examination associated with the study. Failures were described in this study as any intervention to the restored tooth, ie, extraction, re-repair, or new crown. It is possible that CMR restorations were still intact with sound restorative margins and that the tooth failed due to another reason. Only 29.4% of CMR restorations were associated with a failure (Table 5). The average time of the observed failures were 2.7 years, with only 3.1 years when a CMR was censored (Table 5). A longer observation period or formal patient recalls verifying

the survival of the CMR could lead to a potentially higher survival rate. Second, the severity and extent of the defective crown margins were not observed. The severity of the defective margin would likely be a contributing variable in the longevity of a CMR. This would be useful in making clinical decisions as whether to repair or replace. Identifying CDT-coded surfaces would give some insight to this question; however, the number of recorded surfaces does not indicate the axial depth of the caries defect. Recording this measurement would be done most accurately by using a prospective study design.

Establishing a larger data set would strengthen the data on CMR longevity. This can be done by broadening search criteria to include more departments within the school or utilizing other electronic health record databases. Keywords that were identified in the manual review of treatment notes could expedite larger studies to more easily identify true-positives in future queries.

For this study, only CMRs completed with glass ionomer cements or resin-modified glass ionomer cement material were included. This was done because the general philosophy in the Graduate Operative Dentistry Clinic is to use glass ionomer materials for

CMRs, and this aided in identifying CMRs through axiUm queries and the manual review. There may also be a need to investigate CMRs with resin composite, amalgam, and gold.

A common philosophy of CMR technique was observed, where the caries lesion is removed at the expense of the crown rather than removing excessive sound tooth structure to access the lesion. It cannot be confirmed that all included CMRs were done with this technique, but rather that this is the common CMR philosophy taught in the IUSD Graduate Operative program. CMR technique, as described in the introduction, can be a stepwise assessment to determine whether a defective or carious crown margin should be repaired, or if the crown should be replaced. After initiating a CMR procedure, it may be determined that repairing will be impossible. This may be because complete caries removal cannot be confirmed or that the remaining supporting tooth structure is highly compromised. At that point, the CMR procedure should be terminated and crown removal with complete caries excavation should be done to assess restorability of the tooth.

If patients have active caries lesions, they should be considered at moderate or high risk for caries.¹⁸ Ideally, when creating a comprehensive treatment plan for a patient, the first step is disease control.¹⁹ For many patients, it may be prudent to repair defective margins and attempt to stabilize caries activity before completing the definitive care phase of a treatment planning sequence.

In a recent practice-based study, a 1.2%-3.5% AFR of single unit crowns was reported.²⁰ It may not be accurate to compare the two different treatment options—crown repair of an existing restoration versus a replacement crown—directly. Rather, risk factors and benefits of each option should be considered. A CMR defers more extensive treatment until later, which pushes subsequent treatment further out. This idea is supported by literature published by Benn and Meltzer.²¹ The study showed a significant decrease in the operative workload by applying a mathematical model that investigated deferring initial treatment and projecting operative interventions on a tooth's life cycle.

CONCLUSION

In this retrospective study of EDR data, CMRs demonstrated a 5-year survival of 62.9% and an AFR of 8.9%. There were no differences in CMR survival based on tooth type, location (anterior/posterior; maxillary/mandibular), or patient age or gender. It is reasonable to assume that CMRs extend the functional life of

crowns and should be considered as a valid treatment option to restore defective crown margins. Information gained in this study should be considered by dentists and patients when treatment planning crowns with defective margins, as well as be considered by others such as insurers, government officials, legislators, and administrators of community clinics to facilitate discussions of cost effectiveness and clinical outcomes.²²

Regulatory Statement

This study was conducted in accordance with all the provisions of the human subjects oversight committee guidelines and policies of Institutional Review Board of the Indiana University School of Dentistry, Indianapolis, IN. The approval code issued for the study is 18008963625.

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.

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An Evaluation of the Efficacy of LED Light Curing Units in Primary and Secondary Dental Settings in the United Kingdom

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Clinical Relevance

Clinicians should regularly monitor and maintain their light curing units (LCUs) to ensure an optimal light curing process. It is also essential to appreciate the factors that reduce the performance of the LCU.

SUMMARY

Objective: This study aimed to evaluate the irradiance and the quality of LED light curing units (LCUs) in primary and secondary clinics in the UK and to assess the effect of damage, contamination, use of protective sleeves, and distance of light tips to target on the irradiance and performance of LCUs.

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Methods: The irradiance levels (mW/cm^2) of 26 LED LCUs from general dental practices and 207 LED LCUs from two dental hospitals were measured using a digital radiometer (Blue Phase II, Ivoclar, Vivadent, Amherst, NY). Ten LED light guide tips (Satelec Mini, Acteon, Merignac, France) were selected to evaluate the effect of chipping, contamination (tip debris), and use of protective

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sleeves and tips to sensor distance on irradiance (mW/cm^2) using a MARC Resin Calibrator (Blue Light Analytics, Halifax, Canada). Homogeneity of the light output was evaluated using a laser beam profiler (SP620; Ophir-Spiricon, North Longan, UT, USA). Statistical analysis was conducted using a one-way analysis of variance (ANOVA) with post hoc Tukey test ($\alpha=0.05$) and linear regression with stepwise correlation tests.

Results: Thirty-three percent of the LCUs delivered irradiance output less than $500 \text{ mW}/\text{cm}^2$. The condition of the light curing tips was poor, with 16% contaminated with resin debris, 26% damaged, and 10% both contaminated and damaged. The irradiance output was significantly reduced in contaminated (62%) and chipped (50%) light curing tips and when using protective sleeves (24%) ($p<0.05$). Irradiance was also reduced when increasing the distance with 25% and 34% reduction at 7 mm and 10 mm, respectively ($p<0.05$).

Conclusion: There remains a lack of awareness of the need for regular monitoring and maintenance of dental LCUs. Damaged and contaminated light curing tips, use of protective sleeves, and increasing the distance from the restoration significantly reduced the irradiance output and the performance of the LCUs.

INTRODUCTION

The introduction of light cured dental resins led to a revolution in modern dental practice. Consequently, the dental light curing unit (LCU) has become an integral piece of equipment in every dental practice. However, the lack of knowledge among dental practitioners concerning factors affecting the performance of LCUs raises a major concern, especially as the use of resin based materials has significantly increased worldwide. It was reported that approximately 800 million composite restorations were placed worldwide in 2015,¹ of which 80% were posterior composite restorations, exceeding the use of amalgam restorations in several countries.²⁻⁴ This increase is expected to continue following the Minamata convention and the calls for a phase down of the use of mercury-containing products, which has placed resin composites as the most suitable alternative to amalgam as a direct restorative material.⁵

Current resin composite formulations exhibit enhanced mechanical and physical properties, allowing them to be used as a posterior restorative. However, the

average life span of composite restorations remains just under 10 years, after which clinical intervention may be required.⁶ Recurrent caries and restoration fracture remain as the primary reasons for clinical failures of composite restorations.^{7,8} Inadequate polymerization of resin composites has a major impact on the mechanical and physical properties of the material, including reduced bond strength to the tooth, bulk fractures, increased wear, and increased amount of residual monomers within the resin.⁹⁻¹³ Therefore, a major contributing factor to the early failures of resin composite restorations might be related to limited polymerization and suboptimal curing of the material. While it was reported that an irradiance of $400 \text{ mW}/\text{cm}^2$ was the minimum that must be delivered for effective polymerization of most resin based composites when appropriate curing times were used,¹⁴ most dental composite manufacturers recommend delivering a minimum of $500 \text{ mW}/\text{cm}^2$ for a duration of 40 seconds for optimum curing and many recommend shorter curing times if irradiance is higher, eg $>1000 \text{ mW}/\text{cm}^2$ for 10 seconds. Such arbitrary values may provide some margin for error; however, if the absolute irradiance output is unknown, there would exist a greater risk of suboptimally cured materials. Additionally, there has been an increase in the popularity of bulk-fill composite materials, which are claimed to enable restoration build up in thicker increments of 4-6 mm.¹⁵ The composition of bulk-fill composites varies depending on the type and amount of filler content and the photoinitiator systems used; therefore, adequate curing is essential to achieve adequate polymerization and the desired mechanical properties of these materials.¹⁶⁻¹⁸

LCUs containing light emitting diodes (LED) are the most common LCU used in dental practice¹⁹ as they exhibit specific spectral output to closely match camphorquinone (CQ) absorption without the need for optical filters.^{20,21} LED LCUs have several advantages because they are ergonomic, lightweight, battery operated, and they present greater efficiency compared with quartz tungsten halogen (QTH) LCUs due to the non-filtered irradiation.^{21,22} Furthermore, LED light sources can provide much longer working life compared to QTH and plasma-arc (PAC) light sources.²³ Therefore, nowadays there is a general trend toward using LED LCUs only. The first generation of LED LCUs contained arrays of multiple individual LED emitters that generated low irradiance output and required prolonged curing times.^{21,23} The second generation of LED lights evolved to incorporate small surface-mounted LEDs instead of discrete LED multiple arrays.²² Following this innovation, the irradiance output was significantly increased,²⁴ resulting in less

exposure time being required to adequately photocure restorations.^{25,26}

More recently, alternative photoinitiators to CQ such as phenyl propanedione (PPD), benzil (BZ) and Norrish Type I photoinitiator systems such as mono- (Lucirin TPO) and bi-(Irgacure 819) acylphosphine oxides have been introduced.^{27,28} These have been used in an attempt to increase the curing efficiency and the depth of polymerization in so-called bulk fill resin composites.¹⁶ Additionally, most of these photoinitiators are less pigmented and can therefore be used in bleached shades of resin composites, overcoming the yellowing effect of CQ when used solely. However, these alternative photoinitiators require shorter wavelengths of light at or below 410 nm. Consequently, the third generation of LED lights were introduced by incorporating multiple LED chips generating distinct wavelength bands (~380-500 nm, LCU dependent).²² These LCUs are considered broad-spectrum lights and sometimes they are referred to as polywave LCUs. Polywave lights are proposed to effectively photopolymerize all dental resin-based restorative materials that contain a variety of photoinitiators. Therefore, clinicians need to know if the restorative materials used contain alternative photoinitiators, which will require a polywave LCU rather than assuming that all LED LCUs are suitable.

To achieve optimal photopolymerization of resin based materials, clinicians should aim to deliver sufficient radiant exposure at the correct wavelength(s) of light according to the intrinsic characteristics of the material (thickness, shade, photosensitizers, etc). Many clinicians do not understand proper use of a dental LCU or the critical factors for optimizing the material properties of light cured resin composites.²⁹⁻³¹ Several studies have shown that LCUs used in dental practices are poorly maintained and deliver inadequate light output.³²⁻³⁷ Additionally, most clinicians did not know the irradiance and wavelength of their LCU and were unaware that LCUs with low irradiance output were unable to adequately cure the resin routinely used in restorations.^{30,35}

Evaluating the condition of the light guide is a key factor in optimizing light curing, as the regular and frequent use of LCUs in most dental practices lead to damage and resin contamination, which result in a reduced power output.^{38,39} Furthermore, various clinical factors have been shown to influence the irradiance of the light, such as increasing the distance from the restoration.⁴⁰ It was reported that some LCUs deliver only 25% or less of the irradiance measured at the tip when the distance is increased by 8 mm.^{12,41,42} Further, the use of protective sleeves to minimize potential cross infection from the LCU tip is reported to reduce

the irradiance by 40%.^{43,44} An additional clinically relevant factor to consider is the beam homogeneity of the LCUs, which can be evaluated using the beam profiling technique that is commonly used to examine lasers and other light sources.⁴⁵ It was reported that many LCUs do not have a uniform light beam across the tip with hot spots of high irradiance and areas of significantly reduced irradiance across the tip.⁴⁶ The impact of light guide properties and other clinical factors varies between different LCUs and is dependent upon individual design and optics of the light guide. Therefore, it is important to evaluate the effect of these factors on the performance of commonly used and newly introduced LED LCUs.

Although several studies have evaluated LCUs in various dental settings, to our knowledge no studies have been published to date evaluating the irradiance and the condition of LCUs used in United Kingdom primary and secondary dental settings. Therefore, the aims of this study were: 1) to evaluate the irradiance and the condition of LCUs in both primary and secondary dental care units in the United Kingdom; and 2) to evaluate common clinical and light guide factors that may influence the light output and the performance of contemporary LED-based LCUs.

METHODS AND MATERIALS

Two hundred thirty-three (233) light curing units were evaluated in the first part of this study, which included the following: Leeds Dental Institute (n=102) and Newcastle Dental Hospital (n=105) as secondary care units, and general dental practices in West Yorkshire (n=26) as primary care units. Various LCU brands were used with light curing tip diameters ranging from 6 mm to 12 mm; details of the lights tested are shown in Table 1.

The light output irradiance (mW/cm^2) was measured for each LCU using a Blue Phase II (BP II) digital radiometer (Ivoclar Vivadent, Amherst, NY). The BP II calculates the light irradiance based on the measured power (mW) when the light tip diameter is entered into the meter software and has a minimum detection threshold of $20 \text{ mW}/\text{cm}^2$. The BP II radiometer contains a large sensor area, which enables measurement of the radiant power up to a 13-mm diameter tip size. Higher accuracy of the BP II compared with other commercial radiometers has been reported previously, and an accuracy of $\pm 10\%$ compared to a laboratory-grade meter⁴⁷ has been reported. For each unit tested, three separate measurements of 20 seconds duration were taken and the mean reading was recorded. The LCU type and the size of the fiber optic tip was recorded for each unit using the BP II integrated template to determine the diameter of circular light probes. The

Table 1: Summary of All LCUs Tested in this Study

Light Curing Unit	Manufacturer	Number	Light Guide Diameter
Satelec Mini LED	Acteon, Merignac, France	158	7.5 mm
SmartLite	Dentsply, DE, USA	20	12 mm
Woodpecker LED H	Woodpecker, China	13	8 mm
Dentsply QHL75	Dentsply, DE, USA	8	10 mm
Satelec BlueRay	Acteon, Merignac, France	5	6 mm
BA Optima 10	BA international, Northampton, UK	5	8 mm
Henry Schein LED	Henry Schein Inc, NY, USA	3	8 mm
Coltolux LED	Coltene, NJ, USA	4	12 mm
Demi Plus	Kerr Corporation, CT, USA	3	8 mm
Demi Ultra	Kerr Corporation, CT, USA	2	11 mm
C02-C LED	Premium Plus, Hong Kong	2	10 mm
Flashlite 1401	DenMat Holdings, LLC, Lompoc, CA, USA	2	12 mm
Sliverlight LED	GC Corporation, Tokyo, Japan	2	8 mm
Translux Wave LED	Kulzer GmbH, Hanau, Germany	1	8 mm
GC D-Light Duo	GC Corporation, Tokyo, Japan	1	8 mm
DentMate LED	DENTMATE, New Taipei City, Taiwan	1	8 mm
Radii LED	SDI Ltd, Bayswater, VIC, Australia	1	8 mm
VRN VAFU LED	VRN, China	1	8 mm
SEASKY	Skysea, China	1	8 mm

Abbreviations: LCU, light curing unit; LED, light emitting diodes.

appearance of the light curing tip was also evaluated and observations of chipping and debris noted. The readings were recorded by a single investigator and recordings of light irradiance below a threshold of 500 mW/cm² were considered unsatisfactory. The output intensity (mW/cm²) of all the examined lights were categorized into three groups: <200 mW/cm², 200-500 mW/cm², and >500 mW/cm².

Based on investigator visual examination, 10 Satelec mini LED light guides (Acteon, Merignac, France) were selected to evaluate the effect of chipping, contamination, and tip-debris on the overall light output (mW/cm²) using a MARC Resin Calibrator (Blue Light Analytics, Halifax, Canada). The MARC Resin Calibrator was fixed to an optical board and a universal joint, and clamps were used to allow accurate and concentric positioning of the tip and sensor. The exposure time was set to 20 seconds and the energy level of 16 J/cm² for all LCUs.^{14,48} The irradiance of the damaged and contaminated LCU curing tips were measured using the same light source (Satelec Mini LED) of known output with a clean and undamaged (control) tip. LCUs with debris on the fiber optic tip surface were

selected based on residue of up to 50% over the surface of the tip, which was identified after investigator visual examination. Irradiance measurements were taken with the LCU tip placed perpendicular to the sensor surface at 0-mm distance (n=3).

To evaluate the effect of the protective sleeves on LCU output, a light protective sleeve (WRAPAROUND, UnoDent, Essex, England) was placed on the LCU (Figure 1) with a new light curing tip, and irradiance values were recorded (n=10). To evaluate the effect of distance of the light from the restoration, the LCU with a new light guide tip was mounted securely on the optical bench and placed perpendicular to the sensor surface on the MARC Resin Calibrator; three readings were taken at 1 mm intervals from 0 to 10 mm from the sensor surface, the mean reading at each individual distance was then recoded.

The homogeneity of the light beams was evaluated using a laser beam profiler (Ophir Spiricon, SP620, Israel) and analysed in BeamGage 6.3 (Ophir-Spiricon).^{46,49} The laser beam profiler has a high resolution CCD sensor (4.4 µm square pixels) that takes images of the light output and the power received



Figure 1. Satelec Mini LED (Acteon, Merignac, France) with a light protective sleeve (WRAPAROUND, UnoDent, Essex, England) over the tip.

within each pixel. A 50 mm CCTV lens (Ophir, Spiricon) was attached to a camera and was focused directly onto the tip of the light source. Following a linear calibration to correct pixel dimension due to the magnification by the lens, saturation of the CCD sensor was controlled using: 1) neutral density filters (OD 2 and 1, Ophir Spiricon) stacked above the lens, 2) the aperture on the 50 mm lens, and 3) the integration time within BeamGage software. Subsequently, an ambient light correction was performed using the built-in UltraCal function within BeamGage. Pixel response was then calibrated using previously determined power values measured using a photodiode power meter (PD300, Ophir Spiricon). For each LCU, the distance between the camera and the light guide tip was fixed. The beam profile images were then analysed using Ophir-Spiricon software and displayed on a computer screen as a color-coded image of the beam irradiance distribution across the emitting surface.

Three light curing devices that represented second-generation LCUs were used: single diode, one wave and emission; Satelec Mini LED (Acteon), Elipar S10 (3M Oral Care, St. Paul, MN, USA), and Woodpecker LED (Woodpecker, China) and one third-generation LED light: double diode, multi-waveband emission; BluePhase Style (Ivoclar Vivadent) were selected to evaluate the variability of the beam light homogeneity among different LCU brands. Selected LCUs with chipped and contaminated light curing guides were also evaluated using the laser beam profiler. To demonstrate the clinical implications of beam light homogeneity, scaled beam profile images were superimposed over a tooth preparation to demonstrate the radiant power received over various regions within a typical cavity preparation.

Statistical analysis was conducted using IBM SPSS version 21 (IBM Inc, NY, USA). Data were analysed for normality using Shapiro-Wilk Test, and comparisons were made using one-way analysis of variance (ANOVA) and *post hoc* Tukey tests ($\alpha=0.05$). Linear regressions with stepwise correlation were also used to analyze the correlation between the light output and the presence of tip debris and chipping, as well as the effect of increasing the distance from the target and the effect of using protective sleeves.

RESULTS

Data showed that 33% of the tested lights showed irradiance output at or below 500 mW/cm^2 , which was considered unacceptable; details are shown in Table 2. The condition of the light curing guides was also poor, with only 48% identified to be in good condition (Table 3).

Data showed that all variables tested had a highly significant impact on the irradiance output emitted from the LED LCUs; these variables were as follows:

Light Guide Factors: Effect of Debris Build-up, Chipping, and Use of Protective Sleeve

Resin debris build-up ($r^2=0.95$, $p<0.05$)

Chipping of the light curing tip ($r^2=0.96$, $p<0.05$)

Use of protective sleeve ($r^2=0.82$, $p<0.05$)

Table 2: The Irradiance Output (mW/cm^2) of the Light Curing Units (LCUs) Tested

Irradiance Output (mW/cm^2)	Number of LCUs
< 200	3 (1%)
200-400	30 (13%)
400-500	44 (19%)
> 500	156 (67%)

Table 3: The Condition of the Light Curing Tip Guides Tested

Condition of the LCU Guide	Number of LCUs (%)
Debris build up	38 (16%)
Damaged	60 (26%)
Debris build up and damaged	24 (10%)
Good	111 (48%)

Abbreviation: LCU, light curing unit.

Table 4: The Mean Irradiance Values (mW/cm ²) and the Performance (%) of the Satelec Mini LED when Used with New Light Guide Tips, with Debris Build up, Chipped Tips, and when Used with Protective Sleeves		
Group	Mean (SD)	Performance (%)
New tip	1072 (13.03)	100
Debris build up	410 (12.24)	38
Chipping	540 (7.07)	50
Protective sleeve	810 (0.1)	76
Abbreviations: LCU, light curing unit.		

In this study, using a light curing tip with resin debris build-up resulted in a significant reduction in the irradiance output by an average of 62% ($p<0.05$). Similarly, the use of a chipped tip or using protective sleeves resulted in a reduction of the irradiance output by 50% and 24% ($p<0.05$), respectively. Details are shown in Table 4 and include the reported irradiance values and the impact on the light performance.

Operator Factors: Effect of Distance

Distance from the sensor target ($r^2=0.98$, $p<0.05$)

Increasing the distance of the light guide tip from the sensor target also resulted in a reduction in the irradiance output; the irradiance was reduced by 25% at 7 mm and 34% at 10 mm ($p<0.05$), respectively. Figures 2 and 3 show the effect of increasing the distance from the target on the overall irradiance output and the time required to reach an energy level of 16 J/cm² required to cure resin composites. Figure 4 illustrates the clinically relevant distances; for example, the distance between the cusp tip and the base of a posterior interproximal box, which may exceed 7 mm,^{48,50} and its effect on the light output and performance.

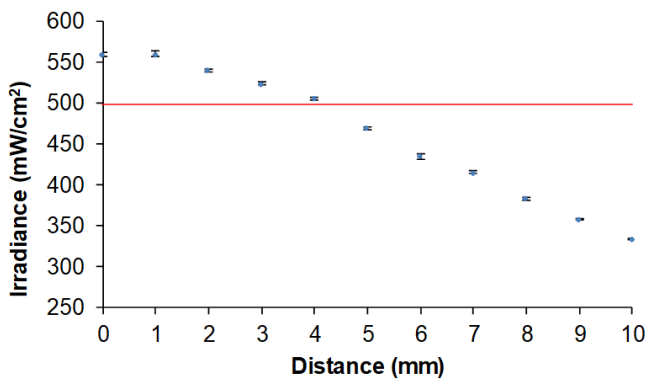


Figure 2. Effect of increasing the distance between the light guide tip and the sensor target on the irradiance output using Satelec Mini LED (Acteon, Merignac, France). The red line represents the manufacturer’s recommended irradiance of 500 mW/cm².

Beam Light Uniformity

The light output uniformity across the emitting tip and the irradiance distribution from four representative lights tested in this study are shown in Figure 5. The beam profiles show differences in the beam diameters among different lights and inhomogeneous irradiance distribution with the presence of hot spots (indicated by the color scales on the right of each beam profile image).

Figure 6 shows examples of beam profile images comparing the effect of contamination and damage on the irradiance output.

DISCUSSION

The dental light curing unit (LCU) is an essential piece of equipment in every dental practice. However, with most operators, proper use and maintenance of LCUs is not very well understood and often underappreciated. This study showed that 33% of the LED LCUs across primary and secondary dental settings were considered to be out of compliance with the minimum recommended light irradiance required to optimally cure resin composites using a convenient exposure time

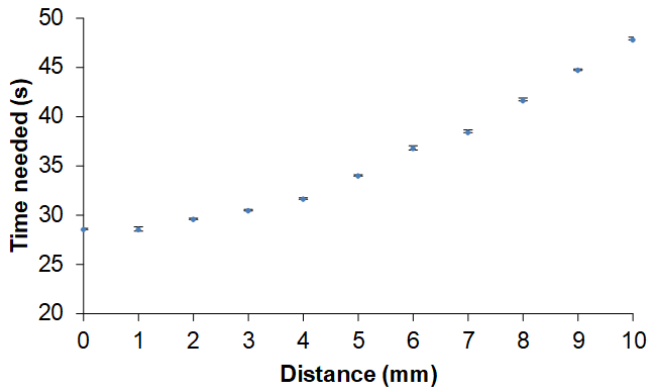


Figure 3. The effect of increasing the distance on the time required to reach 16 J/cm² recommended to cure resin composites using Satelec Mini LED (Acteon, Merignac, France).

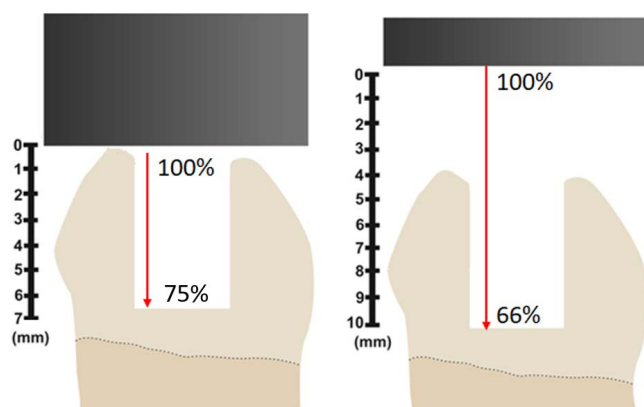


Figure 4. The effect of increasing the distance of the light tip on the irradiance output using Satelec Mini LED (Acteon, Merignac, France). The light irradiance performance is reduced to 75% at 7 mm and 66% at 10 mm.

(~40 seconds). Most dental composite manufacturers recommend delivering a minimum of 500 mW/cm^2 for a duration of 40 seconds for optimum curing, and many recommend shorter curing times if irradiance is higher, eg, $>1000 \text{ mW/cm}^2$ for 10 seconds. It has been previously reported that delivering 400 mW/cm^2 for 60 seconds is required to adequately cure a 1.5-to 2-mm thickness of resin composite.^{14,51} Consequently, when the irradiance is multiplied by exposure time, a sufficient radiant exposure of 16- to 24-J/cm^2 is often quoted. It is possible to compensate for lower irradiance by prolonging the exposure time;¹ however, this is not recommended by the manufacturers due to increased

risks of overheating the pulp. The findings of this study are in agreement with other studies evaluating QTH and LED LCUs in dental practices, which have shown that most curing lights are poorly maintained and deliver inadequate light irradiance for optimal curing process.³²⁻³⁷ This study also found that there was a general lack of awareness of the type and the irradiance output of the LCUs that are already in use. Practitioners were also unaware that a large number of LCUs were unable to deliver a sufficient light output to adequately cure resin composite restorations. Despite their routine use, most operators were simply using any LCU for 20 seconds without further knowledge on the wavelength and irradiance requirements. Additionally, there was a general lack of awareness of the impact of various clinical factors and the light guide factors on the efficiency and the performance of the LCUs.

This study investigated the effect of contamination of the light guide tip with debris, damage, increasing the distance, and using protective sleeves on the irradiance output and the performance of LCUs. Our data showed that all aforementioned factors have significant impact on the overall light output and performance and should be taken into consideration when the LCU is used. These results showed that presence of debris build-up and damage of the light curing tip resulted in reducing the irradiance output by 62% and 50%, respectively.

The effect of increasing the distance from the restoration was also evaluated in this study. It might

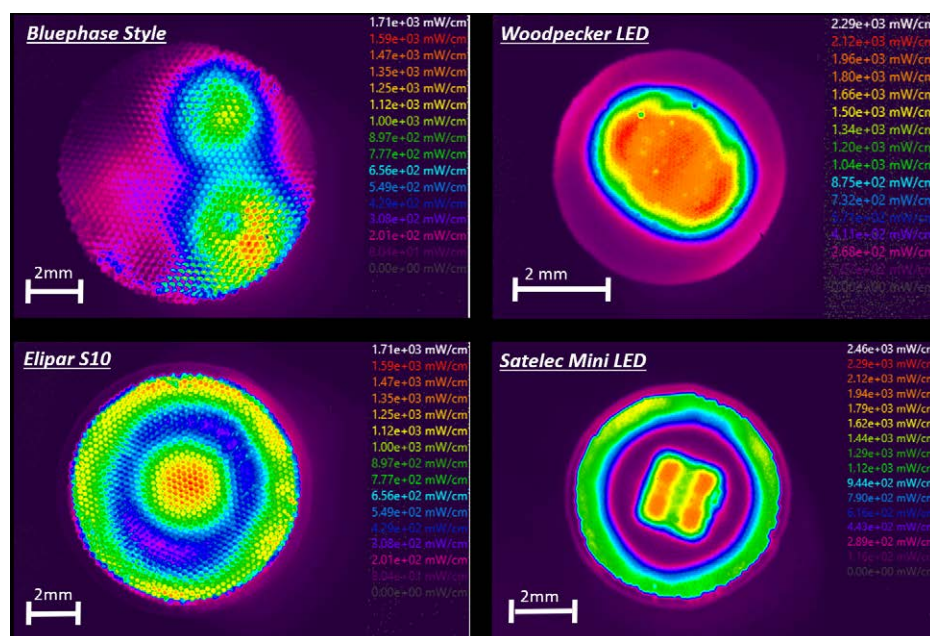


Figure 5. Beam profile images of four LED units showing the differences in the beam diameter and the beam heterogeneity across the tips.

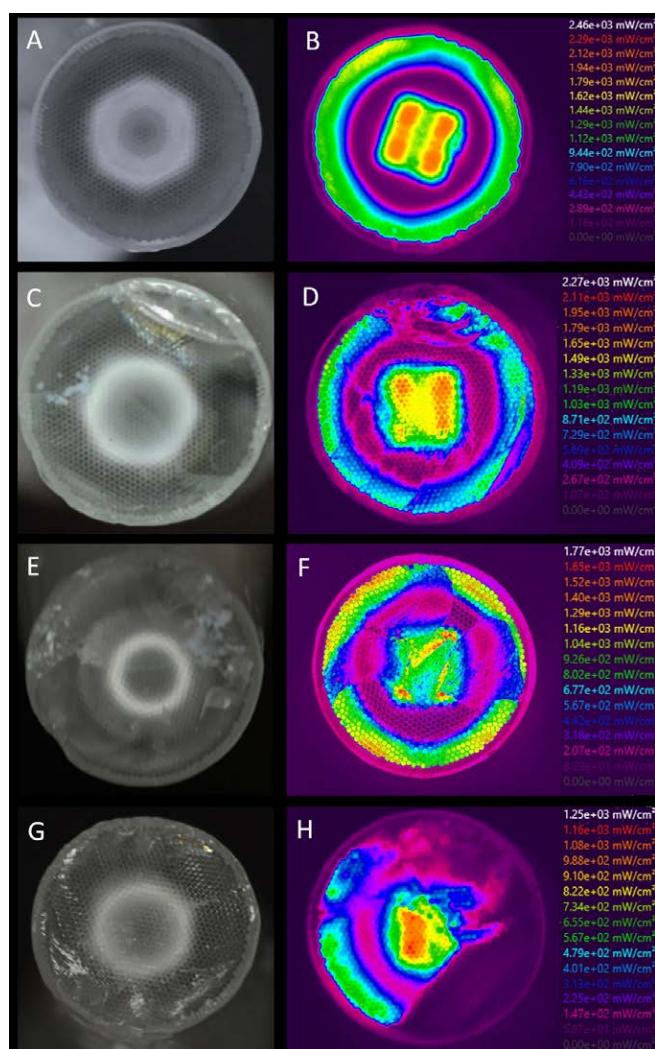


Figure 6. Examples Satelec Mini LED (Acteon, Merignac, France) LCU fiber optic tips and their corresponding beam profile images. (A,B) Representative control showing clean tip with unaffected beam profile distribution albeit with central hot spots of high irradiance output. (C,D) Representative images of chipped light guide tips showing compromised beam profiles where irradiance has significantly decreased in areas of chipping and damage. (E,F) Representative beam profile images of light guide tip with resin build up covering the surface resulting in significantly reduced irradiance in areas of resin build up. (G,H) Severely damaged light guide tip with large cold area in the corresponding beam profile image.

be assumed that this falls under the inverse square law; however, this does not always occur. The inverse law is applicable on a point source of radiation emitting 360° in space, whereas the emission from the light curing unit does not act as a point source. The light emitted from dental LCUs varies depending on the design and the optics within the unit. The findings of this study showed significantly lower irradiance values reached by the surface when the distance of the light source

from that surface increases. The total irradiance output for the Satelec Mini LED (Acteon) was reduced by 25% and 34% at 7 mm and 10 mm, respectively. Previous studies also reported that some curing lights deliver only 25% or less of the irradiance measured at the tip when the distance is increased by 8 mm.^{12,45,50,52} Therefore, operators should take into consideration the clinically relevant distances that may affect the irradiance output delivered to the restoration, especially in a Class II cavity box where the distance between the cusp tip and the base of the box may exceed 7 mm.⁵² Furthermore, it is important to ensure that the LCU is emitting sufficient light to compensate for the reduction over the distance and to consider increasing the exposure times for the initial increments.

The effect of barriers including use of protective sleeves was also evaluated. Our data showed that the use of protective sleeves reduces the overall output by 24%. It was previously reported that when some commercial barriers are used, the light output can be reduced by up to 40%.^{44,53,54} Therefore, it is important to emphasize that when a barrier is used, it should fit tightly over the light tip and not obstruct the light output (Figure 7) in order to minimize the refraction that occurs when light passes through different mediums and the impact on the light output. Additionally, it is recommended that the light output from the LCU should be recorded with the barrier over the tip when they are routinely used. Having a tightly fitted barrier not only will be a good infection control measure, it will also prevent debris build up on the LCU tip, which also affects the irradiance output. It was suggested that clear plastic food wrap can be an inexpensive and effective infection control barrier with minimal effect on light output.^{44,53}

Several studies have shown that the light output from many LCUs is not uniform and the irradiance homogeneity depends on the design of the curing light and optical arrangement.⁵⁵⁻⁵⁸ In this study, beam profiles were not uniform, with hot spots of high irradiance and cold spots of lower irradiance values. Therefore, using a single irradiance value does not describe the irradiance across the entire light tip. Consequently, manufacturers should provide the beam profile of their LCUs. The clinical relevance of the beam profiles is highlighted by overlaying the irradiance beam images on a cavity preparation, shown in Figure 8. This shows that some locations in the cavity may receive different amounts of light depending on effective light tip size and the homogeneity of the light output. It also shows that the size of the light curing tip may not necessarily reflect on the *actual* active tip emitting sufficient irradiance output. Consequently, the light received at the proximal boxes from some LCUs may be inadequate for optimal curing

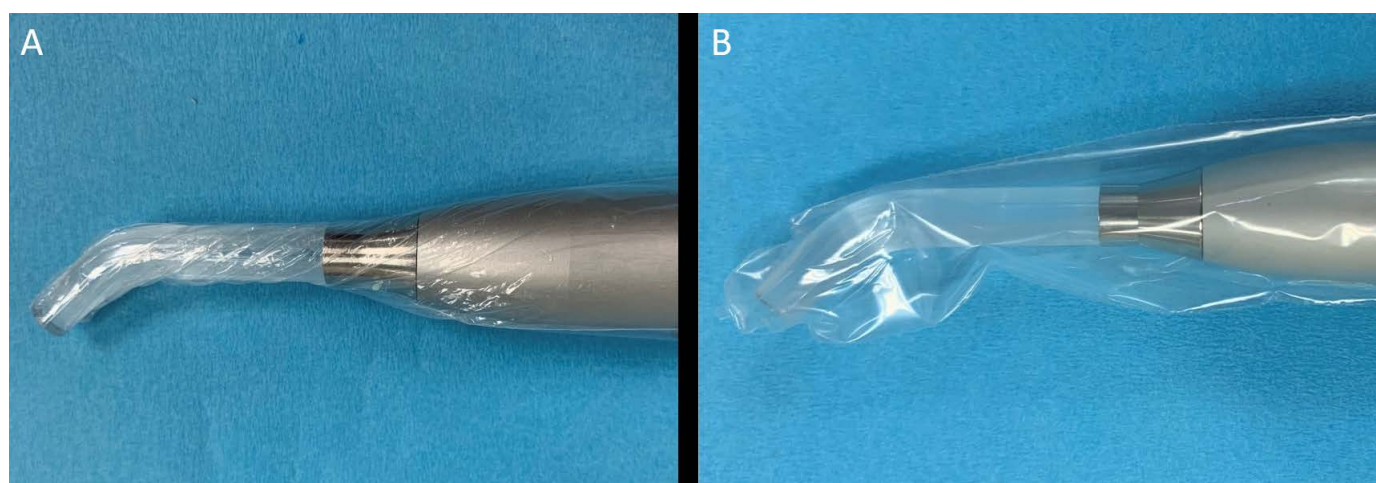


Figure 7. The light protective sleeve is (A) fitted tightly over the light tip whereas (B) shows a less ideal fit, which impedes the light output.

if used for one exposure cycle. Therefore, multiple exposure cycles may be required especially if a small tip is used to cover the entire restoration (Figure 8).

The condition of the light curing tip can degrade over time due to debris build-up or simply damage that may occur with regular use and autoclave procedures.³⁸ Additionally, clinical barriers are often present, such as matrix bands and tooth position, which limit the access of the light curing tip to the intended restoration. It is also important to appreciate that these factors are

usually combined, such as distance of the light from the restoration and the use of a protective sleeve, which would act together, resulting in a significant reduction in the overall light output. Consequently, composite restorations could be undercured and prone to early failure due to decreased bond strength, bulk fractures, and increased wear.^{9,10,12}

Regular monitoring and maintenance protocols for LCUs should be in place in every clinic. This should include regular evaluation of the irradiance output and careful evaluation of the light curing tips for debris build-up and damage. Handheld dental radiometers are widely available and can be used to monitor the light output, even if only as a relative measurement of performance with continued use. However, several studies have reported their inaccuracy in measuring absolute irradiance.⁵⁹⁻⁶² The sensor area of most commercial dental radiometers is usually smaller than the LCU tip diameter, which therefore provides inaccurate values. However, a recently introduced dental radiometer, the BluePhase II from Ivoclar Vivadent (Schaan, Liechtenstein), used in this study, was able to measure the irradiance of up to a 13-mm diameter tip due to its large sensor area. It was reported that the accuracy of the Blue Phase II is comparable to laboratory-grade spectrophotometers, providing the most accurate data compared to other commercial dental radiometers⁴⁷.

It is also important to appreciate the role of education and training on the use of LCUs. It has been reported that there is up to a 10-fold difference in the ability of different operators to deliver adequate light exposure even when the same light source is used.^{63,64} Operator variability can be minimized and improved techniques can be employed if users are trained on how to use the curing lights using a device such as the MARC

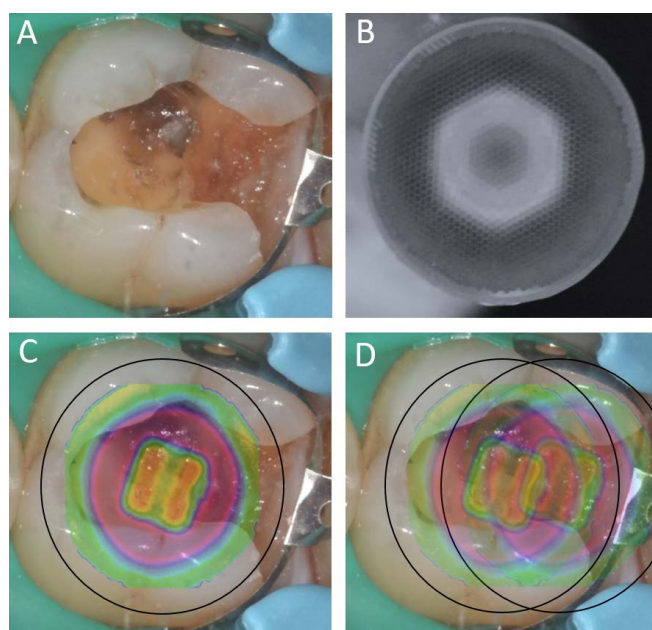


Figure 8. (A-C) Images showing molar tooth preparation, Satelec Mini LED (Acteon, Merignac, France) light curing tip with 7 mm diameter and its corresponding beam profile image superimposed on the cavity preparation. This shows that the light beam does not cover the entire cavity and will require multiple exposures to cover the entire restoration, as shown in (D).

patient simulator (Blue Light Analytics). Training on this device allows operators to learn how to correctly position the light and the patient to improve access to the restoration for effective curing process. The MARC patient simulator has been shown to be effective in teaching appropriate light curing techniques by providing direct feedback to the operator on how much irradiance is delivered and highlights operator factors that result in a suboptimal curing process.⁶⁵⁻⁶⁷

On the basis of this study, in order to help improve the use of LCUs, the authors make the following recommendations:

- Have a protocol in place for regular monitoring and maintenance of LCUs to meet the manufacturers' specifications.
- Inspect and clean the LCU before use to ensure that it is free of defects and debris.
- Use infection control barriers that fit tightly over the light tip without impeding the light output.
- Follow the light exposure times and increment thickness recommended by the resin composite material manufacturer.
- Position the light tip as close as possible (but without touching the uncured resin composite material to avoid debris) and parallel to the surface of the resin composite being cured.
- Stabilize and maintain the tip of the LCU over the resin composite throughout the exposure.
- Be aware that further light exposure cycles may be required when there is limited access, barriers present, curing larger restorations, and when using protective sleeves.
- Ensure eye protection by using appropriate blue blocking filters.

Following the findings of this study, LCUs which were found to be of poor quality and with low irradiance output were immediately removed from the clinics and replaced. Furthermore, local protocols were put in place within both dental hospitals to regularly check and evaluate the LCUs in use. LCUs were then followed up to ensure sufficient output, and are now regularly monitored and audited. General dental practices were also made aware of the findings, and further measures were taken to ensure that their lights are able deliver sufficient light output. General dental practices were also given a suitable maintenance and monitoring protocol to follow.

CONCLUSIONS

This study showed that there is lack of protocols for regular monitoring and maintenance of LCUs used

in primary and secondary care. Thirty-three percent of the LCUs delivered irradiance output less than 500 mW/cm². The condition of the light curing tips was also poor, with 16% contaminated with resin debris, 26% damaged, and 10% both contaminated and damaged. Using damaged and contaminated light curing tips, protective sleeves, and increasing the distance from the restoration significantly reduce the irradiance output and the performance of the LCU.

Conflicts 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.

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Relationship Between the Cost of 12 Light-curing Units and Their Radiant Power, Emission Spectrum, Radiant Exitance, and Beam Profile

CJ Soares • SSL Braga • RB Price

Clinical Relevance

Higher cost light-curing units deliver more power (Watts) and have a wider tip that covers more of the tooth. When choosing their curing light, clinicians should consider evaluating the emitted power, active tip diameter, and tip irradiance value.

SUMMARY

Objectives: To correlate the radiant power (mW), radiant exitance (or tip irradiance in mW/cm²), emission spectrum (mW/cm²/nm), and beam irradiance profile of 12 light-curing units (LCUs) available in the Brazilian market with their market cost.

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Methods and Materials: Six LCUs that cost more than US\$900 (Bluephase G4, VALO Grand, VALO Cordless, Radium Xpert, Elipar DeepCure-S, and Radium plus) and six low-cost LCUs costing less than US\$500 (Radium Cal, Optilight Max, High Power LED 3M, Emitter D, Emitter C, and LED B) were examined. Radiant power (mW) and emission spectrum (mW/nm) were measured using an integrating sphere connected to a fiber-optic spectroradiometer. The internal tip diameter (mm) of each LCU was measured using a digital caliper and was used to calculate the average radiant exitance (mW/cm²). Irradiance profiles at the light tip were measured using a commercial laser beam profiler. The cost of each LCU in Brazil was correlated with internal tip diameter, radiant power, and tip irradiance.

Results: None of the low-cost LCUs were broad spectrum multiple peak LCUs. There was no correlation between the cost of the LCUs and their averaged tip irradiance; however, there was a high

positive correlation between the cost of the LCUs and the radiant power and tip diameter. The VALO Grand, Elipar DeepCure-S, VALO Cordless, and Bluephase G4 all emitted a higher radiant power. They also had a significantly greater tip diameter than other LCUs. For the LCUs with a nonuniform output, some areas of the light tip delivered less than 400 mW/cm², while other areas delivered more than 2500 mW/cm².

Conclusions: In general, LCUs that had a higher cost (US\$971-US\$1800) delivered more power (mW) and had a greater tip diameter (mm), which covered more of a tooth. In general, the low-cost LCUs (US\$224-US\$470) emitted a lower radiant power and had a smaller tip diameter.

INTRODUCTION

The light-curing process is an important step when delivering both indirect restorations^{1,2} and direct resin-based composite (RBC) restorations.^{3,4} Only when an adequate amount of light at the correct wavelength is delivered from the light-curing unit (LCU) to the RBC will the resin manufacturer's claimed esthetic and mechanical properties be achieved.^{5,6} The light emitted from the LCU should be uniformly distributed across the entire light tip,^{3,7} and it should also fully cover the RBC.⁷⁻⁹ When deciding which LCU to purchase, clinicians are influenced by the claimed irradiance and the price. However, there are other factors to consider, such as the power output, emission spectrum, beam collimation, beam profile, ergonomics of the LCU, and the ability to disinfect the unit.^{8,10}

The commonly used tip irradiance value is a calculated value that is based on the radiant power (mW) and the internal tip diameter (mm) from which the tip area (mm²) is calculated.⁷ Since handheld dental radiometers are inaccurate¹¹ and unable to measure the emission spectrum (mW/nm), it is recommended that the total output from the LCU be measured using laboratory-grade equipment and then the average irradiance (mW/cm²) across the light tip can be calculated. Dental radiometers will often measure the light output in a small area just at the center of the light tip.¹¹ If the light from the LCU is greater at the center area of the light tip, the tip irradiance (radiant exitance) can be artificially increased when measured with most dental radiometers. Another reason is related to the inability of dental radiometers to detect and then adjust for the different emission spectra from dental LCUs.

In vitro studies often follow the ISO 4049 standard that uses a 4.0-mm diameter metal mold.^{12,13} When such a small diameter mold is used, the effects of any

lack in the homogeneity of the light distribution from the LCU are unlikely to be evident. In contrast, if the samples are prepared using larger molds that represent the size of a molar tooth, for example, between 10 and 12 mm in diameter, the beam width, beam homogeneity, and characteristics of the LCUs will have a significant effect on the photoactivation of the RBCs.³

The photo-polymerization process can influence the longevity of both direct and indirect restorations. Unfortunately, most studies do not include a sufficient description of the characteristics and quantity of the light received by the resin composite or resin cement specimens to allow studies to be replicated.¹⁴ Consequently, the results of such studies using inappropriate LCUs can propagate scientific misinformation. The Brazilian dental community produced the second-largest number of papers in 2018 (USA, 3053; Brazil, 2218). Most of these publications are in the fields of operative dentistry/cariology, dental materials, and endodontics;¹⁵ thus, the information about LCUs used in Brazil not only affects the restorations produced in Brazil, but also those produced in the rest of the world.

There are substantial differences in the cost of LCUs. To the best of the authors' knowledge, no study has related the market cost to the different parameters that are used to characterize different LCUs. Most of the LCUs tested in the present study are sold in other countries or are available for purchase on the Internet. Thus, the correlation between market cost and the characteristics of LCUs is important information for all dentists. Therefore, the aim of this study was to measure the radiant power, emitted spectrum, internal and external diameter, and calculated irradiance, and correlate them with the market cost of several low-cost LCUs that are sold in Brazil, and to also show the beam profile of LCUs and how much of a maxillary central incisor and a molar tooth would be covered by the light emitted from the LCU. The research hypotheses tested were that: (1) the cost of the LCU will correlate with its power, tip diameter, and tip irradiance (radiant exitance); and (2) the emitted light from different LCUs will provide similar coverage of a maxillary central incisor and the occlusal surface of a molar tooth.

METHODS AND MATERIALS

Characterization of the LCUs

Twelve commonly purchased LCUs in Brazil were tested (Table 1). Six of the LCUs cost more than US\$900 (Bluephase G4, VALO Grand, VALO Cordless, Radium Xpert, Elipar DeepCure-S, and Radium plus) and six low-cost LCUs cost less than US\$500 (Radium Cal, Optilight

Table 1: LCUs Tested

Light-Curing Units	LCU Serial Number	LCU Type – Wavelength Emission	Battery/ Mains	Tip-light Conductor	Manufacturer
VALO Grand	MFG3227-5	LED – multi-peak	Battery	None	Ultradent, South Jordan, UT, USA
VALO Cordless	C43122	LED – multi-peak	Battery	None	Ultradent, South Jordan, UT, USA
Bluephase G4	1404000004	LED – multi-peak	Battery	Optical fiber with mixer - black	Ivoclar Vivadent, Schaan, Liechtenstein
Elipar DeepCure-S	1521087817	LED – monowave	Battery	Optical fiber - translucent	3M, St Paul, MN, USA
Emitter D	7702023	LED – monowave	Battery	Optical fiber - black	Schuster, Santa Maria, RS, Brazil
Optilight Max	881778249	LED – monowave	Battery	Optical fiber - black	Saevo, Ribeirão Preto, SP, Brazil
Radii plus	52003	LED – monowave	Battery	None	SDI, Basywater, Victoria, Australia
Radii cal	EA1010CL	LED – monowave	Battery	None	SDI, Basywater, Victoria, Australia
Radii Xpert	15055	LED – monowave	Battery	None	SDI, Basywater, Victoria, Australia
LED B	B1205017C	LED – monowave	Battery	Optical fiber - black	Woodpecker, Guilin, China
High Power	7000204142	LED – monowave	Battery	Optical fiber - black	3M, St Paul, MN, USA
Emitter C	L1541282C	LED – monowave	Battery	Optical fiber - translucent	Schuster, Santa Maria, RS, Brazil

Abbreviations: LCU, light-curing unit; LED, light-emitting diode.

Max, High Power LED 3M, Emitter D, Emitter C, and LED B). The LCU's internal and external tip diameters were measured using a digital caliper (Mitutoyo, Tokyo, Japan). The tip area was calculated from the inner diameter of the light tip.

Power and Radiant Exitance (Tip Irradiance)

The total radiant power emitted from each LCU was measured 5 times using a 6-inch integrating sphere (Labsphere, North Sutton, NH, USA) attached to a fiber optic spectrometer (USB 4000; Ocean Insight, Orlando, FL, USA).¹⁶ The light tip was placed at the 12.5-mm diameter entrance to the integrating sphere so that all of the light from the LCU tip was captured. The measurement system, comprising the spectrometer, optical fiber, and integrating sphere, was calibrated before use. The mean radiant exitance across the light-emitting surface of the tip was then calculated as the quotient of the average of the 5 radiant power values

(from the integrating sphere) and the internal optical area of the LCU tip. This result provided the averaged single radiant exitance (tip irradiance value) that is commonly reported by manufacturers and used in the ISO 10650.¹⁷

Beam Profile

The irradiance distribution across the light tip was captured using a laser beam profiler charge-coupled device (CCD) digital camera with a 50-mm focal length lens (SP620U; Ophir-Spiricon, Logan, UT, USA) that was fixed at the focal distance from the diffusing surface of a 60° holographic diffuser target (54-505; Edmund Optics, Barrington, NJ, USA). Two blue glass bandpass filters (34-434; Edmund Optics) and 1 reflective neutral density filter (Edmund Optics) were required to flatten the spectral response of the CCD camera. So that the beam profile images of the LCUs could be compared qualitatively, all the images were made at the same distance using the same exposure time.

After the LCU was turned on, the beam profiler camera captured an image that was recorded using the beam analyzer software (BeamGage Professional version 6.14, Ophir-Spiricon). Using the internal tip diameter (mm) of each LCU, the “Optical Scaling” tool in the BeamGage Professional (Ophir-Spiricon) calibrated the beam profile data in millimeters. The mean radiant power values (mW) previously obtained were then entered into the beam analyzer software to produce color-coded calibrated tip irradiance in mW/cm² images. The calibrated data from BeamGage Professional (Ophir-Spiricon) were then exported into OriginPro 2019 version 9.6. (OriginLab, Northampton, MA, USA), where the images were all scaled to the same irradiance levels and x and y dimensions. These images were then superimposed over the image of a central incisor laminate veneer and over the mesial-occlusal-distal (MOD) cavity in molar for comparison using the software CorelDRAW 2018 (Corel, Ottawa, Ontario, Canada).⁷

Statistical Analysis

Data were first analyzed for normal distribution (Shapiro-Wilk test) and homoscedasticity (Levene's test). Analysis of variance, followed by the Tukey post hoc multiple comparison test, was then used to compare the light output from the LCUs. The Pearson correlation test was used to verify if there was

a correlation between power, tip irradiance, and tip diameter and market cost of the LCUs. All tests used a significance level of $\alpha = 0.05$, and all analyses were carried out with the statistical package Sigma Plot version 13.1 (Systat Software Inc, San Jose, CA, USA).

RESULTS

The external tip diameter, internal tip diameter, radiant power, irradiance, and market cost of the 12 LCUs are reported in Table 2. The external tip diameter ranged from 7.2 to 15.1 mm. The internal tip diameter from where light was emitted ranged between 6.8 and 12.0 mm. The radiant power ranged between 224 and 1092 mW, and the calculated average tip irradiance ranged between 585 and 1467 mW/cm². The market cost ranged from US\$224 to US\$1800.

The radiant power and the emission spectra from the LCUs into the integrating sphere, and the radiant power that the 12-mm diameter specimens received during an exposure time of 20 seconds, are shown in Figures 1 and 2, respectively. None of the low-cost LCUs were broad spectrum multiple peak LCUs. The calibrated three-dimensional beam profiles from the LCUs showing the tip diameter and average radiant exitance (tip irradiance in mW/cm²) distribution across the light tip are shown in Figure 3. In general, the more expensive LCUs (those costing more than US\$900) such as VALO Grand, Bluephase G4, VALO Cordless, and Elipar

Table 2: External and Internal Tip Diameters, Radiant Power, Tip Irradiance (Radiant Exitance), and Cost of the LCUs Tested

Light-Curing Units	External Tip Diameter (mm)	Internal Tip Diameter (mm)	Radiant Power (mW)	Tip Irradiance (mW/cm ²)	Cost (US\$)
Bluephase G4	9.9	9.0	836 ± 1.1 B	1316 ± 2.6	1800
VALO Grand	15.1	12.0	1092 ± 0.3 A	910 ± 1.3	1708
VALO Cordless	13.3	9.7	659 ± 0.7 C	933 ± 1.3	1418
Radii Xpert	11.8	7.8	426 ± 8.8 F	908 ± 13.4	1053
Elipar DeepCure-S	9.8	9.0	859 ± 1.3 B	1350 ± 1.5	1050
Radii plus	11.9	7.2	498 ± 3.3 E	1224 ± 7.6	971
Radii cal	11.9	7.2	501 ± 3.9 E	1238 ± 13.4	470
Optilight Max	7.9	7.0	544 ± 0.9 D	1415 ± 2.5	458
High Power	8.2	7.4	572 ± 1.2 D	1330 ± 3.2	395
Emitter D	8.2	6.8	564 ± 1.9 D	1467 ± 4.5	279
Emitter C	7.2	7.0	224 ± 2.3 G	585 ± 5.4	250
LED B	8.0	6.8	467 ± 1.8 E	1286 ± 6.7	224

Abbreviations: LED, light-emitting diode.

Different capital letters indicate a significant difference in the radiant power values of the LCUs (Tukey test, $p < 0.05$).

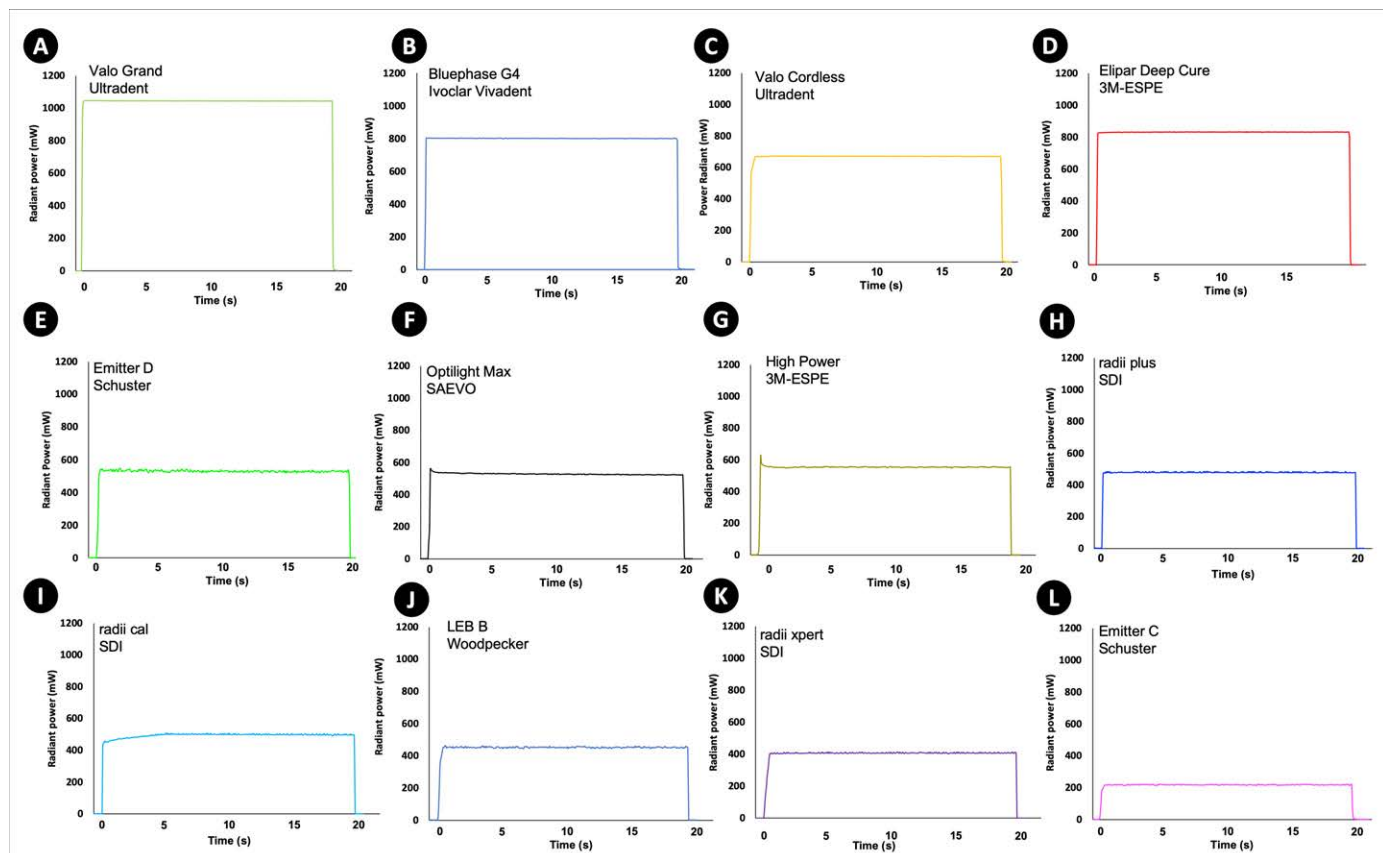


Figure 1. Radiant power (mW) emitted during a 20-second exposure from the 12 LCUs: (A): Bluephase G4; (B): VALO Grand; (C): VALO Cordless; (D): Elipar DeepCure-S; (E): Emitter D; (F): Optilight Max; (G): Radii plus; (H): LED B; (I): Radii Cal; (J): Radii Xpert; (K): High Power; (L): Emitter C. Note the difference in power outputs from these 12 lights. Abbreviations: LCU, light-curing unit; s, seconds.

DeepCure-S delivered more power, had a tip diameter greater than 9 mm, and had a more homogeneous irradiance, with radiant exitance values above 800 mW/cm² across most of the tip area. In general, the lower-cost LCUs (those costing less than US\$500) such as Emitter D, Optilight Max, High Power, Radii cal, LED B, and Emitter C delivered had less power, a tip diameter that was at most 7.4 mm, a light output that was not homogeneously distributed across the tip, and there was often a peak of high irradiance in a small area at the center of the light tip. Some areas across a light tip that had a nonuniform output delivered less than 400 mW/cm², while other areas delivered more than 2500 mW/cm². The Radii Xpert was considered to be in the group of more expensive LCUs, but this LCU had a low power output of 426 mW.

Table 2 shows that there can be almost a 5 mm difference between the outer tip diameter of the LCU and the internal tip diameter from where light is emitted. The spatial irradiance uniformity of the light from LCUs is illustrated by two everyday clinical situations: (1) the MOD cavity in a molar tooth, and (2) across the facial surface of a veneer on a maxillary central

incisor (Figure 4). Figure 4 shows that the irradiance beam profiles of many of the tested LCUs only partially cover these tooth surfaces. In general, LCUs that cost more than US\$900, such as VALO Grand, Bluephase G4, VALO Cordless, and Elipar DeepCure-S, covered more area of the central incisor surface and more of the molar tooth. Radii Xpert, which was also classified as a more expensive LCU, failed to cover a similar area as other LCUs of the same cost.

The Pearson correlations between LCU cost and tip diameter, radiant power, and tip irradiance are shown in Figure 5. There was a significant positive correlation between the cost of the LCU and the active tip diameter ($p < 0.001$, $r = 0.82$) and between the cost of the LCU and the radiant power ($p < 0.001$, $r = 0.76$). However, no correlation was found between cost of the LCU and tip irradiance ($p = 0.234$, $r = -0.019$).

DISCUSSION

This study was designed to determine if there was any correlation between the light tip diameter, power, calculated tip irradiance (radiant exitance), and beam

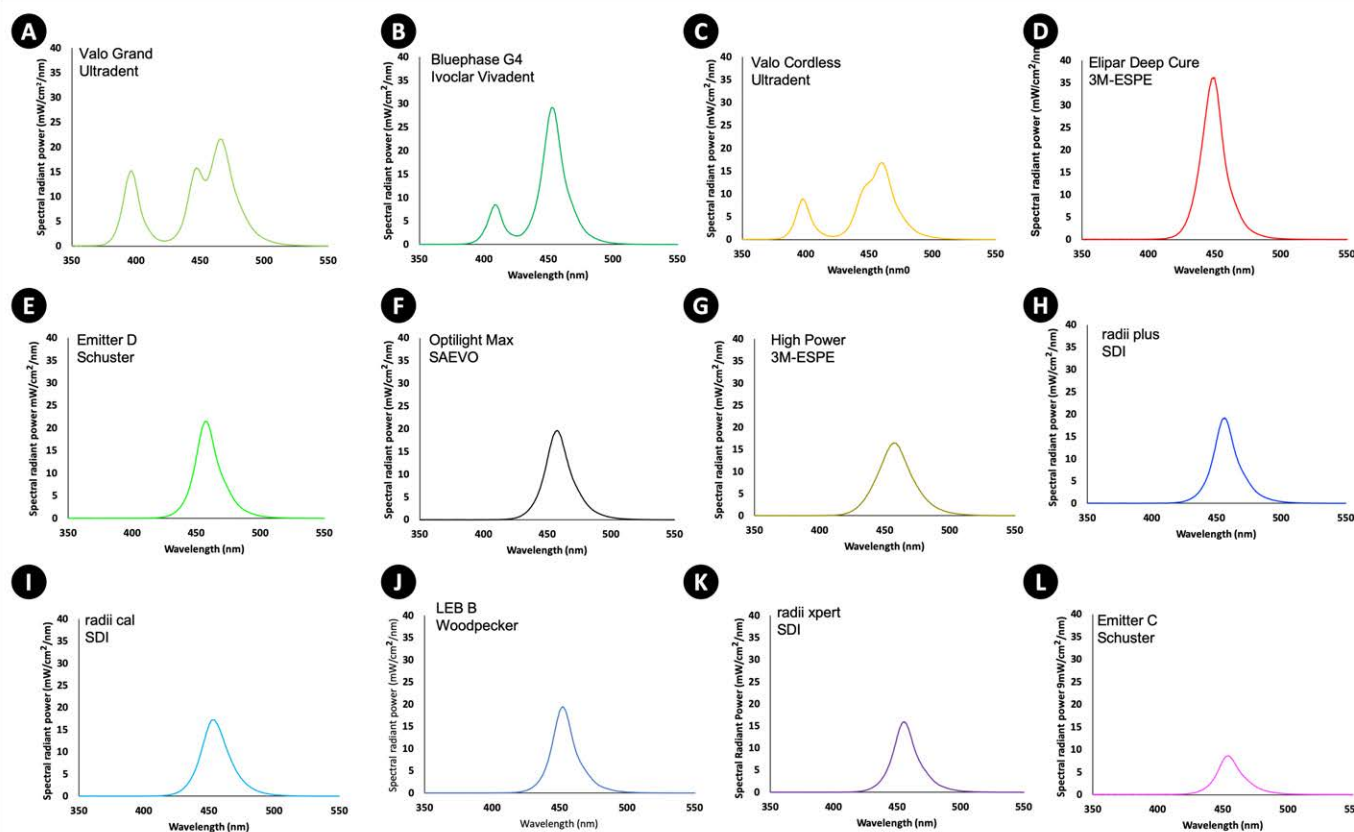


Figure 2. Emission spectrum (mW/nm) from the 12 LCUs: (A): Bluephase G4; (B): VALO Grand; (C): VALO Cordless; (D): Elipar DeepCure-S; (E) Emitter D; (F): Optilight Max; (G): Radii plus; (H): LED B; (I): Radii Cal; (J): Radii Xpert; (K): High Power; (L): Emitter C. Note the different spectra from these 12 lights. Abbreviation: LCU, light-curing unit.

profile of LCUs with their cost (Table 2). The 12 LCUs delivered a wide range of power and tip irradiance values. The fact that there is such a wide range in light outputs among the LCUs tested may help explain why so many resin restorations fail after only 6-7 years, as the dentist will often use these different lights for the same exposure time.¹⁸⁻²⁰ Doing so will deliver a wide range of energy to photocure the resin. Based on the results of our study, the first research hypothesis was partially confirmed. The cost of the LCU had a significant positive correlation with tip diameter ($p < 0.001$, $r = 0.82$) and power ($p < 0.001$, $r = 0.76$); these LCUs had a market cost above US\$900 (US\$971-US\$1800) and were classified as more expensive LCUs (Table 2). The more expensive the LCU, the more power it delivered and had a greater active tip area; however, no correlation was observed between the cost of LCU and radiant exitance (tip irradiance). The lack of any correlation between the cost of LCU and the radiant exitance (tip irradiance) can be explained by how the irradiance value from the LCU can be increased without increasing the power output simply by reducing the internal tip diameter. The lower cost LCUs that had a market cost between

US\$224 and US\$470 had light tips with a smaller diameter, and the light was generally focused on the center area of the LCU tip. Some areas across the light tip delivered less than 400 mW/cm², while other areas delivered more than 2500 mW/cm². Basic mathematics shows that if the tip diameter is decreased from 10 to 7 mm, this 3-mm reduction will halve the area and, as a result, double the radiant exitance (tip irradiance) if the same power is delivered. This also means that if the light tip is reduced by 3 mm, only half the power is required to deliver the same tip irradiance.²¹ Although the averaged radiant exitance from some LCUs, such as the Elipar DeepCure-S, Bluephase G4, VALO Grand, and VALO Cordless, tend to appear lower than that from other LCUs, Table 2 shows that the radiant power and tip diameters are greater on these light units compared with the low-cost lights units. Figure 3 shows that the Optilight Max, Emitter D, and High Power LCUs also have orange or red areas that indicate a high irradiance at the center of the light tip. In contrast, the lower radiant exitance from the more expensive LCUs is evenly distributed across the light tip and will cover a larger surface area of the restoration.⁷

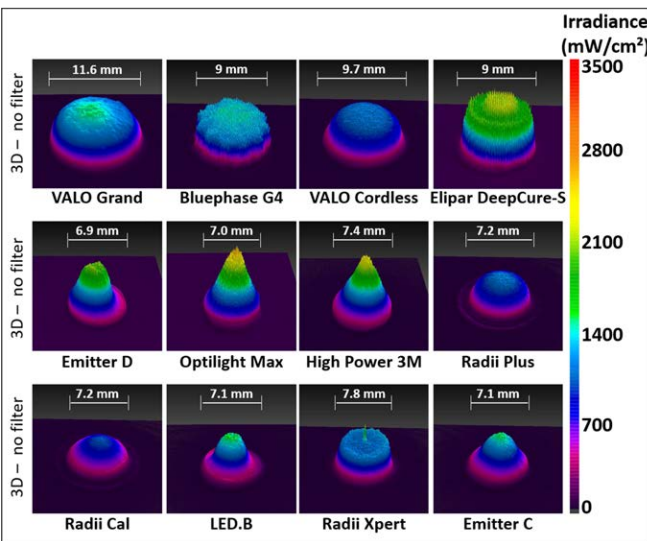


Figure 3. Calibrated beam profiles from the LCUs showing the tip diameter and averaged irradiance (mW/cm^2) distribution across the light tip. Some regions across the light tips with a nonuniform output deliver less than $400 \text{ mW}/\text{cm}^2$, while other regions deliver more than $2500 \text{ mW}/\text{cm}^2$. Note the wide range in beam uniformity. Abbreviations: 3D, three-dimensional; LCU, light-curing unit.

The results reported in Figures 1 and 2 and Table 2 reinforce the need to know the power, emission spectra, active light tip diameter, and irradiance of the LCU. Many manufacturers recommend a 10-second exposure time for their composite resins and resin cements, but this time does not consider the wide range of power, tip area, and beam homogeneity found in the 12 LCUs included in this study. Although the low-cost LCUs (US\$224-US\$470) tested in this study are very popular,

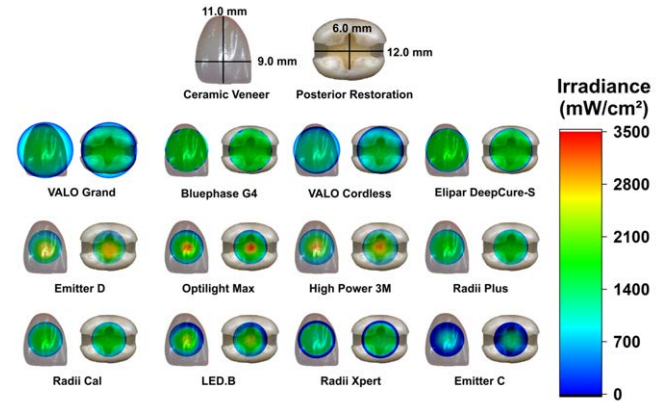


Figure 4. Calibrated irradiance (mW/cm^2) beam profiles from all LCUs superimposed over a mesial-occlusal-distal preparation in a molar and on the facial surface of a maxillary central incisor. Note the difference in light coverage over the teeth. Abbreviation: LCU, light-curing unit.

they should be used with caution. Some LCUs, such as the High Power (3M), Radii cal (SDI), and Emitter D (Schuster), delivered an unstable light output during a 20-second exposure. This behavior is probably caused by a lower quality of electric components that cannot compensate for any power fluctuations from the battery.²²⁻²⁴ Some low-cost LCUs will deliver less power, have an active tip diameter close to 7 mm, and have an inhomogeneous light distribution across the tip, which may compromise the polymerization process across different areas of the resin.²¹ The effects of light output inhomogeneity on the surface microhardness of different resins can be further accentuated if a shortened exposure time is used;^{3,25} this negative aspect will be further accentuated if all of the restoration is

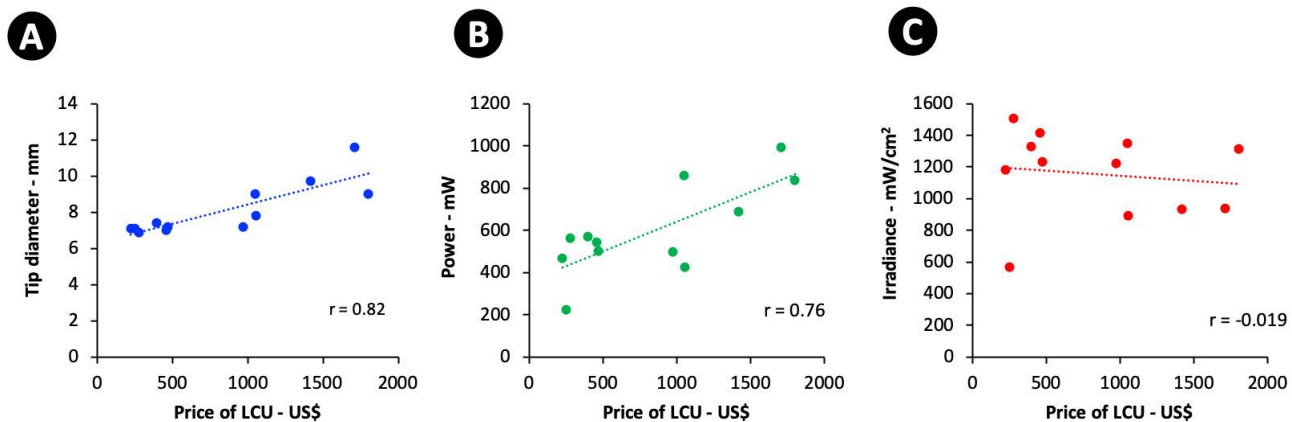


Figure 5. Pearson correlations for cost and tip diameter, power, and irradiance of the LCUs tested. (A): Correlation between tip diameter (mm) and cost (US\$) of the LCU ($p < 0.001$, $r = 0.82$). (B): Correlation between radiant power (mW) and cost (US\$) of the LCU ($p < 0.001$, $r = 0.76$). (C): Correlation between tip irradiance (mW/cm^2) and cost (US\$) of the LCU ($p = 0.234$, $r = -0.019$). Abbreviation: LCU, light-curing unit.

not covered by an adequate amount of light from the tip of the LCU. Figure 4 shows that there was a large range in the area covered by the LCUs tested over the MOD cavity in the molar tooth and over the facial surface of the central incisor. Based on these findings, the second research hypothesis was not accepted. The consequences of a lack of spatial irradiance uniformity from the LCUs are illustrated by two everyday clinical situations. Figure 4 shows the inhomogeneous spatial distribution of the irradiance beam profile of the LCUs when superimposed over a molar Class II MOD preparation and a veneer on a maxillary central incisor. Notably, for the low-cost LCUs, the active light tip from where light is emitted does not cover the tooth. Thus, some lights will deliver a wide range of radiant power and energy to different areas on the tooth, which will produce inhomogeneous photocuring of resin materials, especially if a short exposure time is used for all these LCUs. The effects of these differences will be further accentuated by the cavity depth in MOD restorations^{3,26} or the thickness, shade, and composition of the resin.^{27,28}

The decisions made by clinicians when purchasing a new LCU should not be based on market cost and a questionable tip irradiance value. The clinician should also not be misled into believing that this averaged tip irradiance value is distributed equally across the tip end of LED curing lights.²⁴ Future research should study the potential problems caused by purchasing a low-cost LCU so that this information can be disseminated in dental school curricula and continuing education programs. Studies that are designed to test bond strengths or the mechanical properties of resins should also consider the diameter of the samples tested.^{12,13} For example, the microshear bond strength test is frequently used to test the bonding interaction between resin cement and ceramic materials. However, the area from which the specimens for studies are made is generally small and comes from under the center of the light tip. Specimens made using low-cost lights will likely produce results that are comparable or even better than the more expensive lights because more energy will be delivered from the center of the light tip. The bond strength from specimens made from under the outer areas of the light tip will likely be lower when using low-cost lights because the resin will have received less energy.²⁹ This may be why a previous study that tested two LCUs with a 2.5-mm difference in diameter tip (VALO Cordless, 9.7 mm; Radii Cal, 7.2 mm) found that the choice of LCU had no effect on the microhardness and color change of composite resins when the diameter of the composite resin samples was only 5.0 mm, as these areas of the specimens would have received a relatively homogeneous amount of light from

both LCUs.³⁰ A different conclusion may have been reached had the outer areas of the specimens tested been 9-mm in diameter.

Figures 3 and 4 show that for the Emitter D, Optilight Max, High Power 3M, Emitter C and LED B units tested in this study, different radiant powers were emitted at various areas across the tip of this LCU. When resinous materials are photopolymerized using LCUs that deliver a highly inhomogeneous beam of light, resin polymerization, wear resistance, and microhardness can all be adversely affected.^{23,31} Consequently, if larger samples that are 9-12 mm in diameter are prepared using mold sizes that represent teeth, the effect of the smaller diameter light tips, which are found in several LCUs tested in this study such as Radii plus, Radii cal, Optilight Max, High Power, Emitter D, Emitter C, and LED B, may be more clinically relevant.³ Consequently, clinicians who purchase low-cost LCUs should probably use longer exposure times and multiple exposures from different locations to ensure that they completely cover the resin restoration with the active light tip. This should minimize concerns regarding undercuring of composite restorations when using an LCU with a smaller diameter tip.³²

High cost does not always mean high quality; however, the use of a single averaged tip irradiance (radiant exitance) value for describing the quality of the LCU should be avoided. Manufacturers should provide more information about the range of irradiance values emitted at the light tip and the radiant power to help clinicians decide which LCU to purchase. Additionally, when researchers describe the methodology used in their experiments that involve light curing, a better description of the light received by the specimens is recommended to help clarify the results. A cost-benefit analysis should be conducted to better select an LCU that is used in both a private and public oral health care context and to determine a cost-benefit analysis of undercuring the RBC.

CONCLUSIONS

Within the limitations of a study that only examined 12 LCUs, those that were more costly (US\$971-US\$1800) delivered more power (mW) and had a greater tip diameter (mm), which covered a greater area of a tooth. The lower-cost LCUs (US\$224-US\$470) generally emitted a lower radiant power and had a smaller tip diameter and area. Care should be taken when using these low-cost LCUs since they are less powerful (mW). They may only deliver both a high irradiance in a small area at the center of a small diameter light tip and a much lower irradiance at the outer regions of the light tip.

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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.

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Dentin Permeability and Nanoleakage of Universal Adhesives in Etch-and-rinse vs Self-etch Modes

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MMN Lopes • AJCCS Cavalheiro

Clinical Relevance

Universal adhesives do not seem to have the ability to effectively seal dentin, regardless of the mode of application.

SUMMARY

Purpose: This study evaluates the reduction in dentin permeability (P) and the expression of nanoleakage in resin-dentin interfaces made with universal adhesives, comparing the self-etch mode of application with the etch-and-rinse mode of application.

Methods and Materials: To measure dentin P at the baseline and after adhesive polymerization, 80

extracted noncarious human third molars (N=80) were sectioned to obtain 0.7-mm-thick midcoronal dentin disks. The specimens were randomly assigned to 8 groups according to the different adhesive systems and application modes used: Scotchbond Universal (SBU; etch-and-rinse [ER] mode vs self-etch [SE] mode), OptiBond XTR (OPT; etch-and-rinse mode vs self-etch mode), Clearfil Universal Bond Quick (CL; etch-and-rinse mode vs self-etch mode), and Adhese Universal

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(ADH; etch-and-rinse mode vs self-etch mode). A two-way analysis of variance with interaction was used to evaluate the P reduction differences among the groups ($\alpha=0.05$). Sixteen additional 0.7-mm-thick dentin disks were similarly prepared and treated, immersed in 50 wt% ammoniacal silver nitrate, and then processed according to conventional methods for analysis under transmission electron microscopy.

Results: The differences in P reduction among the adhesives were significant ($p=0.029$). For OPT and ADH ($p=0.0304$ and $p=0.0120$, respectively), the P reduction was higher in the ER mode than in the SE mode. For CL and SBU, no differences in P reduction was observed between the two application modes ($p>0.05$). All the groups showed some pattern of nanoleakage.

Conclusions: No adhesive system completely reduced dentin P. Dentin sealing was higher for OPT and ADH in the ER mode, while for SBU and CL, there was no difference between the two modes. All the adhesive systems showed nanoleakage.

INTRODUCTION

Despite the advancements in dentinal adhesive systems, there are still some cases where resin composite restorations are associated with postoperative sensitivity. The behavior of adhesive systems depends on the quality of their components (chemical composition) and their properties.^{1,2} Their formulations should be based on hydrophobic and high molecular weight monomers, without additives such as water and solvents.³ However, due to the moist nature of dentin, to have good wetting and penetration between the collagen fibers in the demineralized dentin, hydrophilic components and solvents must be incorporated into the composition of these materials.¹

A new version of adhesive systems known as universal or multimode adhesives,^{4,5} consists of mixtures of acidic, hydrophilic, and hydrophobic monomers; organic solvents; additives; and, necessarily, water in their composition. Thus, as with most other types of adhesive systems,^{6,7} the hydrophilic property of the polymers formed by these universal adhesive systems allows water to diffuse from the dentin or the external medium through the hybrid layer. Consequently, dilution of the primer components may occur, impairing the infiltration of resin monomers into the demineralized dentin. If there is inadequate penetration and hybridization of the resin monomers demineralized dentin zone and inside the tubules—

forming a continuous hybrid layer and sealing the dentinal tubules—then several outcomes are possible: dentin fluid movement and nanoleakage,⁸⁻¹² hydrolyses of the collagen and degradation of the resins,¹³⁻¹⁸ leaching of the resin components,⁹ and, ultimately, an increased risk of dentin P¹⁹ and postoperative sensitivity.²⁰⁻²²

Pashley and others²³ referred to two different types of dentin P: intradentinal P and transdentinal P. Intradentinal P is responsible for the monomer diffusion from etched tubule lumens into the surrounding collagen to hybridize the resin tags to the walls of the tubules or for the diffusion of adhesive monomers into the dentin matrix between the dentin tubules.²⁴ Transdentinal P, also called hydrodynamic fluid flux, is the movement of fluid across dentin within the dentin tubules.²⁵ According to the hydrodynamic theory of dentin sensitivity, transdentinal P is responsible for dentin sensitivity of both exposed dentin and restored dentin (postoperative sensitivity). Considering that universal adhesive systems have different application modes, ie, etch-and-rinse (ER) and self-etch (SE), it is necessary to clarify whether the universal adhesives have the same capacity to seal the dentin as the adhesives they replace to avoid cases of postoperative sensitivity.

The P characteristics of the hybrid layer or resin-dentin interdiffusion zone can be studied separately using either quantitative or qualitative methods. Quantitatively, the dentin P measurement method described by Outhwaite and others,²⁶ and Pashley,²⁷ can be used, and qualitatively, transmission electron microscopy can be employed to measure the ultramorphology and nanoleakage. In this study, both methods were used, not only to have a quantitative estimation of the dentin P reduction achieved but also to assess the exact location in the dentin-adhesive interface from where the P is coming.

Therefore, the purpose of this study was to evaluate the reduction in dentin P and nanoleakage of a resin-dentin interface made with universal adhesives, using the SE technique and the ER technique. The null hypothesis was as follows: no differences in dentin P and nanoleakage will be observed among the 8 experimental groups.

METHODS AND MATERIALS

Specimen Preparation for Permeability Study

Eighty recently extracted human third molars that were intact and without evidence of caries or restorations were used in this study. Prior to preparation, the teeth were randomly selected from a group of teeth, stored in 0.5% chloramine-T (Sigma-Aldrich Chemical Co, St

Louis, MO, USA) at 4°C for one week, and then left in distilled water at 4°C, according to the ISO TR 11405 Standard developed by the International Organization for Standardization.

The teeth were sectioned parallel to the occlusal surface 2 mm below the cemento-enamel junction to remove the roots and occlusally to obtain a crown segment containing at least 0.7-mm deep dentin, using a low-speed diamond saw (IsoMet; Buehler, Lake Bluff, IL, USA) with water coolant. The specimen thickness was measured with a digital micrometer (Micro 2000, 0-25 mm; Moore & Wright, Sheffield, UK) to obtain the exact thickness.

The pulpal surfaces were prepared with a diamond bur to gently remove the pulp tissue, which created a smear layer. Then the pulpal surfaces of the specimens were conditioned with 37% phosphoric acid gel (Total Etch; Ivoclar Vivadent, Schaan, Liechtenstein) for 1 minute to completely remove the smear layer and smear plugs, opening all the tubules and thus allowing the fluid to freely flow within the dentin tubules during permeability (P) measurements. The specimens were then glued on standard acrylic pieces (1 cm × 0.5 cm × 1 cm) with an impression compound. These acrylic pieces have a central channel that allows the passage of an 18-gauge needle connected to a hydraulic system. The dentin surface was ground with a 600 grit SiC paper (Carbimet Grit 600/P1200; Buehler) for 60 seconds under water irrigation to produce a uniform smear layer, in accordance with the ISO TR 11405 Standard.

The specimens were treated in random order to avoid any bias due to a particular sequencing of treatments. Thus, the 80 specimens were randomly assigned to 8 groups, with 10 specimens per group: (1) Scotchbond Universal (SBU; 3M Oral Care, Seefeld, Germany) in the ER mode, (2) OptiBond XTR (OPT; Kerr Corporation, Orange, CA, USA) in the ER mode, (3) Clearfil (CL) Universal Bond Quick (Kuraray, Okayama, Japan) in the ER mode, (4) Adhese Universal (ADH; Ivoclar Vivadent, Schaan, Liechtenstein) in the ER mode, (5) SBU (3M Oral Care) in the SE mode, (6) OPT (Kerr Corporation) in the SE mode, (7) CL (Kuraray) in the SE mode, and (8) ADH (Ivoclar Vivadent) in the SE mode. The adhesives were applied according to the detailed instructions provided by the manufacturers. The composition of the adhesives, original manufacturer instructions, and detailed manufacturer instructions are described in Table 1. Dentin P was measured for each specimen at three different points of time: (1) before etching the occlusal side; (2) after etching, which served as the baseline (P_B); and (3) at the end of adhesive polymerization (P_A).

Dentin Permeability Measurements

Each specimen was connected to a hydraulic pressure system, as shown in Figure 1, with 37 cmH₂O, which is close to normal pulpal pressure.²⁸⁻³⁰ The fluid flow was measured by following the movement of an air bubble trapped within a glass capillary tube (0.7 mm inside diameter, Microcaps; Fisher Scientific, Atlanta, GA, USA) that was positioned between the pressure reservoir and the crown segment, according to the hydraulic conductance protocol reported by Pashley and Depew.³¹

The absence of fluid conductance before the exposure of the occlusal dentin was confirmed by separately attaching 5 intact crown segments to the testing apparatus (as described above) and observing the (absence of) fluid movement for 2 hours.^{28,29}

During the application of the adhesive system, the pressure was interrupted to avoid any interference with the effectiveness of the adhesive system.^{30,32} The progression of the air bubble was measured every 2 minutes over a 6-minute interval to determine the rate of saline solution flow in millimeters per minute.

Calculations to Determine Dentin Permeability

The dentin P of each specimen was measured at 2 points in time: (1) after conditioning with the acid (P_B measurement), and (2) P_A . These 2 measurements were used to calculate, as a ratio, the reduction in dentin P. The value of dentin P, measured after conditioning with the acid (P_B), was initially assigned as 100%. The P_A of each specimen was determined after the application of the adhesive system, and the adhesive system was applied without taking the specimen out of the system. The reduction in dentin P after P_A was expressed as a percentage of this maximum value [$100 - (P_A/P_B \times 100)$]. Thus, each specimen served as its own control.

Statistical Analysis

Sample size calculations were performed using the G*Power Program Statistical Analysis,^{33,34} with $\alpha=0.05$, a desired power of 80%, and data from the pilot study. The results were statistically analyzed by two-way analysis of variance (ANOVA) with interaction (IBM SPSS Statistics version 23.0; IBM, Armonk, NY, USA) to evaluate the effects of the mode of application and the choice of adhesive on the reduction in dentin P.

Specimen Preparation for Nanoleakage Study

Sixteen additional 0.7-mm-thick dentin disks were prepared similar to those in the P study. Two dentin disks were used for each of the 8 adhesive groups, and the adhesives were applied in a manner similar to that in the P study. After storing them in distilled water at

Table 1: Components, Compositions (Information Supplied by the Manufacturer) and Application Mode of the Tested Adhesives

Material	pH	Components	Manufacturer's Instructions Detailed
Scotchbond Universal (3M Oral Care)	2.7	Bis-GMA; 10-MDP; hydroxyethyl methacrylate; decamethylene dimethacrylate; ethanol; water; silane-treated silica; 2-propenoic acid, 2-methyl-, reaction products with 1,10-decanediol and phosphorous oxide (P_2O_5); copolymer of acrylic and itaconic acid; dimethylaminobenzoate; camphorquinone; (dimethylamino)ethyl methacrylate; methyl ethyl ketone	<u>Etch-and-rinse mode:</u> 1. Apply phosphoric acid etching gel (Total Etch; Ivoclar Vivadent) for 15 seconds. Rinse the occlusal surface with water. Remove the excess water using a moist cotton pellet, so that the surface remains shiny and visibly moist. 2. Apply adhesive, using a microbrush for 20 seconds. 3. Dry the surface, beginning with a soft blow of air from a distance of approximately 10 cm (the air pressure was increased while decreasing distance), finishing at a distance of approximately 1–2 mm from the surface at maximum air pressure. 4. Light-cure for 10 seconds. <u>Self-etch mode:</u> 1. Apply adhesive, using a microbrush for 20 seconds. 2. Dry the surface, beginning with a soft blow of air from a distance of approximately 10 cm (the air pressure was increased while decreasing distance), finishing at a distance of approximately 1–2 mm from the surface at maximum air pressure. 3. Light-cure for 10 seconds.
Clearfil Universal Bond Quick (Kuraray)	2.3	10-MDP; Bis-GMA; HEMA; hydrophilic amide monomers; colloidal silica, silane coupling agent; sodium fluoride; dl-camphorquinone; ethanol; water	<u>Etch-and-rinse mode:</u> 1. Apply phosphoric acid etching gel (Total Etch; Ivoclar Vivadent) for 15 seconds. Rinse the occlusal surface with water. Remove the excess water using a moist cotton pellet, so that the surface remains shiny and visibly moist. 2. Apply adhesive, using a microbrush for 20 seconds. 3. Dry the surface, beginning with a soft blow of air from a distance of approximately 10 cm (the air pressure was increased while decreasing distance), finishing at a distance of approximately 1– mm from the surface at maximum air pressure. 4. Light-cure for 10 seconds. <u>Self-etch mode:</u> 1. Apply adhesive, using a microbrush for 20 seconds. 2. Dry the surface, beginning with a soft blow of air from a distance of approximately 10 cm (the air pressure was increased while decreasing distance), finishing at a distance of approximately 1–2 mm from the surface at maximum air pressure. 3. Light-cure for 10 seconds.

Table 1: Continued			
Adhese Universal (Ivoclar Vivadent)	2.5	10-MDP; dimethacrylate resins; HEMA; ethanol; water; MCAP; fillers; initiators	<u>Etch-and-rinse mode:</u> 1. Apply phosphoric acid etching gel (Total Etch, Ivoclar Vivadent) for 15 seconds. Rinse the occlusal surface with water. Remove the excess water using a moist cotton pellet, so that the surface remained shiny and visibly moist. 2. Apply adhesive, using a microbrush for 20 seconds. 3. Dry the surface, beginning with a soft blow of air from a distance of approximately 10 cm (the air pressure was increased while decreasing distance), finishing at a distance of approximately 1–2 mm from the surface at maximum air pressure. 4. Light-cure for 10 seconds. <u>Self-etch mode:</u> 1. Apply adhesive, using a microbrush for 20 seconds. 2. Dry the surface, beginning with a soft blow of air from a distance of approximately 10 cm (the air pressure was increased while decreasing distance), finishing at a distance of approximately 1–2 mm from the surface at maximum air pressure. 3. Light-cure for 10 seconds.
Optibond XTR (Kerr Corporation)	3.4	Primer: GPDM, various methacrylate monomers; HEMA; acetone; ethanol; water; CQ initiator Adhesive: GPDM; tri-functional monomer; HEMA; ethanol; disodium hexafluorosilicate; MEHQ	<u>Etch-and-rinse mode:</u> 1. Apply phosphoric acid etching gel (Total Etch, Ivoclar Vivadent) for 15 seconds. Rinse the occlusal surface with water. Remove the excess water using a moist cotton pellet, so that the surface remains shiny and visibly moist. 2. Apply the primer, using a microbrush for 20 seconds. 3. Dry the surface, beginning with a soft blow of air from a distance of approximately 10 cm (the air pressure was increased while decreasing distance), finishing at a distance of approximately 1–2 mm from the surface at maximum air pressure. 4. Apply adhesive, using a microbrush for 20 seconds. 5. Light-cure for 10 seconds. <u>Self-etch mode:</u> 1. Apply the primer, using a microbrush for 20 seconds. 2. Dry the surface, beginning with a soft blow of air from a distance of approximately 10 cm (the air pressure was increased while decreasing distance), finishing at a distance of approximately 1–2 mm from the surface at maximum air pressure. 3. Apply adhesive, using a microbrush for 20 seconds. 4. Dry the surface, beginning with a soft blow of air from a distance of approximately 10 cm (the air pressure was increased while decreasing distance), finishing at a distance of approximately 1–2 mm from the surface at maximum air pressure. 5. Light-cure for 10 seconds.

Abbreviations: 10-MDP, 10-Methacryloyloxydecyl dihydrogen phosphate; Bis-GMA, bisphenol A-glycidyl methacrylate; GPDM, glycerol phosphate dimethacrylate; HEMA, 2-hydroxyethylmethacrylate; MCAP, methacrylated carboxylic acid polymer; MEHQ, methoxyphenol; pH, potential hydrogen.

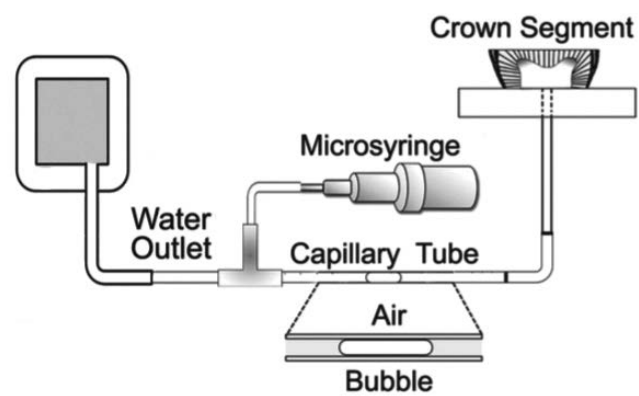


Figure 1. Schematic diagram of the apparatus used for dentin permeability measurements (adapted from Sahin & others¹⁸).

37°C for 24 hours, a 1-mm-wide slab containing the resin-dentin interface was prepared from the widest portion of each bonded disk. They were immersed in a 50 wt% ammoniacal silver nitrate tracer solution (Sigma Aldrich, St. Louis, MO, USA) for 24 hours according to the silver impregnation protocol for nanoleakage examination reported by Tay and Pashley.¹⁶ After the reduction of the diamine silver ions, the silver-impregnated slabs were processed for transmission electron microscope (TEM) examination without demineralization. Epoxy resin-embedded sections 90-nm-thick were prepared and examined unstained¹⁶ using a transmission TEM (FEI Tecnai G2 Spirit BioTWIN, operating at 120 keV, equipped with an Olympus-SIS Veleta CCD camera).

RESULTS

Dentin Permeability Study

The Kolmogorov-Smirnov test of normality at $\alpha=0.05$ revealed that the data presented a normal distribution,

and Levene's test was used to verify the homogeneity of the variances ($p=0.5596$), enabling a parametric analysis.

The data on percent P reduction are summarized in Table 2 by adhesive types and application modes as a mean and standard deviation; the median, range (minimum, maximum), and p-values from the normality test are also presented. The medians and means were similar and consistent for each group, and the normality tests were not significant ($p>0.10$) for any of the groups. OPT in the ER mode had the largest mean (83.8%), and CL in the ER mode had the lowest mean (35.8%). Tables 3 and 4 present the results from the two-way ANOVA with interaction. Table 3 lists the estimates, the standard error, and the p-values.

The significant interaction suggested that the effect of adhesive types on P reduction depended on the mode or that the mode effect varied with the adhesive types. Table 3 presents the results in detail. In the ER mode, the adhesive type was significant ($p=0.0007$), while in the SE mode it was less significant ($p=0.0170$). In the ER mode, the results obtained for OPT were significantly greater than those obtained for SBU and CL ($p<0.05$), and the results obtained for ADH were significantly better than those obtained for CL. In the SE mode, only a marginal significance was found for OPT over ADH ($p=0.0577$), with OPT obtaining a better result. For OPT and ADH ($p=0.0304$ and $p=0.0120$, respectively), the P reduction was higher in the ER mode than in the SE mode. For CL and SBU, no differences in P reduction were observed between the 2 application modes ($p>0.05$).

Nanoleakage Study

The OPT ER group did not show significant nanoleakage, and isolated spots of silver grains (Figure 2, black arrows) could only be discerned at high magnification. They were randomly distributed

Table 2: Data Description of Percentage Permeability Reduction (%)		
Mode and Adhesive	Mean $\pm$ SD (%)	Median (min, max)
Etch-and-rinse		
Scotchbond Universal	53.2 (37.6)	54.8 (0.0, 100.0)
Optibond XTR	83.8 (15.1)	89.2 (50.0, 100.0)
Clearfil Universal Bond Quick	35.8 (29.6)	29.2 (0.0, 85.7)
Adhese Universal	66.0 (19.3)	66.7 (37.5, 100.0)
Self-Etch		
Scotchbond Universal	54.5 (19.8)	50.0 (25.0, 95.2)
Optibond XTR	58.6 (22.1)	60.9 (25.0, 100.0)
Clearfil Universal Bond Quick	56.4 (25.2)	56.3 (20.0, 95.0)
Adhese Universal	36.6 (28.4)	35.9 (0.0, 86.4)

Table 3: Results from Two-way ANOVA with Interaction

Study Groups		Estimates	Standard Error	p-value	p-value (overall)
Adhesive	Scotchbond Universal	17.9	11.4	0.1207	0.0170
	Optibond XTR	22.2	11.4	0.0577	
	Clearfil Universal Bond Quick	19.9	11.4	0.0859	
	Adhese Universal	0.00	—	—	
Mode	Etch-and-rinse	29.4	11.4	0.0120	—
	Self-etch	0.00	—	—	
Adhesive*mode	ER*SBU	-30.7	16.1	0.0613	0.0081
	ER*OPT	-4.2	16.1	0.7946	
	ER*CL	-50.0	16.1	0.0028	
	ER*ADH	0.00	—	—	

Abbreviations: ADH, Adhese Universal; ANOVA, analysis of variance; CL, Clearfil Universal Bond Quick; ER, etch-and-rinse; OPT, OptiBond XTR; SBU, Scotchbond Universal; SE, self-etch.

exclusively in the hybrid layer (Figure 2). In this group, the hybrid layer was approximately 2- μ m thick.

In the OPT SE group, 2 types of nanoleakage patterns could be observed within the resin-dentin interfaces: a spotted pattern (Figure 3, black arrows) and a reticular

pattern (Figure 3, gray arrows). The spotted pattern consisted of isolated spots of silver grains that were observed in the hybrid layer in various amounts. The reticular pattern consisted of discontinuous islands of silver deposits exclusively observed in the hybrid layers

Table 4: Stratified Evaluation of the Effects of Adhesives and Mode on Permeability Reduction

Adhesive Effect	Estimate	Standard Error	p-value
Given mode: ER			$p < 0.0001$ (overall)
SBU vs OPT	-30.6	11.4	0.0092
SBU vs CL	17.4	11.4	0.1321
SBU vs ADH	-12.8	11.4	0.2674
OPT vs CL	48.0	11.4	$< .0001$
OPT vs ADH	17.8	11.4	0.1234
CL vs ADH	-30.2	11.4	0.0101
Given mode: SE			$p = 0.0170$ (overall)
SBU vs OPT	-4.1	11.4	0.7212
SBU vs CL	-2.0	11.4	0.8649
SBU vs ADH	17.9	11.4	0.1207
OPT vs CL	2.1	11.4	0.8518
OPT vs ADH	22.0	11.4	0.0577
CL vs ADH	19.9	11.4	0.0859
Mode effect			
Given Adhesive = SBU	-1.3	11.4	0.9131
Given Adhesive = OPT	25.2	11.4	0.0304
Given Adhesive = CL	-20.6	11.4	0.0755
Given Adhesive = ADH	29.4	11.4	0.0120

Abbreviations: ADH, Adhese Universal; CL, Clearfil Universal Bond Quick; ER, etch-and-rinse; OPT, OptiBond XTR; SBU, Scotchbond Universal; SE, self-etch.

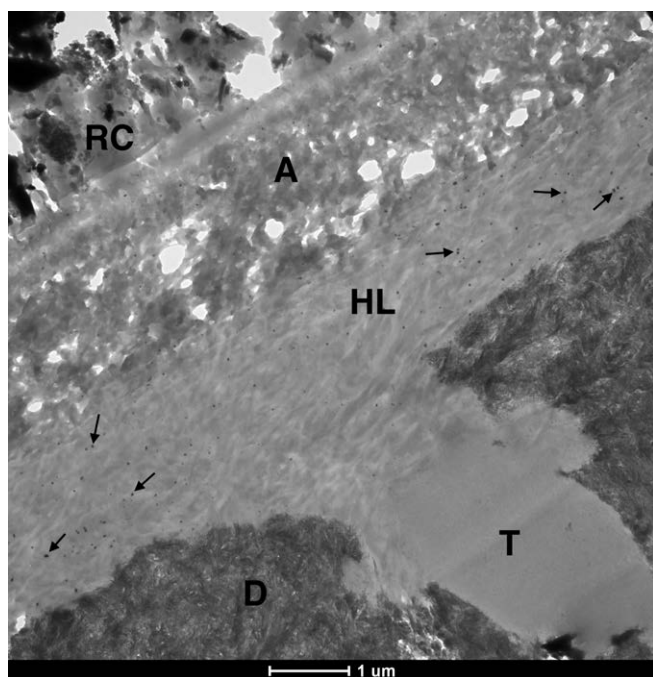


Figure 2. Transmission electron microscope (11,500x) micrograph of representative area of nonstained, demineralized, nonsilver-impregnated sections of the OPT ER group. Abbreviations: A, adhesive layer; D, mineralized dentin; ER, etch-and-rinse; HL, hybrid layer; OPT, OptiBond XTR; RC, resin composite; T, dentin tubule.

or in the hybridized areas of resin tags. In this group, a thin hybrid layer was observed ($<0.5 \mu\text{m}$).

The SBU ER group did not show any significant nanoleakage. Isolated spots of silver grains (Figure 4, black arrows) that were distributed in the hybrid layer were noted, with a higher concentration at the base of the hybrid layer. A hybrid layer with a thickness between 0.5 and $1 \mu\text{m}$ was observed, with good infiltration throughout.

In the SBU SE group, isolated spots of silver grain (Figure 5, black arrows) were randomly distributed across a thin hybrid layer (about $0.5\text{-}\mu\text{m}$ thick).

In the CL ER group, a hybrid layer with a thickness of approximately $2.5 \mu\text{m}$ was observed. The hybrid layer was impregnated with an extensive spotted type (Figure 6, black arrows) of nanoleakage and reticular silver deposits (Figure 6, gray arrows).

In the CL SE group, a thin hybrid layer was observed ($<0.5 \mu\text{m}$), with the presence of a linearly distributed reticular nanoleakage pattern along the base. A spotted type of nanoleakage (Figure 7, black arrows) was also noted.

In the ADH ER group, a hybrid layer of about $2\text{-}\mu\text{m}$ thick was observed, with the presence of 2 nanoinfiltration patterns: a spotted-type pattern (Figure 8, black arrows) and reticular silver deposits (Figure 8,

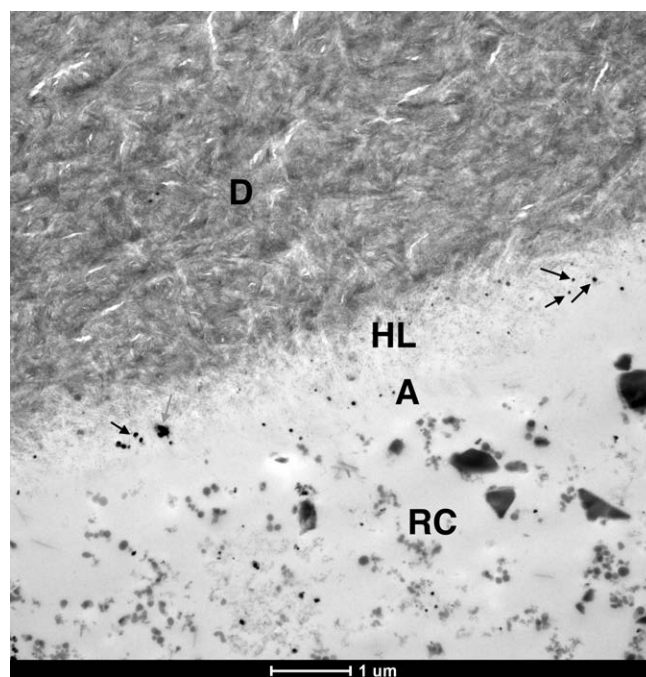


Figure 3. Transmission electron microscope (11,500x) micrograph of representative area of nonstained, demineralized, nonsilver-impregnated sections of the OPT SE group. A, adhesive layer; D, mineralized dentin; ER, etch-and-rinse; HL, hybrid layer; OPT, OptiBond XTR; RC, resin composite; SE, self-etch.

gray arrows). A layer of dendritic silver-impregnated water channels (ie, water trees shown as white arrows) can also be seen in the hybrid layer.

In the ADH SE group, a thin hybrid layer ($<0.5 \mu\text{m}$) was observed, with a spotted nanoleakage pattern (Figure 9, black arrows) randomly distributed. Occasionally, at the base of the hybrid layer, silver deposits were also agglomerated in a reticular pattern (Figure 9, gray arrows).

DISCUSSION

Studies of P characteristics of dentin and their interactions with dentin adhesive systems may help to explain some of the reasons for restorative failure or postoperative dentin sensitivity. Prati and Pashley³⁵ found a significant correlation between bond strength and dentin P of the restoration for some adhesive systems. Moreover, in some studies, the application of the restorative material was not able to achieve a perfect seal and block the passage of fluid.^{36,37}

A hydraulic conductance study has advantages over other types of leakage studies²⁷ because it gives a quantitative measurement of the interfacial leakage, assesses whether the dentin tubules are effectively sealed, allows repeated measurements on the same specimen longitudinally and nondestructively, and,

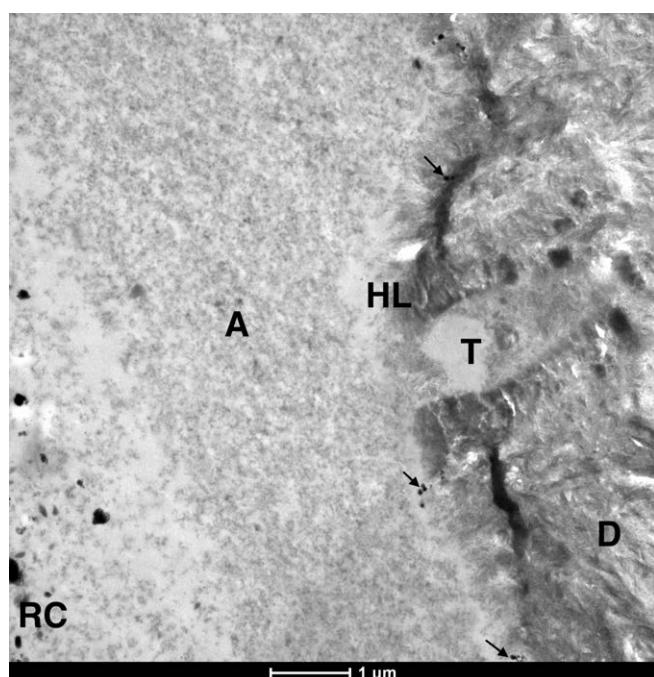


Figure 4. Transmission electron microscope (11,500x) micrograph of representative area of nonstained, demineralized, nonsilver-impregnated sections of the SBU ER group. Abbreviations: A, adhesive layer; D, mineralized dentin; ER, etch-and-rinse; HL, hybrid layer; RC, resin composite; SBU, Scotchbond Universal; T, dentin tubule.

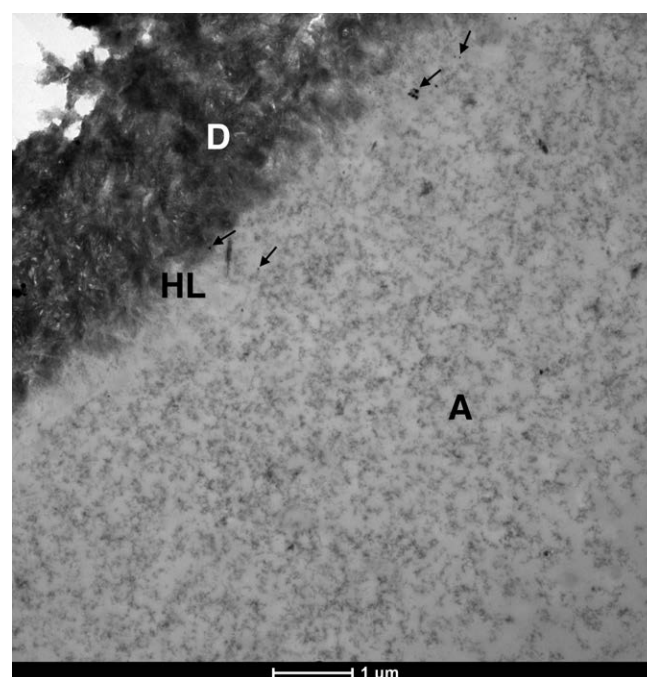


Figure 5. Transmission electron microscope (11,500x) micrograph of representative area of nonstained, demineralized, nonsilver-impregnated sections of the SBU SE group. Abbreviations: A, adhesive layer; D, mineralized dentin; HL, hybrid layer; SBU, Scotchbond Universal; SE, self-etch.

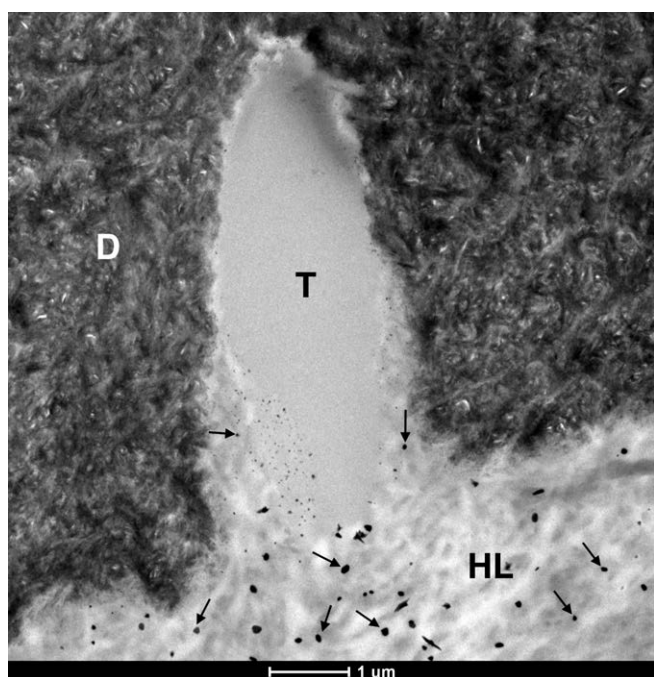


Figure 6. Transmission electron microscope (11,500x) micrograph of representative area of nonstained, demineralized, nonsilver-impregnated sections of the CL ER group. Abbreviations: A, adhesive layer; CL, Clearfil Universal Bond Quick; D, mineralized dentin; ER, etch-and-rinse; HL, hybrid layer; T, dentin tubule.

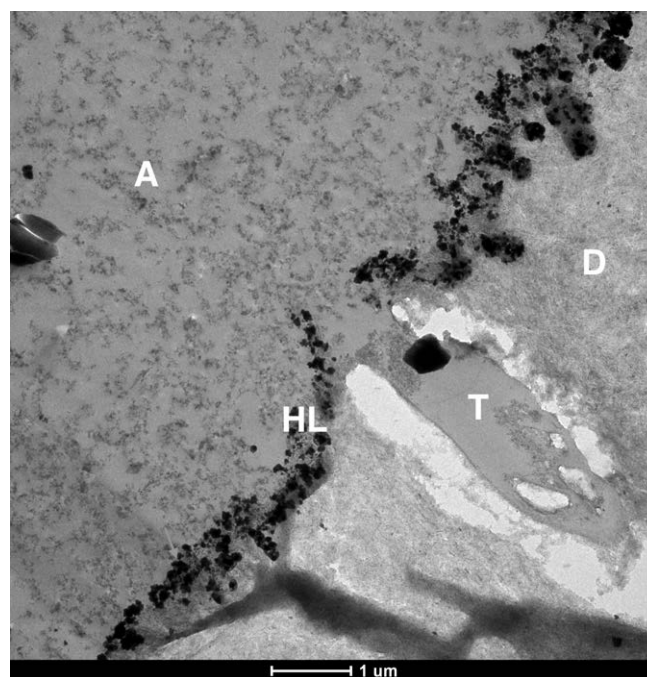


Figure 7. Transmission electron microscope (11,500x) micrograph of representative area of nonstained, demineralized, nonsilver-impregnated sections of the CL SE group. Abbreviations: A, adhesive layer; CL, Clearfil Universal Bond Quick; D, mineralized dentin; HL, hybrid layer; RC, resin composite; SE, self-etch; T, dentin tubule.

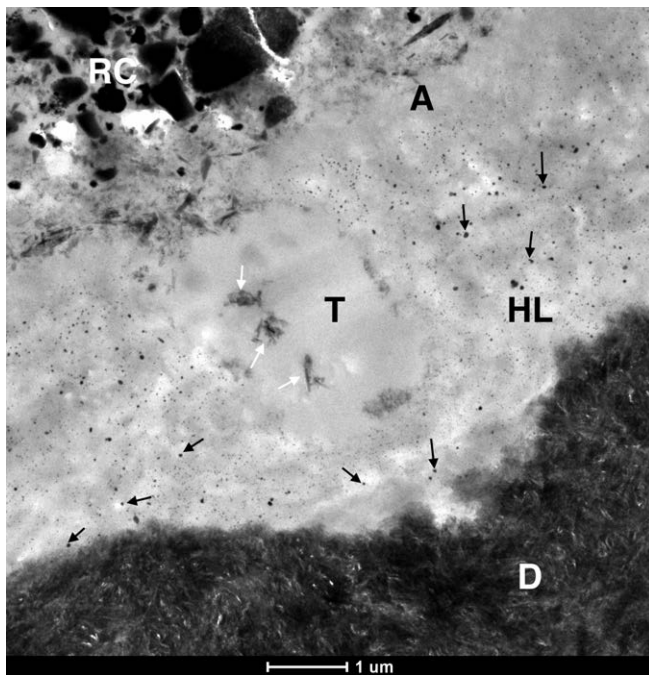


Figure 8. Transmission electron microscope (11,500x) micrograph of representative area of nonstained, demineralized, nonsilver-impregnated sections of the ADH ER group. Abbreviations: A, adhesive layer; ADH, Adhese Universal; D, mineralized dentin; ER, etch-and-rinse; HL, hybrid layer; RC, resin composite; T, dentin tubule.

finally, measures dentin P_B (after etching) and P_A (after the adhesive polymerization), allowing each specimen to serve as its own control.

Quantitatively measuring dentin P by means of hydraulic conductance²⁶ involves forcing a fluid through the dentin by applying pressure. In this study, high pressure could have flushed out the resin tags, resulting in an overestimation of dentin P . To avoid any disturbance of the intratubular content—the hybrid layer or the resin tags—a low hydraulic pressure of 37 cmH₂O was used in this study. The use of this low hydraulic pressure, which is close to the physiological pressure (14 cmH₂O),³⁸ is expected to result in hydraulic conductance measurements comparable to reality.

According to Tao and Pashley,¹⁹ it is desirable that all adhesive systems reduce dentin P or, at least, not increase it.

All the adhesive systems used in this study were able to reduce P (35.8%-83.8%); however, no adhesive system was able to completely seal the dentin after P_a , which is in agreement with Hashimoto,³⁹ who stated that all adhesive systems are permeable to water but at different levels. The most satisfactory results for reduction in dentin P were obtained with OPT ER, which may indicate that the separate application of primer and adhesive is more favorable to achieve good

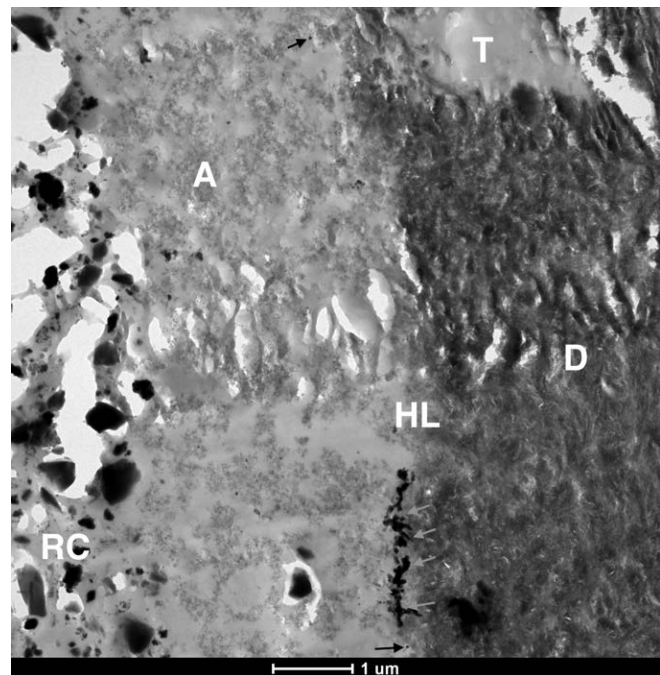


Figure 9. Transmission electron microscope (11,500x) micrograph of representative area of nonstained, demineralized, nonsilver-impregnated sections of the ADH SE group. Abbreviations: A, adhesive layer; ADH, Adhese Universal; D, mineralized dentin; HL, hybrid layer; RC, resin composite; SE, self-etch; T, dentin tubule.

hybridization.⁴⁰ Therefore, hybridization effectiveness can be reduced by simplifying the application procedure of adhesive systems through combining the primer and adhesive into a single application step.

OPT does not contain the 10-methacryloyloxy-decyl-dihydrogen-phosphate (10-MDP) monomer, so these results differ from the results of Munoz and others,⁴¹ in which only the adhesive systems containing 10-MDP were able to reduce nanoleakage.

When applying phosphoric acid, which is necessary for the ER technique,⁴² the smear layer and the smear plugs are removed, increasing dentin P 4-9 times depending on the diameter of the tubules and their density at the site of evaluation.⁴³ Considering that no smear layer removal is done in the SE technique, it could be assumed that the use of this technique would be advantageous to minimize dentin P .^{42,44}

However, this was not the case in this study because no statistically significant differences were found between the application modes in the CL and SBU adhesive systems, but differences were observed for the OPT and ADH adhesive systems ($p=0.0304$ and $p=0.0120$, respectively), and the maximum P reduction was obtained by the ER technique. One possible explanation for this may be the poor polymer formation that constitutes the hybrid layer produced by these simplified adhesive systems

in the SE mode. Nevertheless, in these cases, changes in the hybrid layer formation would not be attributed to excess moisture due to the removal of the smear layer and the smear plugs, but rather to the retention of solvents and water that make up the formulation of these adhesive systems.⁴⁵

An examination of the results demonstrates that the adhesive system for any of the groups were not capable of completely reducing the dentin P produced after etching. This seems to indicate that the use of a universal adhesive may present clinically postoperative sensitivity, regardless of the mode of application: SE or ER.⁴⁶

All the adhesive systems in this work presented at least one nanoleakage pattern, irrespective of the application technique used. The nanoleakage results are consistent with the results of the dentin P study and with other studies,^{7,47} where no adhesive has been fully able to eliminate P. In fact, hydrophilic polymers, like the adhesives used in this study, function as permeable membranes that allow the movement of water through the dentin even after polymerization. Thus, universal adhesives may not have the capacity to seal the dentin and can cause some postoperative sensitivity.

In this methodology, the variables related to the tooth itself—such as the regional differences in dentin P,⁴⁸ dentin sclerosis,⁴⁹ or aging⁵⁰—are beyond the researcher's control. Nevertheless, other variables are controlled by the researcher and need to be set before running the study. The adhesive manufacturers' instructions are well designed; however, they are not very detailed and have some level of ambiguity. For this reason, an effort was made to specify each step to the greatest extent possible to ensure some degree of standardization of the protocol (Table 1).

Although the differences in dentin P among the experimental groups are statistically significant, it does not necessarily mean that they are also clinically significant. It is important to note that when interpreting laboratory research results, one must be aware that the main goal is to study specific variables and compare them to what could be the perfect result. With that critical observation in mind, however, it can be expected that the existence of statistically significant differences has a higher probability of corresponding to clinically significant differences than their absence. Additional clinical studies are essential to further evaluate the performance of these adhesives because clinical trials remain the best way to collect scientific evidence on the effectiveness of an adhesive.

CONCLUSIONS

The results of this study require the rejection of the null hypotheses. No adhesive system, regardless of the

application mode, was able to completely eliminate dentin P. It was observed that the differences in P reduction by the application mode were dependent on the adhesive system used. For OPT and ADH, the P reduction was higher in the ER mode than in the SE mode. For CL and SBU, no differences in P reduction were observed between the 2 application modes. All the adhesive systems showed nanoleakage, and the nanoleakage patterns were different depending on the adhesives used.

Regulatory Statement

The teeth were gathered after obtaining informed consent under a protocol reviewed and approved by the Ethics Committee, School of Dentistry, Universidade de Lisboa.

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.

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Evaluation of Color-matching Ability of a Structural Colored Resin Composite

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Clinical Relevance

Although excellent color-matching ability was confirmed for the structural colored resin composite Omnichroma, care should be taken to ensure that the appropriate chromatic color conditions for restoration are achieved in the oral environment.

SUMMARY

Purpose: The present study evaluated the color-matching ability of a structural colored resin composite to compare it with resin composites employing pigments.

Methods and Materials: A structural colored resin composite (Omnichroma [OMC]), a supranano-filled resin composite (Estelite Σ Quick [ELQ]), and a nano-filled resin composite (Filtek Supreme Ultra [FSU]) were used. Each resin composite was packed into a Teflon mold and pressed down with a clear strip under a glass slide. The specimens were light irradiated through the slide with a

light-emitting diode curing unit. The thickness of the specimens (n=6) was measured with a digital caliper before being transferred to distilled water and stored at 37°C for 24 hours. The measurements of the optical characteristics of the specimens on a black-and-white background were performed using a spectrophotometer. D65 (CIE D65) was used as a light source for the spectrophotometer. Measurements were repeated three times for each specimen under each color-measurement condition, and average values for three same-shade specimens were calculated. One-way analysis of variance and Tukey post hoc tests were used ($\alpha=0.05$). To determine its ability to match

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the color of artificial teeth, each shade of resin composite was placed in a cavity before performing color measurements. Using a spectrophotometer (CMS-35F S/C) with a flexible sensor, L^* , a^* , and b^* values were obtained.

Results: The spectral reflectance curve of OMC showed that it reflected light wavelengths from 430-700 nm regardless of the background color and thickness of the specimens. The percentage of reflectance of ELQ decreased near wavelengths of 550-580 nm. Regarding the influence of background color on CIE L^* , a^* , b^* values, the L^* level showed significantly higher values for all tested materials with white backgrounds, and OMC was most affected by the difference in background color. However, a^* values of ELQ and FSU were significantly higher with a black background than with a white background, and OMC showed a significantly higher value with a white background than with a black background. The b^* values were higher with a white background than with a black background and were significantly higher for all three products, and these tendencies were much greater for ELQ and FSU.

Conclusions: The ability of OMC to match the color of artificial teeth showed acceptable color compatibility, regardless of the shade of the artificial teeth and the depth of the cavity. However, ELQ and FSU showed reduced color compatibility, especially for a cavity depth of 3.0 mm. Excellent color matching ability was confirmed for the structural colored resin composite OMC, resulting in reduced color differences and therefore improving the esthetic appearance of the restoration, simplifying shade matching, and compensating for any color mismatch.

INTRODUCTION

Resin composites have been widely used because of their esthetics, good mechanical properties, and ease of handling.¹ The color matching and esthetic success of resin composite restorations depends on complex factors, including the translucency, opacity, light scattering and transmission, brightness, fluorescence, and opalescence of the restorative materials.² When light penetrates resin composites, different phenomena associated with the material may occur, such as specular transmission of the light flux through the material, specular reflection at the surface, diffuse light reflection at the surface, and absorption and scattering

of the flux within the material.³ Colored pigments are incorporated into resin composites to produce clinically acceptable shades for restorative materials, and it was reported that pigments could influence the translucency and color of resin composites.⁴ Thus, care should be taken to consider the pigments incorporated into resin composites as an important factor in achieving an optimal esthetic restorative outcome in clinical situations.

The color development is produced by the natural or artificial pigments with an exchange of chemical energy between the light and the pigments.⁵ When light of a certain wavelength is absorbed by the pigmented material and the other wavelengths are reflected and transmitted, then the material color can be identified. In contrast to pigmented materials, those utilizing structural color employ a color based on light interacting selectively with nanostructures.⁶ Structural color is expressed only by the physical properties of light without a change in the light energy, as with pigments. Unlike pigment and fluorescence color expressions in materials, structural color is generated from light reflection, diffuse reflection, diffraction, and interference with spatially ordered nano- or microstructures in photonic materials.⁷ A structural color is generated when certain structures are active in the visible region. The characteristic wavelengths of the diffracted light can be expressed by the Bragg equation,⁸

$$m\lambda = 2nd \cdot \sin\theta,$$

where m is the diffraction series, λ is the diffraction wavelength, n is the average refractive index, d is the lattice constant, and θ is the angle between the incident light and normal crystal plane. According to the theoretical basis provided by the Bragg equation,⁸ changes in the parameters of the above formula can be employed in principle to design a modulated material having structural color.⁹

Structural colors can be divided into two classes according to their optical properties as iridescent and noniridescent colors. An iridescent color is produced by periodic structures with regular lengths of the order of the wavelength of visible light, known as photonic crystals.¹⁰ Noniridescent structural color has angle-independent characteristics, meaning that the color impression is the same for different illuminations and observation angles.¹¹ Noniridescent structural colors produced by amorphous structures in nature are mostly blue with short wavelengths, since the typical bands of scattered wavelengths are located at the edge of the sensitivity range of the human eye.¹²

Longer wavelength structural colors toward red are difficult to obtain with photonic structures because of significant scattering at short wavelengths. Short wavelength resonances in the single-particle scattering cross-section near backscattering introduce a blue peak in the spectrum that changes the red structural color to purplish or pink. The use of lithography, liquid crystals, block copolymers, and colloidal particles have all been investigated to create artificial structural color materials.¹³ Among these methodologies, structural color materials based on the assembly of colloidal particles were thought to be the most interesting, since these can create longer wavelength structural colors easily by various routes and can be used in bottom-up nanotechnology.¹⁴

A resin composite with a structural color containing spherical fillers, with an average particle size of 260 nm, with a filler loading of 79 wt% (68 vol%), expressed yellow to red colors.¹⁵ Simultaneously, structural colors depend on the refractive index distribution, and differences in the refractive indices of the resin matrix and inorganic filler should also be considered. If there is a mismatch between the refractive indices of the filler and resin matrix, the filler will increase and interfere with light scattering.¹⁶ Greater refractive index differences between the inorganic fillers and the matrix phase of the resin composites increased the opacity of the materials due to multiple reflection and refraction events at the filler-matrix interfaces.¹⁷ The refractive indices increase from monomer mixtures to polymerized structures by around 0.04,¹⁸ so it would be appropriate to make the refractive index of the filler slightly higher than those of the base resin monomer mixtures, so that the refractive index of the resin phase

might coincide with that of the filler during curing. The structural color can be modulated by changing the differences in the refractive indices of the monomer mixtures and inorganic fillers. When the refractive index of the uniformly sized spherical filler exceeds that of the matrix resin, a stronger structural color might be expressed due to scattering of incident light.¹⁹

The color of a material is influenced by various factors, and differences in the light-transmittance characteristics of resin composites can affect their ability to match the color of the restored tooth. The inherent translucency of resin composites might contribute to their optical properties by allowing the background shade to shine through.²⁰ Although it is well known that the reflected color of resin composites is affected by the background color, little is known about the optical properties of structural colored resin composites. The aim of this study was to determine the color matching ability of a structural colored resin composite to compare it with resin composites employing pigments, with respect to their material colors. The null hypothesis to be tested was that neither the background color nor material thickness influenced the optical characteristics of the structural colored resin composite.

METHODS AND MATERIALS

Study Materials

A structural colored resin composite, Omnichroma (OMC; Tokuyama Dental, Tokyo, Japan), a supranano-filled resin composite, Estelite Σ Quick (ELQ, Tokuyama Dental), and a nano-filled resin composite, Filtek Supreme Ultra (FSU; 3M Oral Care, St. Paul, MN, USA), as listed in Table 1, were used.

Table 1: Materials Used and Their Main Components				
Material	Manufacturer	Code	Main Component	Shade
Omnichroma	Tokuyama Dental (Tokyo, Japan)	OMC	Uniformly sized supra-nano spherical filler (260 nm, SiO ₂ -ZrO ₂) Composite filler (260 nm, SiO ₂ -ZrO ₂) UDMA, TEGDMA	Universal
Estelite Σ Quick	Tokuyama Dental (Tokyo, Japan)	ELQ	Supra-nano spherical filler (100–300 nm; average size: 200 nm, SiO ₂ -ZrO ₂) Bis-GMA, TEGDMA	A1 A2 A3 A4
Filtek Supreme Ultra	3M Oral Care (St. Paul, MN, USA)	FSU	Aggregated zirconia/silica cluster (zirconia and silica, 4–20 nm, 0.6–10 nm; non-agglomerated filler (4–20 nm) Bis-GMA, Bis-EMA, UDMA, TEGDMA, PEGDMA	A1B A2B A3B A4B
Abbreviations: Bis-EMA, ethoxylated bisphenol A glycol dimethacrylate; Bis-GMA, bisphenol A glycidyl methacrylate; PEGDMA, polyethylene glycol dimethacrylate; TEGDMA: triethylene glycol dimethacrylate; UDMA, diurethane dimethacrylate.				

Specimen Preparation for Investigating the Influence of Background Color

Standardized specimens, 8.0 mm in diameter and 1.5 and 3.0 mm in thickness, were made with selected composite shades, as shown in Figure 1 (universal for OMC, A2 for ELQ, and A2B for FSU). Each resin composite was packed into a Teflon mold and pressed down with a clear strip under a glass slide. The specimens were light irradiated through the slide at 1000 mW/cm², for the time recommended by each manufacturer, with a light-emitting diode (LED) curing unit (Pen Cure, J. Morita, Kyoto, Japan). The light irradiance of the curing unit was confirmed using a dental radiometer (Model 100, SDS Kerr, Danbury, CT, USA). The resin disk was then removed from the mold, and the specimen surfaces were not polished after curing. The thickness of the specimens (n=6) was measured with a digital caliper (Digimatic Caliper 500-151-30; Mitutoyo, Tokyo, Japan) before transferring to distilled water and storing at 37°C for 24 hours.

Spectral Reflectance and Color Value Measurement

The optical characteristics were measured using a spectrophotometer (CMS-35F S/C; Murakami Color Research Laboratory, Tokyo, Japan) with a flexible sensor (FS-3; Murakami Color Research Laboratory). The diameter of the illuminated area was 6 mm and the diameter of the area that received light from the object was 3 mm. Commission Internationale de l'Eclairage D65 (CIE D65) was used as a light source for the spectrophotometer, and the illuminating and viewing configurations were set at CIE 45°/d, and spectral reflectance (%) measurements were performed at 10-nm intervals. The color was measured in reflectance mode over white (Y=90.56, X=92.14, Z=110.90) and black (Y=0.01, X=0.01, Z=0.01) backgrounds. All color measurements were performed at wavelengths ranging from 380-740 nm, at 2-nm intervals, and subsequently

converted to CIE L*, a*, and b* values. The L* value determines the psychometric lightness from black to white (achromatic coordinate). The a* value (green–red coordinate) and b* value (blue–yellow coordinate) are the psychometric chroma coordinates and indicate hue and chroma factors. Measurements were repeated thrice for each specimen under each color measurement condition, and average values for three same-shade specimens were calculated.

Statistical Analysis

To determine the appropriate sample size for the color value measurements in different backgrounds, a statistical power analysis was performed. After gathering the data, post hoc power tests were performed using two statistical software systems (G Power calculator, <http://www.gpower.hhu.de/>; and Sigma Plot version 13.0; Systat Software, Chicago, IL, USA), with an f value of 0.75, α value of 0.05, and power of 0.95. This test indicated that the sample size was adequate.

The data obtained were analyzed using a commercial statistical software package (SPSS Statistics Base; International Business Machines, Armonk, NY, USA). One-way analysis of variance and Tukey post hoc tests were used with a significance level of 0.05.

Ability to Match the Color of Artificial Teeth

Maxillary central incisal artificial teeth (Mold A19, Shade A2, A4; Zenopal, GC, Tokyo, Japan) were used to assess the color matching ability of the resin composites. A standardized cavity preparation, 4 mm in diameter and 1.5 mm or 3.0 mm in depth, was performed in the center of the labial side of each artificial tooth. The prepared cavities in the artificial teeth were air abraded with 50 μ m aluminum for 5 sec at 0.2 MPa pressure, then treated with a universal adhesive (Bondmer Lightless [known as Tokuyama Universal Bond outside of Japan], Tokuyama Dental, Tokyo, Japan), according to the manufacturer's instructions.

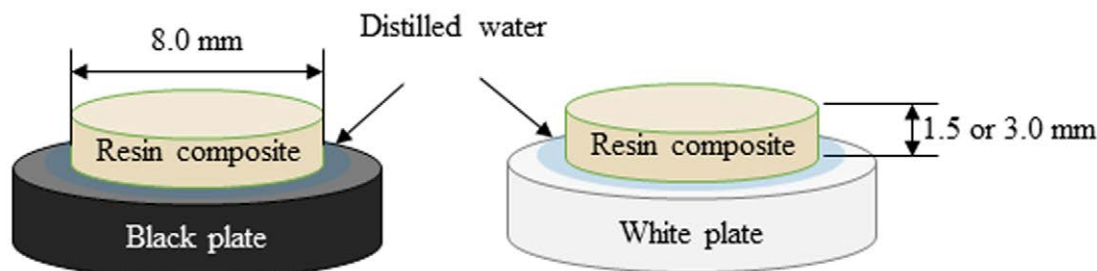


Figure 1. Color measurement of resin composite specimens. Resin composite discs were prepared, and the spectral reflectance and color values of the specimens were measured against black and white backgrounds using a fast spectrophotometer (CMS-35FS/C, Murakami Shikisai).

Each shade of resin composite (Table 1) was placed into the cavity with a single application of paste (Figure 2). A layer of transparent strip was placed on top of the resin paste and then pressed with a cover glass, and this was light irradiated for the time stipulated in each manufacturer's instructions using the LED curing unit Pen Cure. After storage in distilled water at 37°C for 24 hours, these specimens (n=3) were submitted to mechanical polishing in a grinding/polishing machine (Ecomet 4 Grinder Polisher, Buehler, Lake Bluff, IL, USA) with a sequence of 2000-grit SiC papers under running water. A final polish was accomplished with a composite polishing paste (PRG CompoGloss, Shofu, Kyoto, Japan) using a polishing disk with a synthetic velvet polishing cloth on the outer surface (Super-Snap Buff Disk, Shofu), for a total of 108 specimens. Using a spectrophotometer (CMS-35F S/C) with a flexible sensor, L*, a*, and b* values were obtained. The color difference (ΔE^*_{ab}) was calculated using the following equation:

$$\Delta E^*_{ab} = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2},$$

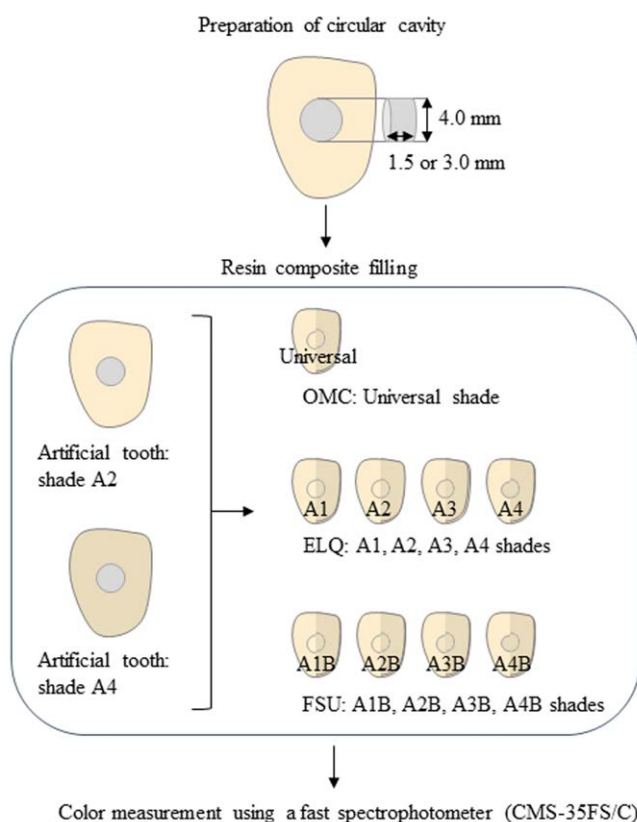


Figure 2. Evaluation of color-matching ability of resin composites. Color measurements of artificial teeth and resin fillings were performed. Abbreviations: ELQ, Estelite Σ Quick; FSU, Filtek Supreme Ultra; OMC, Omnicroma.

where ΔE^*_{ab} corresponds to the color difference between single resin composite specimens and the corresponding area of surrounding artificial teeth. Measurements were repeated thrice for each specimen and the obtained data values were averaged. The color adaptability was determined from the color differences among teeth and resin composites through 50:50% perceptibility and 50:50% acceptability thresholds, as described in a previous review paper.²¹

RESULTS

Influence of Background Color on Spectral Reflectance

The influence of the background color on the spectral reflectance curves of the resin composites is illustrated in Figure 3. The spectral reflectance curve of OMC showed that it reflected wavelengths from 430-700 nm regardless of the background color and thickness of the specimens. The percentage of reflectance of ELQ decreased near wavelengths of 550-580 nm (green color) and presented as sigmoid-like curves except with a black background with a thickness of 1.5 mm. Comparing the background colors showed that the spectral reflectance on the white background increased in comparison with that on the black background for all the materials tested, although the reflectance increased at longer wavelengths for ELQ and FSU regardless of the specimen thickness. The spectral reflectance curves of ELQ and FSU showed decreases at longer wavelengths, and these tendencies were clearer with black backgrounds.

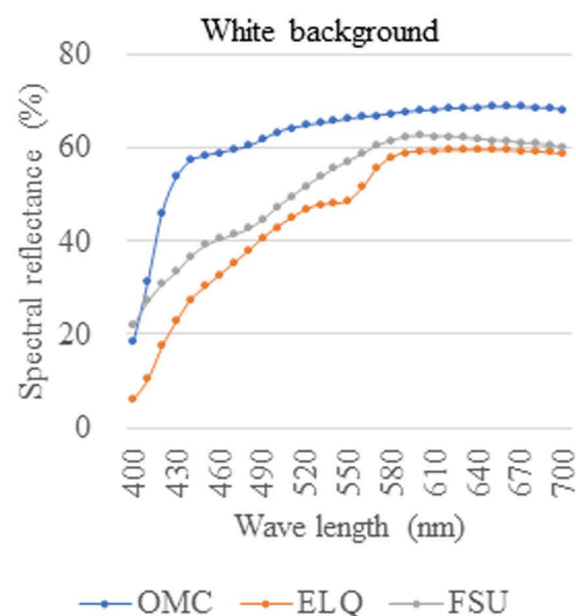
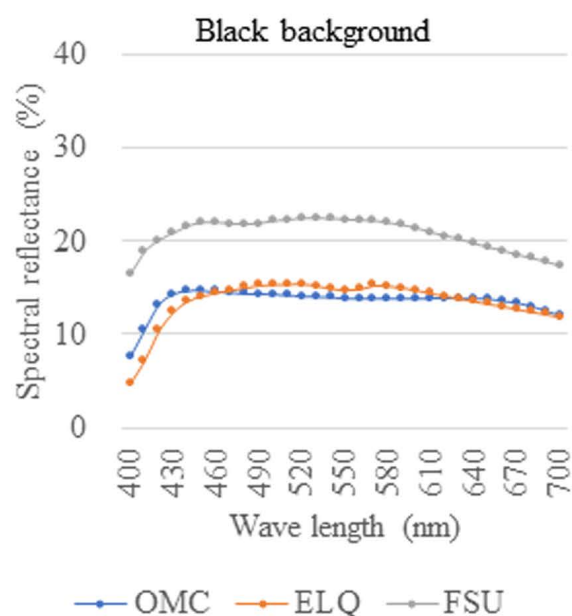
Influence of Background Color on CIE L*, a*, and b* Values

The influence of background color on CIE L*, a*, and b* values is shown in Figure 4. The L* level showed significantly higher values for all tested materials with white backgrounds, and OMC was most affected by the difference in background color. However, a* values of ELQ and FSU were significantly higher with a black background than with a white background, and OMC showed a significantly higher value with a white background than with a black background. The b* values were higher with a white background than with a black background and were significantly higher for all three products, and these tendencies were much greater for ELQ and FSU.

Color-matching Ability

The abilities of resin composites to color match to artificial teeth of shades A2 and A4 are presented in

Specimen thickness: 1.5 mm



Specimen thickness: 3.0 mm

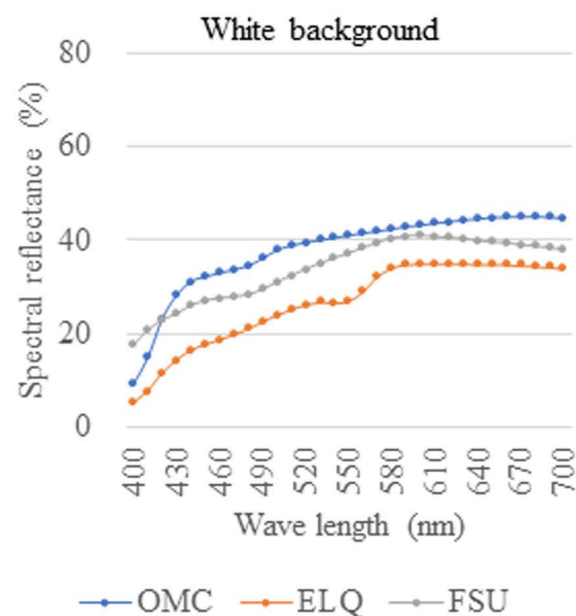
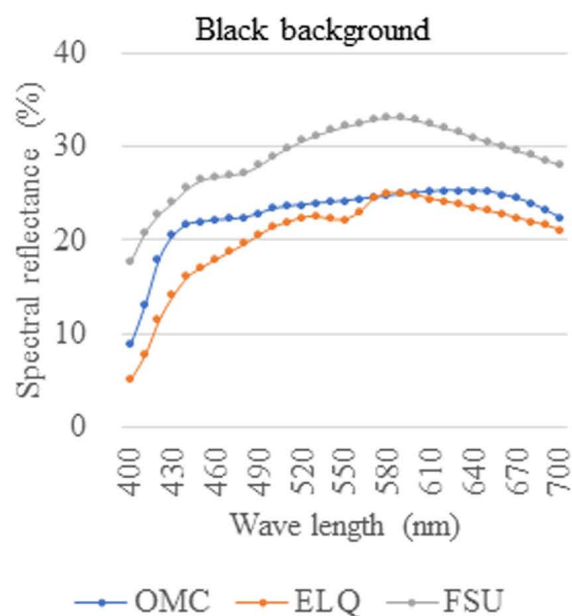


Figure 3. Influence of background color and specimen thickness on spectral reflectance curves of resin composites ($n=6$). Abbreviations: ELQ, Estelite Σ Quick; FSU, Filtek Supreme Ultra; OMC, Omnichroma.

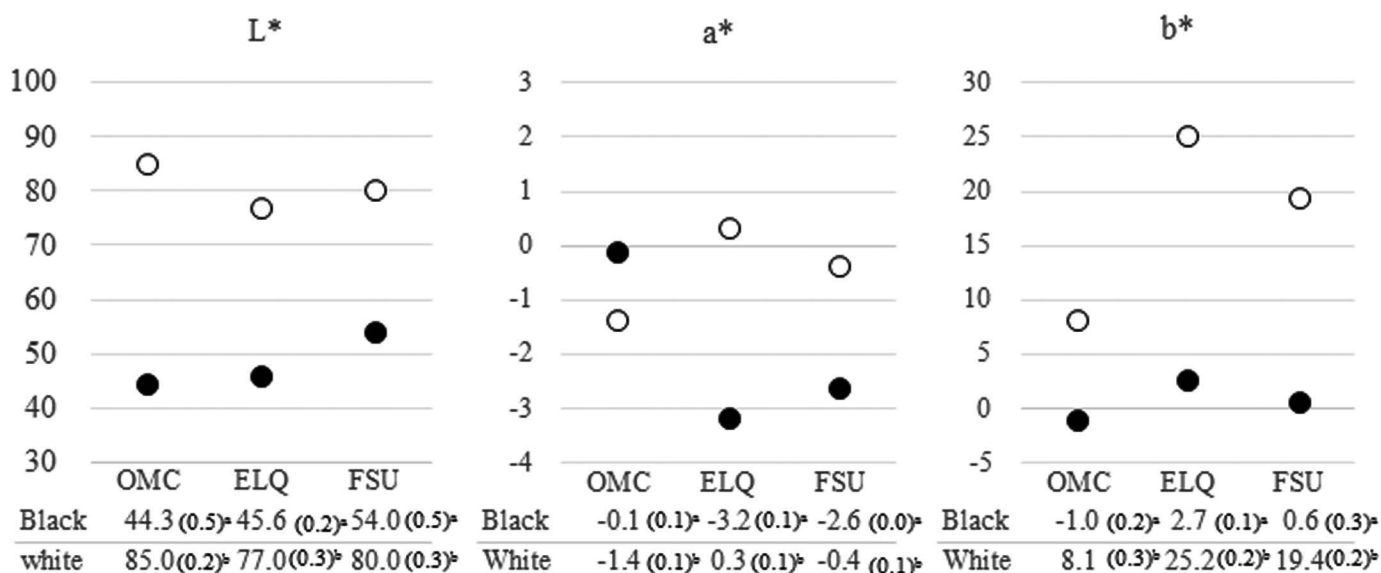
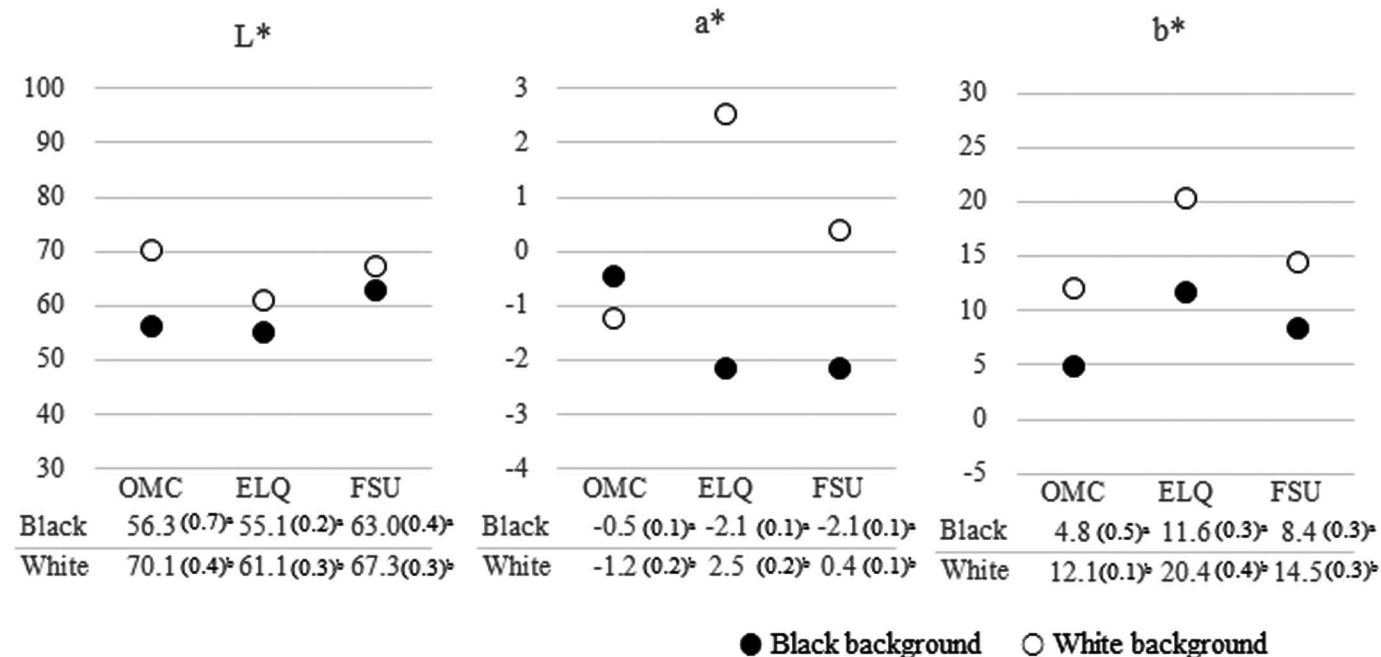
Specimen thickness: 1.5 mm**Specimen thickness: 3.0 mm**

Figure 4. Influence of background color and specimen thickness on L*, a*, and b* values of resin composites (n=6). Values in parenthesis indicate standard deviations. For the same materials, means with the same lowercase letter are not significantly different (p>0.05). Abbreviations: ELQ, Estelite Σ Quick; FSU, Filtek Supreme Ultra; OMC, Omnicroma.

Table 2. The color difference (ΔE^*ab) ranged from 1.4-2.4 for OMC, from 2.9-15.4 for ELQ, and from 2.6-13.4 for FSU. The color matching of OMC to the artificial teeth showed excellent and acceptable color compatibilities, regardless of the shade of the artificial teeth and the depth of the cavity. However, ELQ and FSU showed reduced color compatibilities, especially for a cavity depth of 3.0 mm, and these tendencies were remarkable with shade A4 artificial teeth.

DISCUSSION

The color of a resin composite is correlated with the light scattering and absorption characteristics, reflectivity, and translucency of the material.²² Inside the composite, incident light is reflected by the filler, resin matrix, pigments, and background color, then recognized as a certain color. The spectral reflectance curve of OMC showed that it reflected almost all wavelengths from 430-700 nm evenly on the black background regardless of the specimen thickness (Figure 3). However, the spectral reflectance curves for the white background showed slightly increased values compared to those on the black background, and the spectral reflectance increased with the wavelength range. Transmitted light contains optical information regarding the background and may affect the appearance of the resin composite.²³ When the background color has higher hue and chroma values, the light coloration from the background is absorbed,

leading to structural color expression. However, when the background chromaticity is low, the incident light is scattered, so the structural color is weak. The results of this study indicated that the reflection of light from the white background and from the spherical fillers might overlap, making it difficult to detect the structural color due to increased brightness.

Based on the results of this study, the a^* values of ELQ and FSU were significantly higher with the white background than with the black background (Figure 4). This was because the color development of the resin composite was affected by the change in the background color, leading to increased reflectance of incident light. The background color is quite important with respect to reflection of the incident light. When ELQ and FSU were placed on a dark color, the specific reflectance visible spectrum corresponding to the colored light was clearly confirmed. When the resin pastes were placed on the white background, uniform light reflection occurred. In this situation, certain reflections of the visible spectrum did not appear, leading to colorlessness. If the resin composite was placed in a low chromaticity environment, weak colored light was generated due to the pigments or dyes, leading to the effective ability to match the color of various peripheral color environments. However, when the background color was black, which has a much lower value than a white background, the a^* values of structural colored resin composite OMC showed different tendencies compared to those of ELQ and FSU.

Table 2: Results of Color Matching Ability Assessment as ΔE^*ab Rating

Cavity Depth	Artificial Tooth Shade	OMC	ELQ				FSU			
		Universal	A1	A2	A3	A4	A1B	A2B	A3B	A4B
1.5 mm	A2	2.2 (0.6)	2.9 (0.4)	10.2 (0.5)	12.4 (1.4)	15.4 (1.0)	2.6 (0.2)	3.2 (0.2)	6.7 (0.3)	11.5 (0.7)
	A4	1.4 (0.3)	10.8 (0.9)	5.2 (0.5)	4.5 (0.6)	3.1 (0.2)	7.3 (0.7)	6.9 (0.7)	3.8 (0.3)	3.5 (0.1)
3.0 mm	A2	2.4 (0.9)	8.2 (0.7)	11.6 (0.4)	14.3 (0.9)	18.0 (1.8)	3.3 (0.2)	4.8 (0.3)	7.7 (0.5)	13.4 (0.7)
	A4	1.5 (0.2)	11.1 (1.3)	7.9 (0.6)	6.5 (0.7)	3.9 (0.6)	9.2 (0.6)	6.9 (0.6)	6.3 (0.2)	6.0 (0.6)
Rating and interpretation							ΔE*ab			
Excellent match							≤1.2			
Acceptable match							>1.2		≤2.7	
Mismatch: moderately unacceptable							>2.7		≤5.4	
Mismatch: clearly unacceptable							>5.4		≤8.1	
Mismatch: extremely unacceptable							>8.1			
Abbreviations: ELQ, Estelite ∇ Quick; FSU, Filtek Supreme Ultra; OMC, Omnicroma.										

To determine the color-matching ability of the structural colored resin composite OMC, a standardized cavity was prepared in the artificial teeth, which was filled with the resin pastes. To assess the color-matching ability, ΔE^*ab , which is designed to provide a quantitative representation of the color difference, was used. Determining the thresholds of perceptibility and acceptability is important for interpreting and evaluating clinical outcomes.²⁴ The acceptability threshold ranges between 2.0 and 4.0, where as much as one-third of the literature refers to a value of 3.7 as being the threshold at which 50% of observers accepted a color difference. Another paper reported that the CIELAB 50:50% perceptibility threshold in dentistry was found to be $\Delta E^*ab = 1.2$, whereas the 50:50% acceptability threshold was found to be $\Delta E^*ab = 2.7$, and more than half the studies used a threshold of perceptibility of one ΔE^*ab unit under controlled conditions. In this study, ΔE values below 1.2 were considered as excellent matches and values of >1.2 and ≤ 2.7 were considered as acceptable matches.²¹ The research hypothesis was rejected because the background color and material thickness influenced the optical characteristics of the resin composites tested.

The results of this study showed that the color difference (ΔE^*ab) values of OMC (1.4-2.4) were smaller than those of ELQ (2.9-15.4) and FSU (2.6-13.4). All the ΔE^*ab values of OMC were rated as acceptable matches regardless of cavity depth or artificial tooth shade, meaning that OMC exhibited the most significant and pronounced color-matching ability in this study. Regarding the color adaptation properties of the structural colored resin composite OMC, it is important that more than 90% of the individual spherical filler has an average particle size of 260 nm.¹⁵ With this material, colored light can be clearly observed due to scattering without using pigments or dyes. The structural color may be unobservable because of increased opaque tones, or the refractive index difference between the filler and organic matrix may increase;²⁵ thus, the size and refractive index of the filler are important in determining the color characteristics of the structural colored resin composite. If the filler size is far below the wavelength of visible light, it will not scatter or absorb the light, making structural color less likely to occur. The reflective index of the filler particles should be in the range of 1.47-1.52 and correspond to that of the polymerized resin matrix. To obtain uniformly sized spherical particle fillers with a defined reflective index, a bottom-up colloidal assembly approach known as the “sol-gel method” has been used.²⁶ The assembly

of colloidal particles is thought to be one of the most facile and cost-effective methods for fabricating three-dimensional structural color materials.²⁷

Individual differences exist in the color of natural teeth, and the color varies according to the area for restoration. Resin composites must mimic the color appearance of the restored teeth to efficiently achieve patient satisfaction with desirable esthetics.

CONCLUSION

Within the limitations of this study, excellent color matching ability was confirmed for the structural colored resin composite OMC. However, since color changes over the white background showed decreased color matching even when using OMC, care should be taken to ensure that the appropriate chromatic color conditions for restoration are achieved in the oral environment.

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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.

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Fatigue Behavior of Monolithic Zirconia-Reinforced Lithium Silicate Ceramic Restorations: Effects of Conditionings of the Intaglio Surface and the Resin Cements

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Clinical Relevance

Clinical longevity with the zirconia-reinforced lithium silicate glass-ceramic dental restoration may be influenced by the intaglio surface treatment and the resin cement used. Hydrofluoric acid etching plus self-adhesive resin cement provided better fatigue results.

SUMMARY

Objective: This study assessed the effect of conditioning of the intaglio surface and resin cements on the fatigue behavior of zirconia-reinforced lithium silicate ceramic (ZLS) restorations cemented to a dentin analogue.

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Methods: ZLS ceramic ($\varnothing=10$ mm, thickness=1.5 mm) and dentin analogue ($\varnothing=10$ mm, thickness=2.0 mm) discs were produced and allocated according to the study factors, totaling nine study groups: ceramic surface treatment (three levels: hydrofluoric acid etching [HF]; self-etching ceramic primer [EP]; tribochemical silica coating [TBS]) and resin

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cement (three levels: 10-methacryloyloxydecyl dihydrogen phosphate [nMDP]; MDP-containing conventional resin cement [MDP]; self-adhesive resin cement [SA]). The ceramic bonding surfaces were treated and cemented on the dentin analogue, and all the specimens were aged for 5000 thermal cycles (5°C-55°C) prior to fatigue testing. The stepwise fatigue test (20 Hz frequency) started with a load of 400 N (5000 cycles) followed by steps of 500, 600, and up to 1800 N (step-size: 100 N) at a maximum of 10,000 cycles each step. The specimens were loaded until failure (crack), which was detected by light transillumination and visual inspection at the end of each step. The fatigue failure load and number of cycles for failure data were analyzed by the Kaplan-Meier (log-rank test; $\alpha=0.05$). Topographic and fractographic analyses were also performed.

Results: HF- (973.33-1206.67 N) and EP- (866.67-1066.67 N) treated specimens failed at statistically similar loads and higher than TBS (546.67-733.33 N), regardless of the cement used. All the fractographical inspections demonstrated failure as radial crack.

Conclusion: The HF and EP treatments promoted better mechanical fatigue behavior of the ceramic restoration, while tribochemical silica coating induced worse fatigue results and should be avoided for treating the ZLS surface prior to bonding.

INTRODUCTION

The zirconia-reinforced lithium silicate glass-ceramic (ZLS) is composed of a glassy matrix reinforced by lithium silicate crystals and dissolved zirconia (56%-64% silicon dioxide, 15%-21% lithium oxide, 8%-12% zirconium oxide), among other components.^{1,2} The reduction in the glass content and the crystalline microstructure (0.5-0.7 μm) of the lithium silicate creates a material with high strength and easy machining and polishing, associated to good esthetic properties.^{3,4} Due to its glassy content, this ceramic is considered acid-sensitive, being the hydrofluoric acid (HF) etching followed by the silane coupling agent application is the most recommended protocol for its surface conditioning and adhesive bonding to resin cements.^{5,6}

The HF acid selectively dissolves the glassy matrix, inducing pull-out of some lithia crystals without glassy support from the surface, revealing the microstructure of the ceramic surface and creating a micromechanical

pattern that, associated to the siloxane bonds provided by the silane between the exposed silica and methacrylate group of the resin cement,⁷ results in bond improvements.^{6,8} However, if all the microporosities and defects created by the HF are not completely filled by the cement, the restoration could be weakened by reducing its resistance to intermittent masticatory loading over time.⁹ In addition, the HF acid is considered to be potentially toxic to human health and should be used with caution or even avoided.^{5,10} Therefore, it is important to understand this mechanism and to consider other safer alternatives for surface treatment.¹¹⁻¹³

A promising possibility for dental glass-ceramic treatment is the use of a self-etching ceramic primer, which is a single-step ceramic initiator that facilitates handling and reduces the clinical time and the technique sensitivity when compared to conventional HF etching. However, there is little information available in the literature about the efficacy of these products.^{11,12} Wille and others¹¹ showed that the self-etching ceramic primer (Monobond Etch & Prime, Ivoclar Vivadent) provided bond strength to the lithium disilicate ceramic comparable to the well-established HF etching plus silane application, indicating that this surface treatment may be promising for use in glass ceramics. However, in a study by Strasser and others,¹³ the use of this self-etching ceramic primer did not cause significant changes in the surface of a zirconia-reinforced lithium silicate ceramic when compared with 5% HF acid etching.

Another alternative for treating the ZLS ceramics is to apply the tribochemical silica coating (silica coating by air abrasion with silica-coated aluminum oxide particles followed by the silane application). Al-Thagafi and others¹⁴ observed the application of tribochemical silica coating provided higher bond strength values compared to 5% HF etching plus silane in a zirconia-reinforced lithium silicate ceramic. The tribochemical silica coating consists of a silica deposition into the ceramic surface through an air-abrasion process, followed by the application of a silane-based coupling agent. The CoJet system (SiO_2 -coated Al_2O_3 , 30 μm particles, CoJet Sand, 3M ESPE, Seefeld, Germany) is a versatile and portable option for clinical use, which creates chemical bonds by applying mechanical energy.

The increase in bond strength is also directly influenced by the cement characteristics such as viscosity, elastic modulus, and its ability to fill the defects created by the surface treatments.^{9,15} There is a high tendency to simplify and reduce steps of the adhesive bonding process in dentistry; therefore,

different simplified resin cements were created (e.g., self-adhesive) to chemically interact with the dentin without the need of previous treatment, but the ceramic surface treatment is still required.¹⁶ In addition, they exhibit a lower polymerization shrinkage, resulting in less tooth/restoration interface failure, presenting bond strength values similar to conventional methacryloyloxydecyl dihydrogen phosphate (MDP)-containing cements when used with hybrid ceramics.¹⁷

On the other hand, resin cements containing phosphate monomers, like the 10-MDP, are composed of bifunctional molecules that directly bond to the oxides of the ceramic surface, through their phosphate ester group, and to the resin matrix of the cement, through their methacrylate groups, providing a better bond strength between the components.¹⁸ Gundogdu and Aladag¹⁹ obtained better values of bond strength when a zirconia ceramic was cemented with an MDP-containing conventional resin-cement compared with a self-adhesive resin cement. However, there is no data in the literature about its real effect on zirconia-reinforced glass ceramics, such as ZLS.

Furthermore, the data presented in the literature evaluating the ZLS related to their different surface treatments are scarce, especially regarding the effects on their fatigue behavior; therefore, some questions remain. Since surface treatments promote distinct topographic changes (different shape, size, and population of defects) on the ZLS ceramic surface, would this affect the fatigue behavior of such restorations? Different resin cements might promote different adhesion potential, therefore, could this affect the fatigue behavior of such restorations?

METHODS AND MATERIALS

The materials used in the study are described in Table 1.

Specimen Preparation

Ceramic—

Prefabricated ZLS blocks ($18 \times 14 \times 12$ mm³; VITA Suprinity, VITA Zahnfabrik, Bad-Säckingen, Germany) were ground into cylinders ($\varnothing=10$ mm) using #150-grit size silicon carbide paper (SiC) (Norton Abrasives, Saint-Gobain, São Paulo, SP, Brazil) in a polishing machine (EcoMet/AutoMet 250, Buehler, Lake Bluff, IL, USA). After, 1.7-mm-thick discs were obtained in a diamond saw machine (Isomet 1000, Buehler) under constant water cooling. For the removal of any cutting irregularities, the discs were polished with SiC papers of #400, #600, and #1200 grit (Norton Abrasives, Saint-Gobain) on both sides up to the final thickness of 1.5 mm.

To simulate the roughness produced by the computer-aided design/computer-aided manufacturing (CAD/CAM) milling process, the cementation surface was ground with #60-grit size SiC paper (Norton Abrasives, Saint-Gobain) 15 times on each axis, x and y , providing an initial roughness (mean $R_a=2.11$ μm and mean $R_z=12.77$ μm) similar to that of CAD/CAM milled restorations.²⁰

The specimen's dimensions were based on literature data^{21–23} considering the mean diameter of the occlusal surface of the first permanent molars ($\varnothing=10$ mm)²⁴ and their mean thickness based on the distance between the occlusal surface and the dental pulp chamber roof.^{25,26} After, the discs were washed in an ultrasonic bath (1440D, Odontobras, Ind and Com Equip Med Odonto, Ribeirão Preto, SP, Brazil) with distilled water for 10 minutes, dried with air-spray, and crystallized in a specific furnace (VACUMAT 6000MP, VITA Zahnfabrik) according to the manufacturer's instructions (840°C, eight-minute vacuum).

Dentin Analogue—

Dentin analogue discs (2.5 mm) were obtained from an epoxy resin plate (elastic modulus of 18 GPa; Carbotec GmbH & Co KG, Königs Wusterhausen, Germany) using a cylindrical diamond drill ($\varnothing=10$ mm) under constant water cooling and then ground (SiC #400-, #600- and #1200-grit sizes; Norton Abrasives, Saint-Gobain) until a final thickness of 2.0 mm.

The ceramic and dentin analogue discs were randomly distributed (www.randomizer.org) in nine groups ($n=15$) according to the factors under study, as shown in Table 2.

Surface Treatments

Ceramic—

Hydrofluoric acid etching. HF (5% IPS Ceramic Etching Gel, Ivoclar Vivadent) was applied and scrubbed on the ceramic surface with a microbrush and kept to react for 20 seconds, as recommended by the manufacturer. After, the specimens were washed with air/water-spray for 30 seconds, gently air dried, subjected to the ultrasonic bath (1440D, Odontobras, Ind and Com Equip Med Odonto) with distilled water for 5 minutes and air-spray dried for 30 seconds. The silane coupling agent (Prosil, FGM, Joinville, SC, Brazil) was then actively applied for 15 seconds with a microbrush, left to react for 60 seconds, and air dried for 15 seconds.

Etch & prime ceramic primer (EP). The self-etching ceramic primer (Monobond Etch & Prime, Ivoclar Vivadent) was actively applied on the ceramic surface with a microbrush for 20 seconds, left to react for 40

Table 1: Materials Used and Their Respective Characteristics: Commercial Name, Manufacturer and Composition	
Material and Manufacturer	Composition
Zirconia-reinforced lithium silicate glass-ceramic, VITA Suprinity, VITA Zahnfabrik	SiO ₂ ; Li ₂ O; K ₂ O; P ₂ O ₅ ; ZrO ₂ ; Al ₂ O ₃ ; CeO ₂ ; pigments
Hydrofluoric acid 5% (IPS Ceramic Etching-gel), Ivoclar Vivadent	Hydrofluoric acid < 5%
Hydrofluoric acid 10% (Condac Porcelana), FGM	Hydrofluoric acid 10%, water, thickener, surfactant and coloring
Monobond Etch & Prime, Ivoclar Vivadent	Tetrabutyl ammonium dihydrogen trifluoride, methacrylated phosphoric acid ester, trimethoxysilylpropyl methacrylate, alcohol, water
CoJet Sand, 3M ESPE	Aluminum oxide; free amorphous synthetic silica
MDP-free conventional resin cement (Multilink Automix), Ivoclar Vivadent	Base: ytterbium trifluoride, ethoxylated bisphenol A dimethacrylate, Bis-GMA, 2-HEMA, 2-dimethylamanoethyl methacrylate Catalyst: ytterbium trifluoride, ethoxylated bisphenol A dimethacrylate, urethane dimethacrylate, 2-HEMA, dibenzoyl peroxide and silica filler (68 wt%), pigments
MDP-containing conventional resin cement (Panavia F 2.0), Kuraray Noritake	10-methacryloxydecyl dihydrogen phosphate, bisphenol-A-polyethoxy dimethacrylate, hydrophobic aliphatic methacrylate, hydrophilic aliphatic methacrylate, silanated silica filler, silanated barium glass filler (78 wt%), sodium fluoride
Self-adhesive resin cement (RelyX U200, 3M Oral Care)	Base paste: methacrylate monomers containing phosphoric acid groups, methacrylate monomers, silanated fillers, initiator components, stabilizers, rheological additives Catalyst paste: methacrylate monomers, alkaline (basic) fillers, silanated fillers (72 wt%), initiator components, stabilizers, pigments, rheological additives.
Silane (Prosil), FGM	3-methacryloxypropyl trimethoxy silane (< 5%); ethanol (> 85%); water (< 10%)
Abbreviations: Bis-GMA, glycidyl methacrylate; HEMA, hydroxyethyl methacrylate; MDP, 10-methacryloyloxydecyl dihydrogen phosphate.	

seconds, and then washed with air/water-spray for 20 seconds.

Tribochemical silica coating (TBS). The TBS was performed with 30 µm silica-coated aluminum trioxide particles (CoJet Sand, 3M ESPE) on the intaglio ceramic surface using a micro-etcher (DENTO-PREP microblaster, Ronvig, Daugaard, Denmark) at a distance of 15 mm from the blast nozzle to the ceramic surface, with a blast pressure of 2.5 bar,²⁷ in oscillatory movements for 15 seconds.¹⁴ After, a light air-spray was applied to remove loose particles, and a silane coupling agent (Prosil, FGM) was actively applied for 15 seconds, left to react for 60 seconds, and air-spray dried for 15 seconds.

Dentin analogue. To simulate, as close as possible, a clinical setting, dentin analogue discs were used to mimic the hydrated human dentin, being similar in terms of bond strength and elasticity.²² Prior to cementation, the dentin analogue discs were cleaned

in an ultrasonic bath (1440D, Odontobras, Ind And Com Equip Med Odonto) with distilled water for five minutes and air-spray dried. After, they were acid etched with 10% HF (Condac Porcelana, FGM) for one minute, removed with air/water-spray for 30 seconds, and washed in an ultrasonic bath with distilled water for five minutes and air-spray dried for 15 seconds.

Cementation

MDP-free Conventional Resin Cement (nMDP; Multilink Automix)—

The primers A and B of the Multilink Automix system were mixed (1:1) and applied in the dentin analogue surface for 30 seconds with a microbrush, and a light air-spray was applied to create a thin and uniform layer. The base and catalyst pastes of the resin cement were

Table 2: Study Design and Study Groups		
Resin Cements	Ceramic Surface Treatments	Groups
Multilink Automix – nMDP MDP-free conventional resin cement	HF → 5% hydrofluoric acid etching (IPS Ceramic etching-gel) + Silane (Prosil)	nMDP+HF
		nMDP+EP
		nMDP+TBS
Panavia F 2.0 – MDP MDP-containing conventional resin cement	EP → Self-etching ceramic primer (Monobond Etch & Prime)	MDP+HF
		MDP+EP
		MDP+TBS
RelyX U200 – SA Self-adhesive resin cement	TBS → Tribochemical silica coating (CoJet Sand) + Silane (Prosil)	SA+HF
		SA+EP
		SA+TBS
Abbreviations: MDP, 10-methacryloyloxydecyl dihydrogen phosphate; SA, self-adhesive resin cement.		

dispensed from the double-push syringe, mixed for 20 seconds, and applied on the dentin analogue surface.

MDP-containing Conventional Resin Cement (Panavia F2.0)— ED primers liquid A and liquid B were mixed (1:1) and applied on the dentin analogue surface for 60 seconds with a microbrush and dried with a light air-spray. The base and catalyst pastes of the resin cement were dispensed from the syringes, mixed for 20 seconds, and applied on the dentin analogue surface.

Self-adhesive Resin Cement (RelyX U200)—

The base and catalyst pastes of the resin cement were dispensed from the double-push syringe, mixed for 20 seconds and applied on the dentin analogue surface.

After the resin cements were placed in the treated dentin analogue, the ceramic disc was seated over the cement and a constant load of 2.5 N was applied on the ceramic surface to promote a uniform cement spreading, standardizing its thickness.²⁸ After removing the cement excesses with a microbrush, the light curing was performed (LED light, 1200 mW/cm², 440–480 nm, Radium-cal, SDI Limited, Bayswater, Australia) for 40 seconds on the occlusal surface of the ceramic followed by 20 seconds on each lateral side of the interface (0°, 90°, 180° and 270°).

Aging – Thermocycling

After bonding, the specimens were stored for 24 hours submerged in distilled water at 37°C in a laboratory incubator. Then, the specimens underwent intermittent 5000 thermal cycles (model 521-6D, Ethik Technology Limited, Vargem Grande Paulista, SP, Brazil) with temperatures ranging from 5°C to 55°C with 30 seconds of dwell time at each temperature and 4 seconds of transfer time.²⁹

Fatigue Testing—Stepwise Method

The specimens (n=15) were tested submerged in distilled water in an electrodynamic testing machine (Instron ElectroPuls E3000, Instron Corp, Norwood, MA, USA) over a flat metal base, and the load was applied on the ceramic surface with a 40-mm-diameter stainless steel hemispherical piston.²² Prior to testing, an adhesive tape (110 µm) was placed between the piston and the ceramic to improve the contact between them and to avoid contact damage.²⁸ The test started with a load of 200 N at a frequency of 20 Hz per 5000 cycles (preconditioning phase to ensure predictable positioning of the piston with the sample), followed by steps of 400 N, 500 N, 600 N, and so on with increments of 100 N to 1800 N to a maximum of 10,000 cycles each step. At the end of each step, the specimens were analyzed by transillumination to check the presence of a crack. The specimens were tested until fracture (presence of a minimal radial crack) or until all steps were complete.

Topographic Analysis

Micrographs of the ceramic surface at control (CAD/CAM milling simulation) and after the surface treatments were analyzed (100× magnification) to inspect the topographical changes (micromechanical patterns). Representative specimens (n=2) were ultrasonically cleaned, gold sputtered, and analyzed in a scanning electron microscope (SEM) (Secondary electrons, 20kV; VEGA3 Tescan, Brno-Kohoutovice, Czech Republic).

Fractographic Analysis

After the fatigue testing, the specimens were analyzed in a stereomicroscope (100× magnification; Stereo Discovery V20, Carl-Zeiss, Göttingen, Germany) to identify their crack path. Representative specimens

were cut under water-cooling (Isomet 1000, Buehler) in the middle and perpendicular to the crack, ultrasonically cleaned in distilled water for 10 minutes, sputtered with a gold-palladium alloy, and analyzed in the SEM (500× magnification; Secondary electrons, 20kV, VEGA3 Tescan) to identify the crack features.

Statistical Analysis

The fatigue failure load and number of cycles for failure data were recorded and analyzed by the Kaplan-Meier and Mantel-Cox (log-rank) tests at $\alpha=0.05$.

RESULTS

Kaplan-Meier analysis showed that surface treatments with HF and EP presented loads to failure and number of cycles for failure statistically similar to each other and higher than TBS, regardless of the type of cement (Table 3). When only the cement was considered, the self-adhesive cement obtained statistically greater results for the HF and TBS treatments, and no difference among cements was found when applying EP (Table 3). Regarding the survival rate, the similar findings could be noticed: for instance, at 900 N, all the specimens in the TBS group had already failed, whereas HF and EP samples had more than 47% and 27% of survival chance, respectively (Table 4).

The topographic analysis showed distinct ceramic surface patterns depending on the surface treatment. Whereas the EP seems to not alter the surface created during CAD/CAM milling simulation (in the section Specimens Preparation: Ceramic), HF etching seems to soften the roughness created during this process,

and TBS created a more irregular surface than the other treatments (Figure 1).

The fractographic analysis showed that the failure pattern was similar for all the groups. The origin of the radial cracks seemed to be located at the ceramic intaglio surface, and it propagated toward the surface of the load application (ceramic occlusal side) (Figure 2). In addition, no failures due to contact damage (Hertzian cone cracks) were observed.

DISCUSSION

The results of the present study show that the surface treatment and the type of cement used influenced the fatigue failure load, number of cycles for failure, and the survival rates of the ZLS (VITA Suprinity), and the study hypotheses were rejected. As a glass-ceramic, the most recommended surface treatment for ZLS is the etching with 5% HF followed by the silane agent application.³⁰ This treatment promotes selective removal of the glassy matrix, cleans the surface, and creates microretention, increasing the surface wettability,^{13,27} besides removing and/or smoothing the surface defects resulting from CAD/CAM process.^{27,31} Strasser and others¹³ stated that the HF etching followed by the silane agent application provided a greater flexural strength when compared to the TBS followed by the silane application in a ZLS, corroborating our results (Table 3).

During the TBS with silica-coated alumina particles, the high energy generated by the impact of the particles onto the surface leads to incrustation and coating of the silica layer to the ceramic surface,^{27,30} modifying it chemically.³² However, the impact of the particles also

Table 3: Results for Fatigue Failure Load (FFL) and Number of Cycles for Failure (CFF)^a

Groups	FFL (N) - Mean (CI)	CFF - Mean (CI)
nMDP+HF	973.33 (891-1055) B	72,333 (64,113-80,553) B
nMDP+EP	866.67 (759-974) B	61,666 (50,902-72,430) B
nMDP+TBS	546.67 (514-579) D	29,666 (26,428-32,905) D
MDP+HF	986.67 (920-1052) B	75,000 (67,843-82,156) B
MDP+EP	1066.67 (993-1139) AB	81,666 (74,341-88,991) AB
MDP+TBS	546.67 (520-572) D	29,666 (27,053-32,280) D
SA+HF	1206.67 (1086-1326) A	95,666 (83,650-107,683) A
SA+EP	1026.67 (942-1111) AB	77,666 (69,227-86,105) AB
SA+TBS	733.33 (702-764) C	48,333 (45,209-51,456) C

Abbreviations: CI, confidence interval; EP, etch & prime ceramic primer; HF, hydrofluoric acid; MDP, 10-methacryloyloxydecyl dihydrogen phosphate; SA, self-adhesive resin cement; TBS, tribochemical silica coating.

^aDifferent uppercase letters in each column indicate significant statistical difference based on the Kaplan-Meier and Mantel-Cox (log-rank) tests ($\alpha=0.05$).

Table 4: Survival Rates (Probability of the Specimens to Exceed the Respective Fatigue Failure Load and Number of Cycles for Failure Without Fail) of the Study Groups and Their Respective Standard Error Measurements^a

Fatigue Failure Load (N) / Number of Cycles ($\times 10^3$) on the Respective Step ^b	Groups								
	nMDP+HF	nMDP+EP	nMDP+TBS	MDP+HF	MDP+EP	MSP+TBS	SA+HF	SA+EP	SA+TBS
400 / 15×10^3	1	1	1	1	1	1	1	1	1
500 / 25×10^3	1	1	0.40 (0.12)	1	1	0.47 (0.13)	1	1	1
600 / 35×10^3	1	1	0.06 (0.06)	1	1	0.00 (0.00)	1	1	0.93 (0.06)
700 / 45×10^3	1	0.67 (0.12)	0.00 (0.00)	0.93 (0.06)	1	—	1	1	0.40 (0.12)
800 / 55×10^3	0.73 (0.11)	0.27 (0.11)	—	0.87 (0.08)	0.93 (0.06)	—	1	0.87 (0.09)	0.00 (0.00)
900 / 65×10^3	0.47 (0.13)	0.27 (0.11)	—	0.73 (0.11)	0.80 (0.10)	—	1	0.60 (0.12)	—
1000 / 75×10^3	0.27 (0.11)	0.20 (0.10)	—	0.20 (0.10)	0.53 (0.12)	—	0.80 (0.10)	0.40 (0.12)	—
1100 / 85×10^3	0.20 (0.10)	0.13 (0.09)	—	0.13 (0.09)	0.27 (0.11)	—	0.47 (0.13)	0.27 (0.11)	—
1200 / 95×10^3	0.07 (0.06)	0.07 (0.06)	—	0.00 (0.00)	0.13 (0.09)	—	0.20 (0.10)	0.13 (0.09)	—
1300 / 105×10^3	0.00 (0.00)	0.00 (0.00)	—	—	0.00 (0.00)	—	0.13 (0.09)	0.00 (0.00)	—
1400 / 115×10^3	—	0.00 (0.00)	—	—	—	—	0.13 (0.09)	—	—
1500 / 125×10^3	—	—	—	—	—	—	0.13 (0.09)	—	—
1600 / 135×10^3	—	—	—	—	—	—	0.13 (0.09)	—	—
1700 / 145×10^3	—	—	—	—	—	—	0.06 (0.06)	—	—
1800 / 155×10^3	—	—	—	—	—	—	0.00 (0.00)	—	—

Abbreviations: EP, etch & prime ceramic primer; HF, hydrofluoric acid; MDP, 10-methacryloyloxydecyl dihydrogen phosphate; SA, self-adhesive resin cement; TBS, tribochemical silica coating.

^a“—” indicates absence of specimen being tested on the respective step.

^bThese values are approximated.

causes a certain amount of abrasion, creating sharper defects and cracks at the ceramic surface,¹³ as observed in the present study (Figure 1), which could be potential sites for the crack growth during function. According to Griffith's weakest link theory,³³ the greater the number of critical defects that exist, the greater the chance an

earlier crack growth when the material is subjected to intermittent loading, as occurs in the oral environment during chewing. This is corroborated by others^{9,34,35} who have shown the deleterious effect of a rougher ceramic surface when the defects are not properly filled by the adhesive bonding.

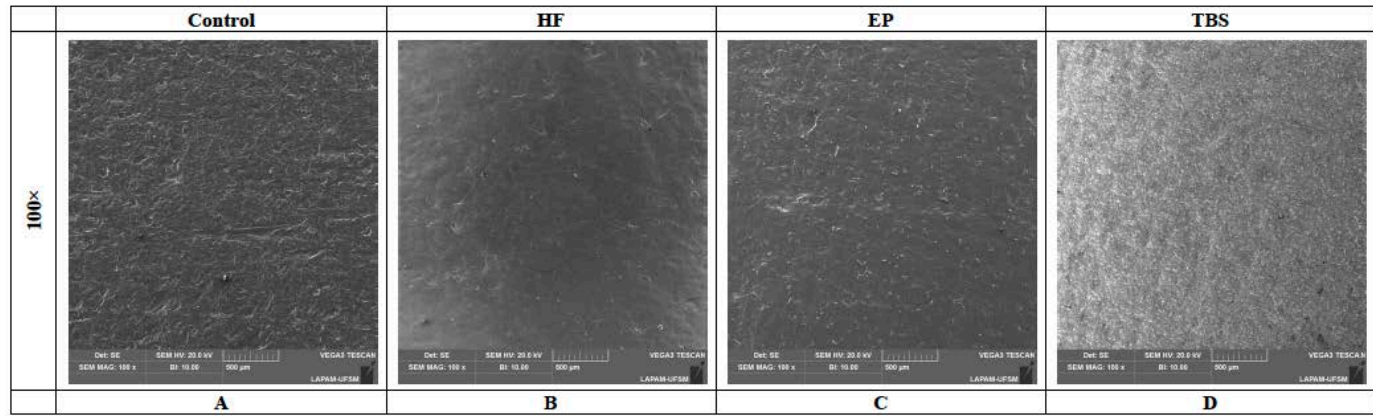


Figure 1. Topographic images on scanning electron microscopy (100× magnification) of the ceramic surface on control (CAD/CAM milling simulation) (A) and after the surface treatments: (B) 5% hydrofluoric acid etching (HF); (C) Monobond Etch & Prime application (EP); (D) tribochemical silica coating (TBS).

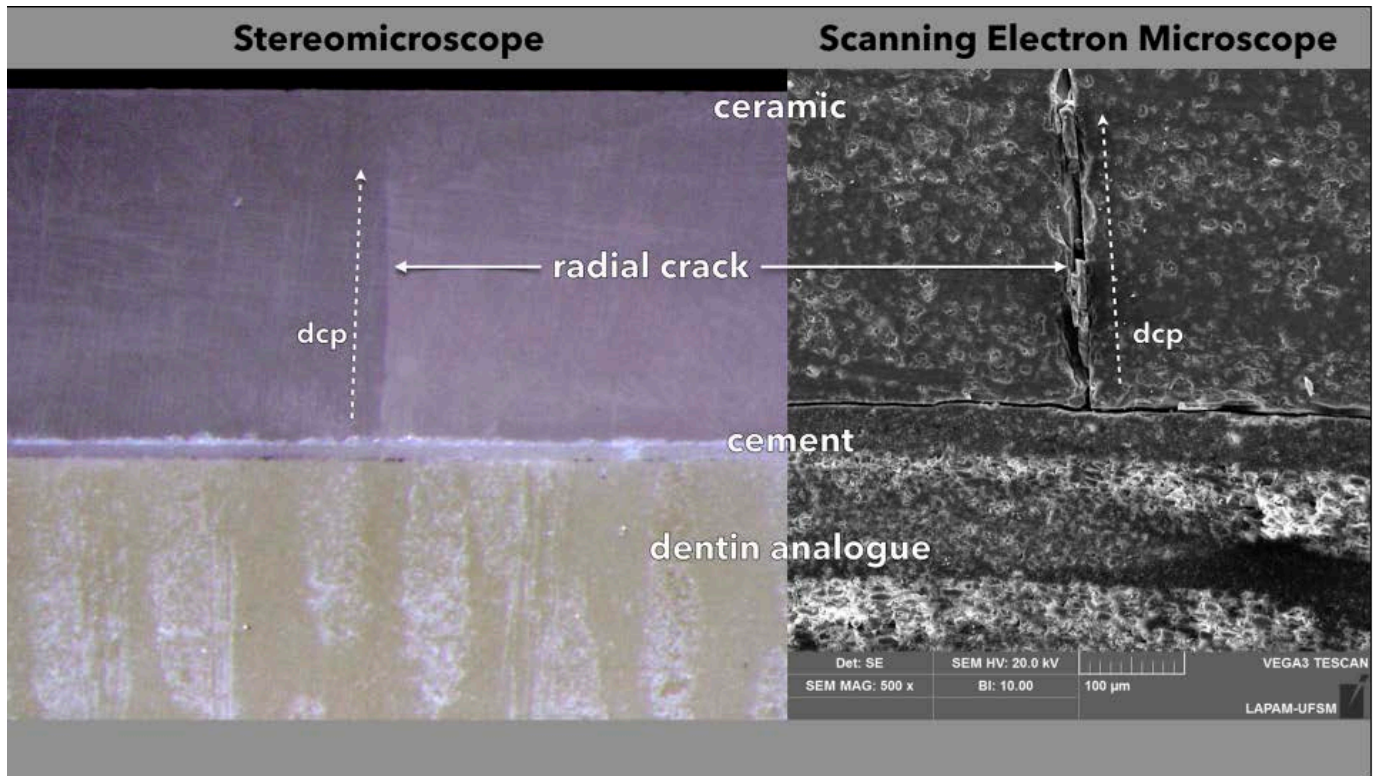


Figure 2. Images on stereomicroscope (100× magnification) and scanning electron microscopy (500× magnification) of a representative failed specimen showing the crack characteristics after failure during the fatigue test. It seems that the failure origin is located at the intaglio ceramic surface, propagating toward the ceramic occlusal side. Abbreviation: dcp, direction of crack propagation.

Another alternative for surface conditioning of vitreous ceramics is the application of a self-etching ceramic primer, such as the Monobond Etch & Prime (Ivoclar Vivadent), which consists of a combination of ammonium polyfluoride and silane (trimethoxysilypropyl methacrylate) in a single bottle, simplifying the conditioning technique.³⁶ Studies have shown a poor ability of such ceramic primer to properly modify the surface when compared to 5% HF etching in

a lithium disilicate ceramic and in a ZLS ceramic.^{12,13,37} Our study corroborates those finding since EP was not able to significantly modify the surface created during the CAD/CAM milling simulation (Figure 1). In the study of Prado and others,³⁶ the use of a self-etching ceramic primer, although providing lower bond strength values than HF etching followed by the silane application, promoted more stable long-term results. According to our results, the surface treatment with

EP was as effective as the HF, regardless of the cement applied; therefore, it could be a viable option for the ZLS ceramic surface treatment from the mechanical fatigue performance viewpoint.

The use of resin cements to bond the vitreous ceramic restorations improves their mechanical performance.^{9,34,38,39} This finding has been related to the ability of resin cements to seal and modify the ceramic surface defects, possibly by creating compressive forces at the crack tips or simply by sealing the critical defects.³⁹ However, the explanation for this strengthening mechanism has not yet been fully clarified and requires further investigation.³⁹ The characteristics of the bonding systems can determine their ability to fill these defects, and the type, size, and content of the cement filler particles,⁴⁰ as well as the presence of bisphenol-A-diglycidylether dimethacrylate (Bis-GMA),⁴¹ directly influence such ability. An increase in the filler content and the presence of Bis-GMA result in an increase in their viscosity (Table 1).^{41,42} In this sense, a low viscosity cement is preferable since it generates a better intimacy between the ceramic surface defects and the infiltrating bonding system, resulting in a greater capacity of filling the defects.^{43,44} Furthermore, it also provides a thinner cement thickness, resulting in lower shrinkage stress, reducing the possibility of gaps and resin cement sorption and solubility.^{40,45}

The results of our study show a difference between the cements used when the ceramic surface was treated with HF or TBS, and the self-adhesive resin cement presented better fatigue performance than the other cements in such groups (Table 3). Although MDP-free conventional resin cement (Multilink N) has a lower filler particle content,⁴³ which would decrease its viscosity in relation to the other resin cements, the presence of a Bis-GMA monomer in its composition is responsible for increasing its viscosity (Table 1).⁴⁶ Thus, even with a higher filler content (Table 1), the self-adhesive resin cement (RelyX U200)⁴⁴ seems to be more effective in penetrating deeper into the irregularities of the glass ceramic surface and improving the adhesive bonding and consequently its fatigue performance.⁴⁰ Also, the methacrylate monomers with phosphoric ester functional groups in the self-adhesive resin cement are able to improve adhesion by creating hydrogen bonds with the ceramic surface.⁴⁵ However, no difference between the cements was observed when the surface was treated with the ceramic primer (EP) (Table 3), which may be explained since the EP did not create an irregular surface and all the cements had the same capacity for filling the defects created on such surfaces.

Although laboratory tests are important in determining properties and characteristics of materials, they do not

fully simulate *in vivo* conditions. Simplified restoration, besides providing a more standardized approach, allows for a less complex stress distribution, and the factors under study are better evaluated. The present study has some limitations, such as it does not apply the load with sliding contact, from which ceramic prostheses are subjected under normal and tangential loads during chewing, and it can generate surface damage accumulation, consequently reducing the load-bearing capacity.⁴⁷ In addition, as an accelerated fatigue test method, caution is required when evaluating the results.

CONCLUSION

1. Different surface treatments and resin cements directly influence the fatigue behavior of a bonded simplified ZLS.
2. The hydrofluoric acid etching and the self-etching ceramic primer provided better fatigue behavior than TBS, regardless of the cement used.
3. HF etching followed by the use of the self-adhesive resin cement created better fatigue results, being only equal to EP-treated ceramic when bonded with self-adhesive resin cement A or MDP cements.

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Conflicts of Interest

The authors 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.

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Effect of Operator Experience on Ability to Place Sequential, 2-mm-thick Increments of Composite

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Clinical Relevance

Because an operator has only about one chance out of three to place a composite increment within this clinically acceptable range, clinicians are advised to use an instrument (e.g., a periodontal probe with a 2-mm mark) to estimate the thickness of each increment of composite they place.

SUMMARY

Objective: To measure and compare the effect of operator experience in their ability to place composite in increments that are 2 mm thick.

Methods and Materials: Fifteen volunteers from each class of freshmen, sophomores, juniors, and senior dental students and 15 clinical faculty (total number of volunteers = 75) were asked to restore a Class I preparation that was 5 mm in diameter and 8 mm deep from the cusp tips using three

increments of composite that were each to be 2 mm thick. Once completed, the models were sectioned, and the thickness of each increment was measured. A repeated-measures analysis of variance (pre-set $\alpha=0.05$) was used to compare the mean increment thickness with respect to operator experience level and increment sequence number. In addition, the proportion of operators placing clinically acceptable increments (between 1.75 and 2.25 mm thick), as well as the proportions from each group who placed increments that either were thinner

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or thicker than this range, was determined using nonparametric analyses.

Results: Overall, there was an increasing trend for groups with a higher experience level to provide mean incremental thickness values close to 2 mm. However, the likelihood of placing an increment that was thicker or thinner than the manufacturer-recommended thickness was not significantly different. Regardless of the increment value, only about one-third of the increments placed fell within the desired range of 1.75 to 2.25 mm.

Conclusions: Operator experience had no overwhelming significant influence on the ability to place increments of composite that were between 1.75 and 2.25 mm thick. An operator has only about one chance out of three to place a composite increment within this clinically acceptable range when using no external measurement system.

INTRODUCTION

When restoring a deep cavity preparation using photo-cured resin-based composites (RBCs), the RBC must be placed in increments. For many RBCs, the recommended maximum thickness of each increment ranges from 1.5 mm¹ to 2.5 mm,² depending on the material translucency, shade, and manufacturer. These increment limits are due to the inability of sufficient light to reach beyond this depth. Within this depth range, the exposure duration specified by the manufacturer will provide adequately polymerized RBCs.³ Failure to provide sufficient radiant energy to these depths can produce inadequate polymerization in the RBC at depths beyond the recommended increment thickness: the “depth-of-cure” issue.⁴ This failure may explain why the median longevity of approximately seven years⁵⁻¹² for posterior RBCs placed in dental offices is far less than their potential to last at least twice as long, a value that has been reported in controlled trials.^{9,13}

When placing photo-cured materials, clinicians must estimate the thickness of each increment and try to balance the need to complete a restoration using the least amount of chairside time, with the maximum allowable increment thickness recommended by the manufacturer. Few practitioners will use instruments to judge the thickness of each increment before light-curing, and once the pulpal floor of a preparation is covered with composite, it becomes difficult to evaluate the thickness of each increment. However, it is not known if the operator experience plays a factor in determining the ability to place increments of RBC that are within thickness specified by the manufacturer.

The longevity of the restoration appears to be influenced more by the operator’s experience than by the choice of material.^{11,14} As novice dental students become more familiar with judging the dimensions within which they work, it seems reasonable to expect that their ability to predictably place a specified thickness of RBC would increase. In addition, one would anticipate that experienced faculty would be able to judge and place increments of RBC that are within the desired limits. The clinical relevance and importance of these target values relate to the fact that if the increment thicknesses are less than those suggested by the manufacturer, more chairside time will be spent placing the restoration.¹⁵ If thicker increments are placed, less chairside time is needed, but the polymerization of the RBC will likely be compromised, leaving the integrity of the total restoration in question.¹⁶⁻¹⁹ Because less than optimal polymerization and suboptimal properties are likely to result when the RBC is placed in increments that exceed the manufacturer’s instructions, it is important to evaluate the ability of clinicians to place increments within a controlled range of values.

The purpose of this study was to measure and compare the ability of dental students (having varying degrees of experience) and more experienced faculty clinicians, when placing three sequential, 2.0-mm-thick increments of RBC. In addition, the proportion of participants who successfully placed increments that fell within, lower than, or above a clinically realistic and acceptable range of 1.75-2.25 mm was determined.

The following research hypotheses were considered. With respect to the thickness of each increment of RBC:

1. The percentage of operators meeting the increment target range would not significantly improve with experience at any increment level.
2. The likelihood of placing an increment of RBC that was either thicker or thinner than the target range (1.75-2.25 mm) would not be significantly different among experience levels.

METHODS AND MATERIALS

Fifteen students from each of the four years of training at the Dental College of Georgia at Augusta University volunteered for the study: freshmen (D1), sophomores (D2), juniors (D3), and seniors (D4), as well as 15 experienced clinical faculty from the Department of Restorative Sciences. The volunteers were solicited via e-mail and represented a diverse group having no targeted ability equivalence. Before starting, the participants were asked to read and sign an informed consent. The list of participants was kept only for record-keeping purposes.

A 3D printed, toothlike molar model, adapted from freeware (<https://www.thingiverse.com/thing:1485531>), was modified to meet the requirements of the specific project (OpenSCAD version 2017.01.20, <https://www.openscad.org/about.html>). A filament-based 3D printer (Model 30M, Hyrel 3D, Norcross, GA, USA) was used to fabricate individual models made from 1.75-mm black PLA filament (PN: 88855, 3D Universe, Algonquin, IL, USA). This model tooth was of similar dimensions as a human molar tooth and included an attached base portion. The final product simulated an occlusal Class I preparation that was 5 mm in diameter and 8 mm deep from the cusp tips (see Figure 1). The base section of the model contained two vertical slots that engaged another 3D printed part such that the filled tooth model could be safely held vertically while pressed against the face of a dental laboratory model trimmer to remove half of the tooth model (sectioned longitudinally mesiodistally).

Working under ideal conditions with unobstructed access to the model on a laboratory bench, the participants were asked to fill the simulated tooth preparation. They were instructed to place three, 2-mm-

thick increments of RBC using their usual technique and to light-cure each increment. Participants were not told the dimensions of the simulated preparation, nor were they given any instrument to measure the dimensions of the preparation. The only items provided to each participant were a gold-tipped composite instrument (TINPF3, Brasseler USA Dental, Savannah, GA, USA), a light-curing unit, and blue blocker glasses. The room was well lit by overhead fluorescent lighting. The use of dental loupes was encouraged, as well as headlamps, if they were part of the participant's customary loupe/light apparatus.

All participants used the same commercial light-cured RBC (Premise, Kerr Corporation, Orange, CA, USA). This material was available in a compule delivery form in a light (B1) shade (item #32655, Lot #5881365) that was used for the bottom and top increments. A dark (C4) shade (item #32662, lot #5943632) was used for the middle increment. The use of different shades allowed the boundaries between each increment to be identified.

After completing the restoration, the molds were coded and sectioned occluso-gingivally using a model trimmer (Whip Mix Corporation, Louisville, KY, USA) to expose the cross-section of the filled preparation. The cut surface was then lightly finished using a fine-grit SiC wet paper abrasive strip (#320, Leco Corporation, St. Joseph, MI, USA). Digital images of the sectioned specimens were taken using a calibrated binocular microscope (SM2-B microscope, 10x digital camera [MU-1000] AmScope, Irvine, CA, USA).

Microscopic Image Analysis

Using a standard method, the thickness of each increment was measured along a vertical axis at the center of the restoration. Before capturing a digital image of the sectioned tooth, the X-Y focal plane was calibrated using a precision microscope stage calibration slide that included a 1-mm-long scale in increments of 0.01 mm (MR095, AmScope). Image recording and dimensional analyses were made using the same software program (AmScope V 3.7.3980, AmScope). Figure 2 shows how each increment layer could be clearly identified by the stark contrast in the shades of RBC that had been used.

Statistical Analyses

Statistical interpretation of the data consisted of two separate analyses. The first analysis addressed only the measurement of increment thickness (dependent variable) as affected by operator experience (between-subjects factor, five levels) and the different incremental layers placed (within-subjects factor, three levels). The

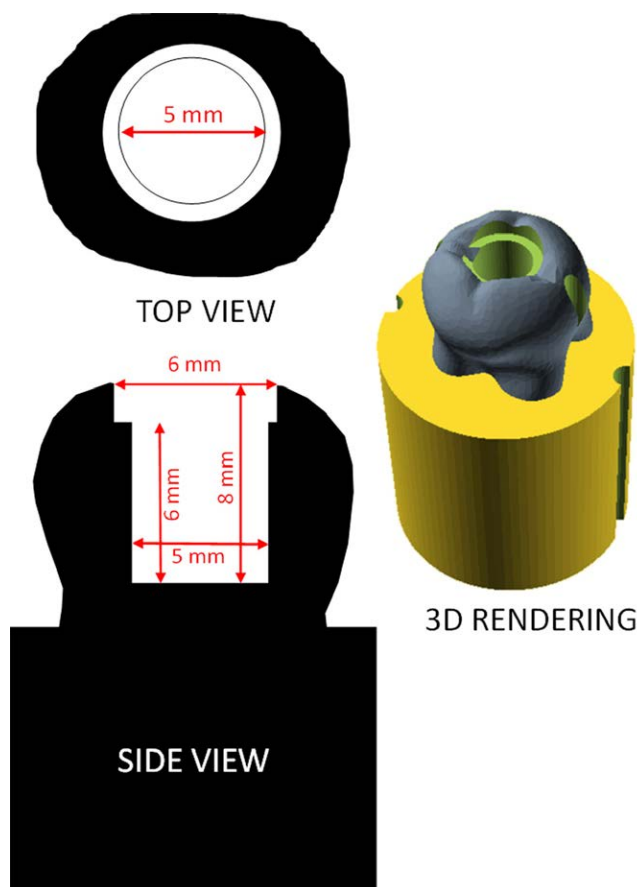


Figure 1. 2D and 3D rendering of the printed mold used to provide the standardized tooth/preparation for restoration.

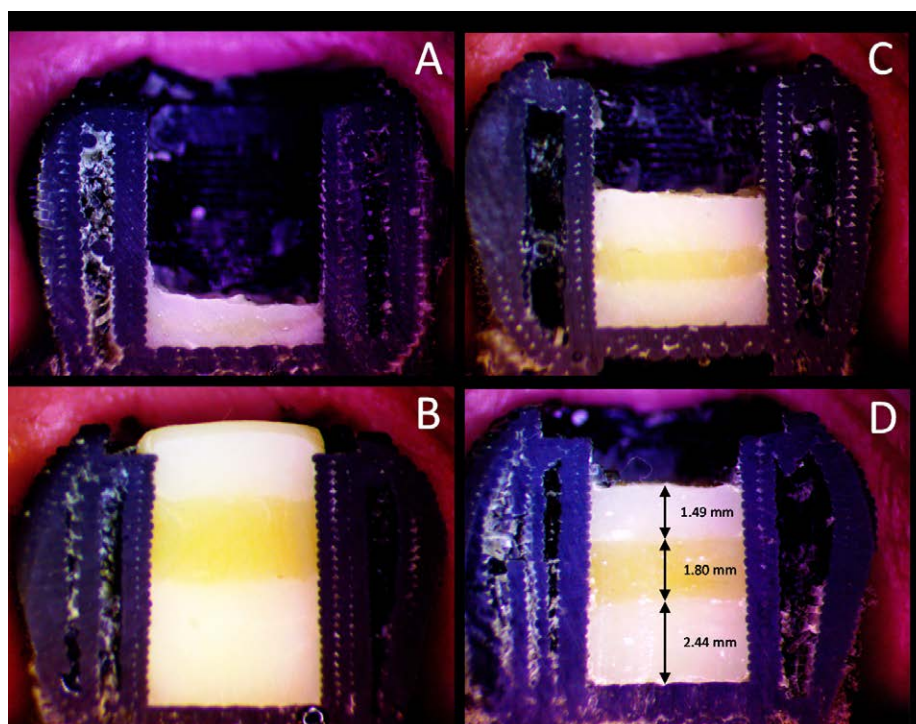


Figure 2. Representative images of the variety of incremental thickness patterns observed. (A) All increments grossly underestimated, (B) first increment too thick, (C) all increments too thin, (D) illustration of how the increment layer thickness was measured.

Shapiro-Wilk test was used to assess the normality of the repeated measures data. A repeated-measures analysis of variance with one between factor ("Experience") and one within factor ("Increment") was performed. The Tukey-Kramer test was used to perform pairwise comparisons among the levels of the Increment factor and levels of the Experience factor. Where the data was not normally distributed, appropriate rank-based methods were used. All statistical tests were two-tailed, using a pre-set alpha of 0.05.

The second analysis was designed to examine the influence of operator experience on the ability to provide an increment thickness (dependent variable) relative to a target range of 1.75 to 2.25 mm, categorized at three levels (less, meets, or exceeds) for each of the increments (first, second, and third). The multinomial test was used to compare the five experience levels in terms of the frequency falling within each "filling" category (i.e., less, meets, or exceeds) separately for each increment. Within each increment, a Bonferroni adjustment was made to control the family-wise error rate at 0.05 for all 30 comparisons among the experience levels ([10 pairwise comparisons among five experience levels] x [three ability categories]). Thus, an adjusted significance level of $0.05/30 = 0.0017$ was used for all tests performed within each increment. All multinomial tests were two-tailed. Statistical analyses

were performed using commercially available software (SAS 9.4, 2012, SAS Institute Inc, Cary, NC, USA).

No previously published or pilot data could be used to reliably estimate an appropriate sample size required for this study. Assuming a coefficient of variation of 55% or less, a sample size of 15 participants in each experience level group would yield an 80% power to detect the anticipated differences in mean increment thickness among the five groups using a two-sided significance level of 0.05. Similarly, with 15 participants in the experience level group, this would yield 93% power for detecting the anticipated differences among the groups illustrated using the multinomial test with $\alpha = 0.05$ (nQuery 8.4.1, 2019, Statistical Solutions Ltd, Cork, Ireland).

RESULTS

Comparison of Mean, Raw Incremental Layer Thickness Values

Figure 2 illustrates an example of the variety of increment thicknesses that was observed, as well as a representative image showing how the thickness of each increment of RBC was measured.

The Shapiro-Wilk test indicated that the assumption of normality was reasonable for the repeated measures

data. Thus, a standard repeated measures analysis was used to examine the effects of Experience and Increment factors, as well as their interaction. The interaction term (Experience x Increment) was significant ($p=0.020$) as were the Experience ($p=0.025$) and Increment factors ($p=0.001$).

Due to the presence of significant interaction effects between the Experience and Increment effects, separate Tukey-Kramer post hoc, pairwise mean comparisons were carried out on the Experience and Increment main effects, as well as on the Experience x Increment interaction. The mean increment thickness placed by the least experienced operators (freshmen) was just barely significantly thinner than those of both the seniors ($p=0.043$) and the faculty ($p=0.046$); these were the only significant differences among the levels of the Experience factor (Figure 3). Ignoring the effect of operator experience, the increment thickness tended to decrease with each layer; in particular, the third (top-most and last) increment was significantly thinner ($\bar{x}=1.63$ mm) than that of the first and deepest increment ($p=0.001$) and the second ($p=0.021$) increment (Figure 4).

Figure 5 displays the overall test results reflecting the parameters. In this figure, the solid, horizontal green line represents the 2-mm increment thickness goal. The only experience level demonstrating significant differences in thickness among the increments were the seniors (bottom>top; $p=0.018$). Within the first increment, the only significant difference was seniors >

freshmen ($p=0.005$). Within both the middle (second) and the top (third) incremental layers, there were no significant differences noted among experience levels ($p=0.562$ and $p=0.136$, respectively).

Comparison of Ability to Provide Increment Thicknesses Between 1.75 and 2.25 mm

The study sought to compare operator experience level groups (freshman, sophomore, etc) in terms of the percentage of participants who either placed an increment within the clinically relevant target range (1.75-2.25 mm) or under- or overfilled that increment. The horizontal light green shaded rectangle in Figure 5 represents the upper (2.25 mm) and lower (1.75 mm) boundaries that were considered as clinically acceptable tolerance values for the requested 2-mm incremental thickness for this portion of the study analysis.

Anticipated Results

Figure 6 is a representation of the expected findings had the second research hypothesis proven true. This expected trend was anticipated to hold true for all increments placed by each level of operator experience. Estimated values from this figure were used to help support the sample size to deliver adequate power to the statistical analysis. With increasing operator experience, it was anticipated that the percentages of observed over- and under-range values would decrease,

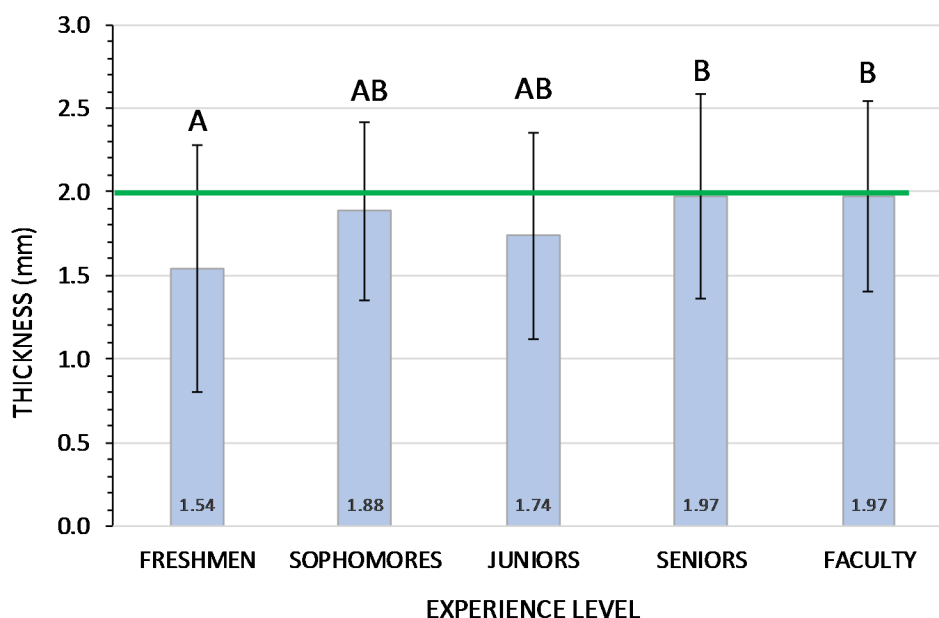


Figure 3. Mean increment thickness among experience levels (disregarding the influence of increment). $N = 45$ values per group. Vertical bar = ± 1 standard deviation. Thickness layers of groups identified by similar uppercase letters are not significantly different. Horizontal green line represents the 2-mm target thickness.

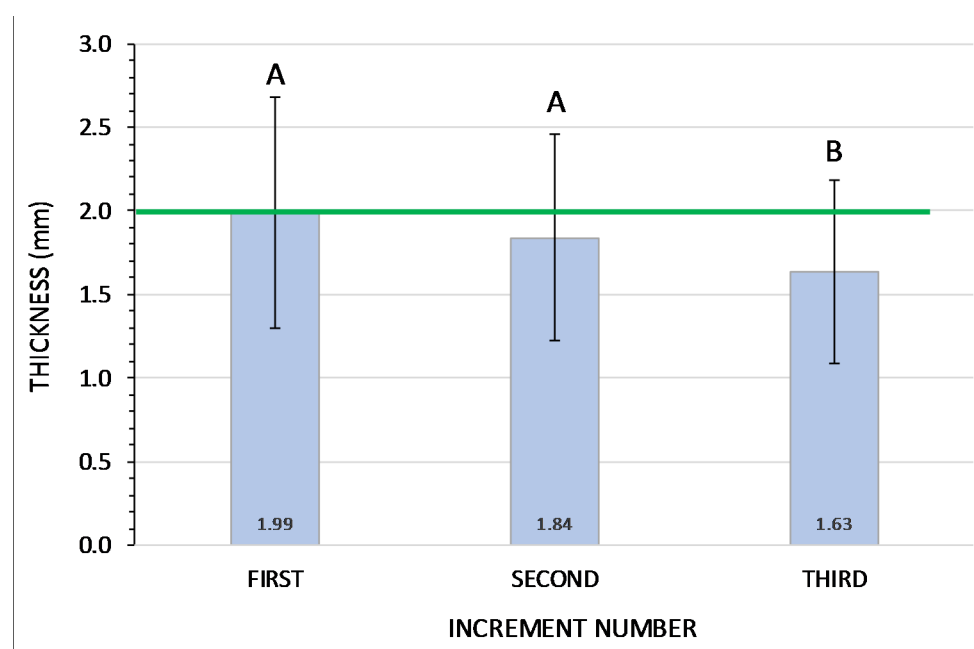


Figure 4. Mean increment thickness among increment placement sequences (disregarding the influence of experience). N = 75 values per group. Vertical bar = ± 1 standard deviation. Thickness layers of groups identified by similar uppercase letters are not significantly different. Horizontal green line represents the 2-mm target value.

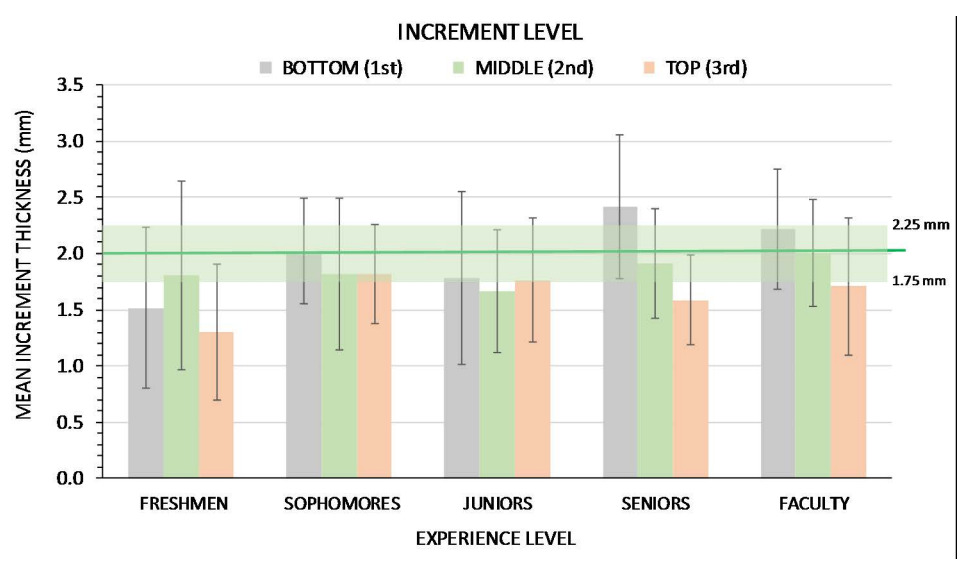


Figure 5. Mean increment thickness with respect to increment sequence number and operator experience level. N = 15 values for each increment. Vertical bar = ± 1 standard deviation.

while the percentage of participants demonstrating increment thickness values within the clinically acceptable range (1.75-2.25 mm) would increase.

The percentage of study participants whose incremental thicknesses were within the three different filling categories as a function of operator experience for the first increment layer is shown in Figure 7. There were no statistically significant differences among the operator experience levels within any of the three filling

categories. Figure 8 depicts the differences in the ability to reach the target range among the operator experience levels for only the second increment. Again, there were no statistically significant differences among the operator experience levels within any of the three filling categories (less, meets, or exceeds). Figure 9 displays the operator’s ability to place the last (top) composite increment within the target range by level of experience. As seen previously, there were no statistically significant

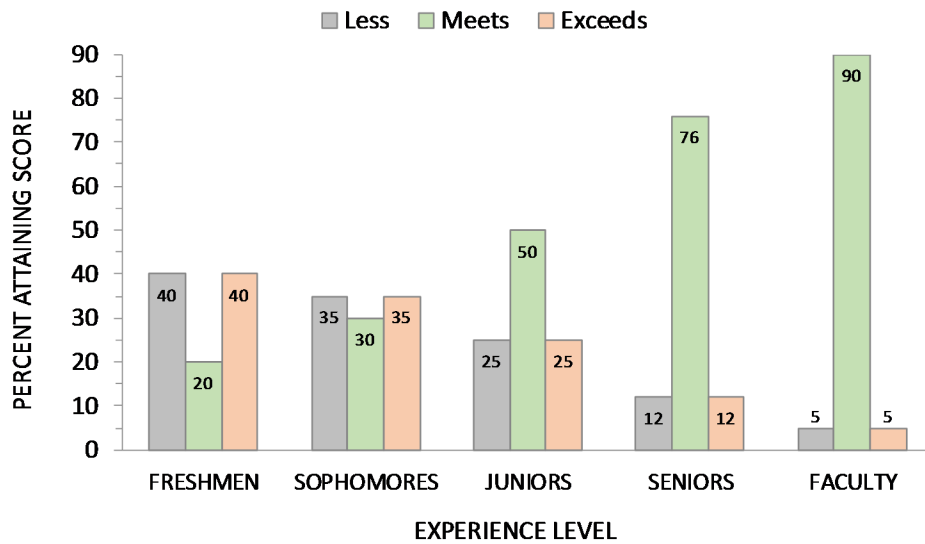


Figure 6. Graph of anticipated trends of over- and underestimating and values falling within the clinically acceptable increment thickness range, as a function of experience level, regardless of increment sequence, had the research hypothesis proven true.

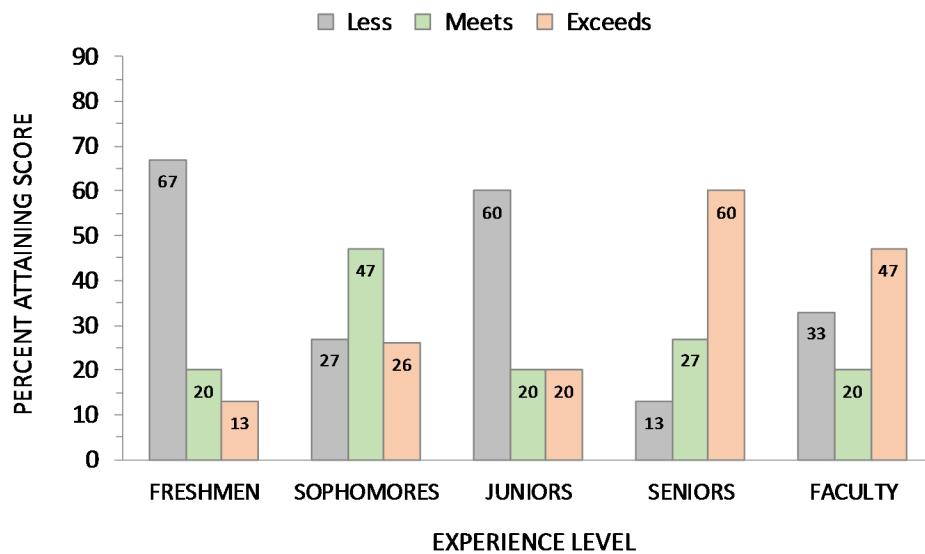


Figure 7. Percentage of each operator experience group able to meet the target increment range value for the first (bottom) increment.

differences among the operator experience levels within any of the three filling categories. However, visually, there appears to be a trend for all experience levels to place increments of RBC that were less than the target range thickness (range from 80% of the least experienced (freshmen) to a low of the sophomore dental students at 40%). Interestingly, in both the senior students and faculty (groups considered as having the most experience), 60% of the participants placed increments of RBC that were less than 1.75 mm thick. Only 20% of

the faculty provided increment thickness falling within the 1.75 to 2.25 mm range, whereas the sophomore and junior students produced acceptable increment thicknesses at twice that rate: 40%. However, none of the differences among the experience level groups were statistically significant.

Because there were no significant differences among the operator experience levels in terms of their ability to place increments of RBC within the desired target range, the operator experience categories were collapsed

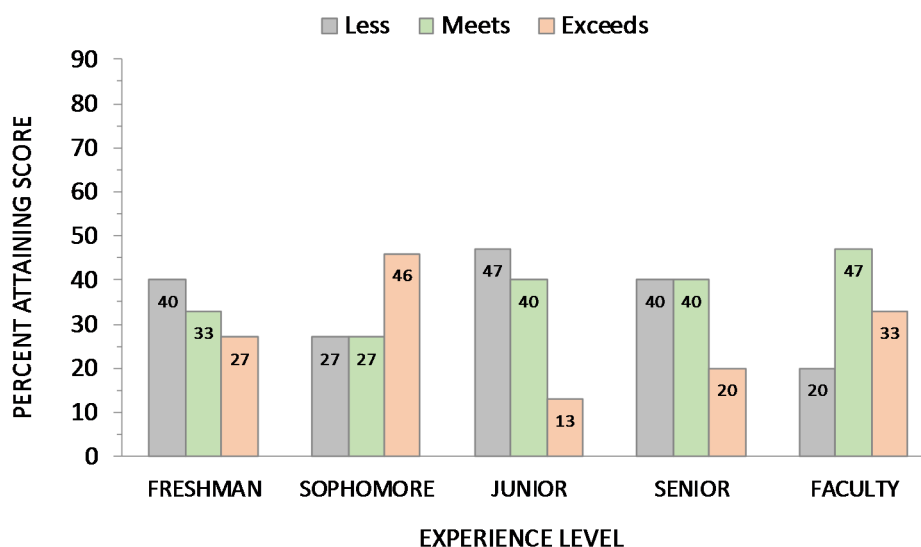


Figure 8. Percentage of each operator experience group able to meet the target increment range value for the second (middle) increment.

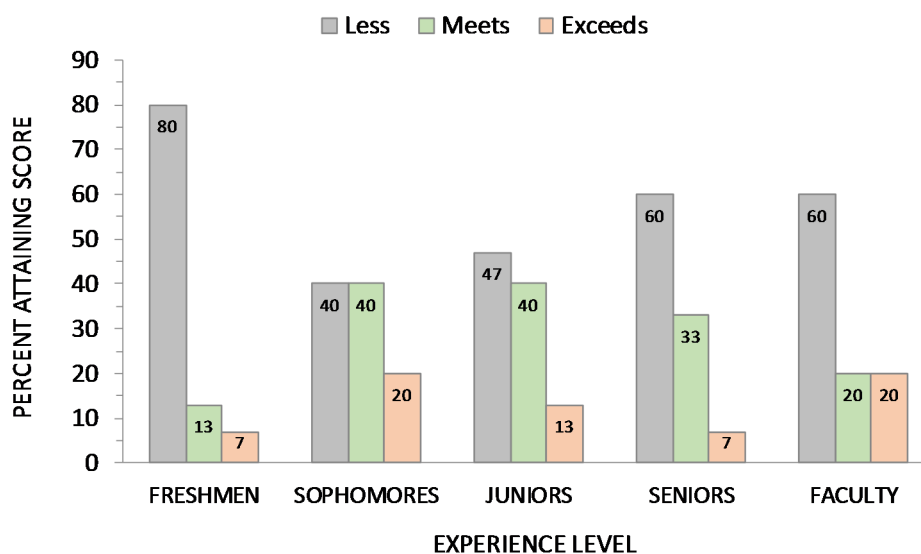


Figure 9. Percentage of each operator experience group able to meet the target increment range value for the last (top) increment.

into one. The data were then evaluated in terms of percentage of all participants placing incremental thicknesses that fell outside of, or within, the desired range. Figure 10 summarizes these data. When this step was performed, the results were almost equally distributed among the three increment categories for the first and second increments.

Removing the effect of discriminating between increments that were less than 1.75 mm or greater than 2.25 mm thick, and only categorizing the ability of operators to reach the desired composite thickness for

each increment or not, provides additional insight into the results. In general, the data indicate that, regardless of the increment, only about one-third of the increments placed fell within the desired range. The percentage of operators providing increment thicknesses falling outside the desired range was significantly greater than the percentage falling within the desired range for both the first and third increments ($p < 0.001$ for both comparisons).

When the data for the increments were pooled, the percentage of participants who either met the

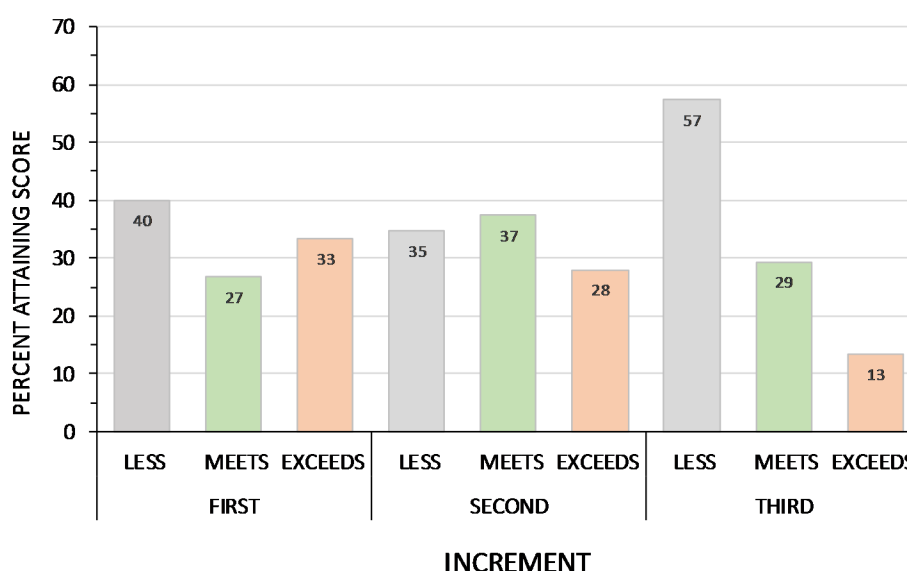


Figure 10. Percentage of operators providing increment thicknesses that were either less than, met, or exceeded the target thickness between 1.75 and 2.25 mm after collapsing the experience level categories. $N = 75$ participants for each increment layer.

incremental thickness range or did not showed that only about 33% of the time was a composite increment placed that ranged between 1.75 and 2.25 mm; furthermore, the percentage of outcomes not meeting the desired thickness was significantly different from the percentage that did ($p < 0.001$). Interestingly, if only the most experienced group (clinical faculty) was analyzed, among all increments, 33% overfilled, 39% underfilled, and only 29% provided increments falling within the desired range. These data, for the highest level of operator knowledge and experience, indicate that 72% did not place increments of RBC to an acceptable thickness, and only 29% were—numbers very much like the overall trend observed when all study participants were pooled together.

DISCUSSION

The first research hypothesis was partially validated. There were no statistically significant differences among the operator experience levels within any of the three filling categories. However, as seen in Figure 5, in general, there was an increasing trend for groups with higher experience levels to place the RBC in mean increment thickness values that were close to 2 mm. Notwithstanding, at all exposure levels and for all increments, there was a large degree of variability in the results. The smallest increment thickness (0.3 mm) was placed as the middle increment by a freshman, and the thickest increment value (3.5 mm) was observed at the bottom increment placed by a junior student. In general, freshmen tended to underfill each increment. Perhaps

this trend reflects the inability of novice American practitioners to judge small differences in metric-unit values. An improved ability to deliver appropriate thickness values was seen in the sophomore and junior students. This increase might be because these students had become more familiar using the metric system to such small values, as well as their enhanced ability to discriminate small visual differences, perhaps arising from their greater experience of placing restorations in dentoforms (sophomores), as well as in clinical patients (juniors). The first increment thickness placed by senior students was commonly the thickest (Figure 5). This increased thickness might result from senior students trying to refine skills and save clinical time during the restoration process. However, this small amount of time saved will likely result in a much less polymerized foundation for the overlying layers of composite yet to be placed. The group showing the least variability in placing a 2-mm increment of RBC was the dental faculty. This result was expected because of their degree of clinical experience, as well as their clinical understanding of the importance of following the manufacturer's instructions and the consequences of not doing so.

The second research hypothesis was rejected, as seen in Figure 4. Even though the thickness of the first RBC layer might have been the most difficult to judge visually, because it was deepest and furthest away from visual examination, its mean thickness value matched the desired 2-mm target value. However, there was a considerable amount of variation in the data. Overall, the thickness of the last (third) increment was

significantly lower than that of the first. This finding might have resulted from participants realizing, with previous increments of unknown thicknesses, a fear of overfilling the restoration, even though no upper limit was ever defined.

With the exception of the sophomores, participants restoring the first increment within the anticipated, acceptable range varied from only 20% to 27%, and there were no statistically significant differences among the experience levels of the participants. The correct thickness of the first increment might be the most important because the RBC at this location is furthest away from the light tip and is more likely to be in a shadow. Proper polymerization of this specific increment is required to provide adequate strength to support all the subsequent overlying increments and to bond to the tooth. If this initial increment is not optimally polymerized, the potential for leaching uncured resin toward the pulpal floor is increased, and the bond strength and flexural strength are lowered. Monomer leaching resulting from undercuring within the deepest restoration layers has significant biological implications.²⁰ Decreased increment flexural strength provides less reliable support for overlying cured composite increments, perhaps allowing them to flex under occlusal load and potentially lead to interfacial debonding over time. This situation might cause postinsertion pain and may result in premature restoration failure. At the top-most increment (Figure 9), the most experienced participants (seniors and faculty) tended to produce a lower percentage of increments that fell within the acceptable range. Still, those values were not significantly different from any other experience group.

In general, it appears that, regardless of experience level, an operator is just as likely to place a composite increment of the desired thickness range (1.75–2.25 mm) than he or she is to over- or underfill that increment (Figure 10). For the first increment of RBC, there was a preponderance of freshmen and juniors who provided less than desirable thickness values, whereas the seniors and faculty produced most of the excess thickness values (Figure 8). For the second increment, the freshmen, juniors, and seniors had the highest percentages of participants generating less than the target range thickness. At the same time, the sophomores and faculty produced the highest amounts of overfilling (Figure 9). At the third increment (Figure 9), all operators tended to show higher levels of underfilling, with 80% of the freshmen falling within this category. Interestingly, as experience levels increased past that of the freshmen, there was a tendency for the top increment to be less than the target range, with senior

and faculty participants producing the same high proportions of underfilling: 60% (Figure 9). However, the third increment showed a definite difference in these trends. There was a much greater incidence of operators placing increments that were less than the desired thickness compared with more than the desired thickness (57% vs 13%; $p < 0.001$). In addition, there were significantly more operators placing increments that were less than the desired thickness range than those who met the desired thickness range (57% vs 29%; $p = 0.009$). The accumulation of the thicknesses of the first two increments appeared to influence the operator to err on the side of underfilling than on overfilling. The last increment also demonstrated the lowest frequency of participants placing an excessively thick RBC layer: 13%.

The clinical implications of the study imply that, regardless of experience level, an operator has only about one chance in three of placing a composite increment within the manufacturer's recommended thickness of 1.75 to 2.25 mm. These findings have profound clinical significance, in that the long-term durability and biocompatibility of a photo-activated resin composite rests on the adequate extent of monomer conversion of each increment placed. For the deepest increments, which are furthest from the light source and provide the foundation for strength for all subsequent increments placed, the variation of increment thickness may have the greatest implications and might demand the closest scrutiny to operator attention. In light of these findings, it may be advisable to place a first increment that is thinner than that recommended by the manufacturer.

This study was subject to several limitations. First, the work was conducted under ideal conditions, where there was full access to the tooth to be restored and a relatively small number of participants in each experience level group ($n = 15$ per group and a total of 75 participants). The 15 participants in the faculty group ranged in experience from less than five to more than 30 years. However, due to the small sample size of dentists ($n = 15$), their ability to provide increments of desired thicknesses was not evaluated with respect to their years of experience. Another limitation was that only a horizontal layering technique was used to fill the cavity. Different results may be achieved using other methods such as nonhorizontal, diagonal types of placement.

Future studies should include placing restorations in a more challenging location, such as a mannequin head attached to a dental chair. Bulk-fill RBCs could be used to evaluate how well participants can estimate the 4- to 5-mm thickness recommended for that class of products. A 3D-printed Class II preparation could also be fabricated to further evaluate increment thickness

accuracy in a larger, more complex preparation. Lastly, future studies could examine the efficacy of using a depth-gauging instrument during composite placement. Such a gauge could be incorporated in the composite delivery system or as a separate instrument.

CONCLUSIONS

Within the limitations imposed, the following conclusions may be reached:

1. There were no statistically significant differences among the operator experience levels within any of the three filling categories. However, in general, there was an increasing trend for groups with higher experience level to provide mean RBC incremental thickness values close to 2 mm thick.
2. In general, regardless of experience level, an operator is just as likely to place an increment of RBC that is within the desired thickness range (1.75-2.25 mm) than he or she is to over- or underfill that increment.
3. In general, regardless of the increment number, only about one-third of the increments placed fell within the desired range of 1.75 to 2.25 mm.

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Regulatory Statement

The project was determined to be a minimal risk project by the Augusta University Internal Review Board (IRB) and was assigned protocol 910480.

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.

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Characterization of Reinforced and Unreinforced Glass-Ceramic Veneers

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Clinical Relevance

Ceramic veneers fabricated using CAD/CAM technology require careful inspection by the dentist before cementation to assess surface smoothness and integrity, as those can affect the esthetics and lifetime of the restoration. Polishing is an effective technique to reduce the surface roughness of zirconia-reinforced lithium silicate and feldspathic ceramics. The presence of residual stress in these ceramics also plays an essential role in predicting their performance over time, as high residual stresses have a negative effect.

SUMMARY

This study aimed to characterize the surface topography, effect of polishing on surface roughness, residual stresses, and hardness in two glass-ceramic veneers. Fifty-two (52) upper incisors were collected, prepared, and scanned for ceramic veneers. Half of

the teeth were restored with veneers made up of feldspathic ceramic (FE), and the other half with zirconia-reinforced lithium silicate ceramic (SZ). All the veneers were designed and milled using a CAD/CAM system and later cemented following the manufacturer's guideline. An optical microscope analyzed the topography of the specimens before and after polishing. The surface roughness was measured using the roughness meter ($n=12$) and the topographical analysis was carried out using an atomic force microscope ($n=6$). The residual stresses and Vickers' hardness were evaluated by the indentation method in a micro-hardness indenter ($n=6$). The surface roughness was analyzed using a three-way analysis of variance (ANOVA) followed by a *post hoc* Tukey test. The Student *t*-test was used to compare the residual stresses and hardness between the two ceramics. The topographical analysis revealed that both glass-ceramic veneers had similar percentages of specimens with cracks, before (34.6%) and after (42.3%) polishing. The surface roughness decreased after polishing ($p<0.001$),

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and the polishing smoothed out the surface of the veneers. The zirconia-reinforced lithium silicate veneer had a lower roughness as compared to the feldspathic one after polishing, while the residual stresses ($p=0.722$) and hardness ($p=0.782$) were statistically similar for both ceramic veneers.

INTRODUCTION

Veneering restorations made of ceramics exhibit chemical stability, biocompatibility, high compressive strength, color stability, and a smooth surface, along with a close appearance to the natural tooth.¹ Ceramic veneers as thin as 0.3 to 0.5 mm have been reported to be clinically successful.²

The feldspathic ceramic (FE) is composed of an amorphous glassy matrix and an irregularly shaped crystalline phase, where leucite stands out (17% to 25%). Although this type of ceramic has excellent optical properties, the large amount of amorphous matrix needed results in lower mechanical properties than glass-ceramics with higher crystalline content.³ The increase of crystalline content within the glass matrix in the microstructure of ceramics yields a significant increase in their mechanical properties. A new ceramic was conceived when zirconium dioxide (approximately 10% by weight) was added to lithium silicate glass, zirconia-reinforced lithium silicate (SZ) ceramic, commercially available as Vita Suprinity (Vita Zahnfabrik, Bad Säckingen, Germany). The zirconia fillers act against crack propagation and provide higher fracture resistance and flexural strength to the ceramic material.^{4,5}

These dental ceramics are available in blocks that can be processed by computer-aided design and computer-aided manufacturing (CAD/CAM) technology.^{6,7} These blocks exhibit a more homogeneous composition with fewer internal defects.^{8,9} However, the literature claims that the abrasive diamond burs used for the milling process can incorporate superficial defects or cracks in the ceramic,^{10,11} and also can roughen the surface that will later require polishing.¹² On rough surfaces, there is a higher risk of biofilm accumulation and development of cracks, in addition to being abrasive and causing more considerable wear of the antagonist.¹³ A smooth ceramic surface is important for patient comfort, esthetics, and biological aspects. Therefore, the finishing and polishing of ceramics are essential steps and can be accomplished using abrasive rubber tips or by the application of glaze, or even by a combination of these two techniques.¹⁴

This study aims to characterize the surface topography, effect of polishing on surface roughness, residual stresses, and hardness of FE and SZ ceramic

veneers. The following hypotheses were tested: 1) the topographic evaluation will identify the presence of surface defects; 2) the polishing will decrease the surface roughness of ceramic veneers; and 3) FE and SZ ceramic veneers will have similar residual stresses and hardness after milling.

METHODS AND MATERIALS

Specimen Preparation

Fifty-two (52) human upper central incisors were collected following ethics committee approval. The teeth were cleaned following the protocol proposed by the tooth bank of the University of Western São Paulo - UNOESTE and stored in deionized water for a maximum of six months.

The teeth were divided into two experimental groups ($n=26$), according to the ceramic materials used to fabricate the veneering restoration, as follows: Group FE - feldspathic ceramic (Vita Mark II, Vita Zahnfabrik); Group SZ - zirconia-reinforced lithium silicate ceramic (Vita Suprinity, Vita Zahnfabrik). For randomization, Research Randomizer software (Version 4.0, <https://www.randomizer.org>) was used, defining the distribution of the specimens.

Before preparation of the teeth, a silicone mold (Scan Putty, Yllor Biomaterials SA, Pelotas, Brazil) of each tooth was taken and used as a guide to control thickness (0.5 mm).

The teeth were prepared by a single trained operator, with diamond burs 4138 F and 4138 FF (KG Sorensen, Barueri, SP, Brazil), following the dimensions and shapes of the conventional preparation for ceramic veneers,¹⁵ preserving the proximal contacts and covering the incisal edge without creating a palatal chamfer. Each set of burs was used to make three preparations.

All teeth were scanned with the InEos Blue optical scanner system (Cerec - Sirona Dental Systems, Bensheim, Germany). The veneer design was standardized to 11 mm height and 0.5-mm thickness using the InLab SW4 software (Cerec - Sirona Dental Systems). The prototypes were transferred to the InLab MC XL milling machine (Cerec - Sirona Dental Systems) to mill 26 veneers in SZ and the other 26 veneers in FE.

The crystallization cycle for SZ was performed in the Vita Vacumat 6000MP (Vita Zahnfabrik) furnace according to the manufacturer's recommendation. All laminates received a layer of VITA AKZENT Plus glaze spray (Vita Zahnfabrik), and were taken to the Vita Vacumat 6000 MP furnace (Vita Zahnfabrik) for firing using the program recommended by the manufacturer.

For cementation, each tooth was conditioned with 37% phosphoric acid (Cond AC 37%, FGM, Joinville, SC, Brazil) for 30 seconds, rinsed (30 seconds), and dried (20 seconds). Then, two layers of the universal adhesive system (Single Bond Universal, 3M Oral Care, St Paul, MN, USA) were applied for five seconds on the surfaces, followed by drying using an air jet for five seconds at a distance of 15 cm. The adhesive was not light-cured.^{16,17}

The cementation surface of both the FE and SZ veneers was etched with 10% hydrofluoric acid (HF, Cond AC Porcelana, FGM) for 60 seconds and 20 seconds, respectively, rinsed (30 seconds), and dried (30 seconds). The ceramic veneers were cleaned in an ultrasonic bath with deionized water for 1 minute and dried. A silane bonding agent (RelyX Ceramic Primer, 3M Oral Care) was applied and allowed to react for one minute.

The veneers were cemented onto the corresponding teeth using the resin cement RelyX Veneer (3M Oral Care). Initial light-curing (3 seconds) was performed to remove the excess resin cement followed by light curing (Bluephase N, Ivoclar Vivadent, Schaan, Liechtenstein) of the buccal, incisal, and lingual free surfaces of the tooth for 20 seconds at a light intensity of 1.2 mW/cm². The restored teeth were then stored in deionized water for two weeks.

Inspection and Determination of Veneer Surface Roughness

All specimens were observed under an optical microscope (VHX-1000, Keyence, Itasca, IL, USA) to check for cracks and irregularities. Any cracks found were recorded for later comparison.

A replica of each specimen was created for analyzing the surface roughness and topography.^{18,19} The replicas of the three thirds (cervical, middle, and incisal) of each veneer were used instead of the real samples to easily accommodate them under the analytical instruments. For this, a mold was prepared using a polyvinylsiloxane impression material (Extrude, Kerr Corporation, Orange, CA, USA) and filled out with epoxy resin (EpoxySet, Allied High Tech Products Inc, Rancho Dominguez, CA, USA). After the epoxy hardened, the replicas were removed from the mold and analyzed using the optical microscope to ensure that they were free of bubbles and artifacts.

The surface roughness was determined using a roughnessmeter (Hommel-Etamic W10, Schwenningen, Germany) on 12 replicas with no cracks from each group. The device was calibrated with a measurement filter of 0.25 mm (cut-off), 0.1 mm/s (speed), and a reading length of 1.25 mm. The surface roughness in

three regions (cervical, middle, and incisal) of the epoxy replica of the ceramic veneer was measured. The same replicas were used for topographical analysis using the atomic force microscope (AFM, Bioscope Catalyst, Bruker, Santa Barbara, CA, USA).

The topographical analysis of those three regions was performed using an AFM (Bioscope Catalyst) on six replicas of each group. The AFM has a limitation in the z range that does not allow placing a sample higher than 3 mm under the probe, which is why a replica of the specific region of interest was used. Studies have shown that there is no difference between the data obtained from a replica and the actual sample.^{18,19} The AFM was used in Peak Force Tapping mode with a Scan-Asyst Air probe (Bruker, Santa Barbara, CA, USA), at a resolution of 512 x 512 pixels. A single region of 50 µm x 50 µm was scanned at a scan rate of 1 Hz. The scanning rate was optimized to the highest value such that the trace and retrace height curve were tracking each other. After leveling, a 3D image of the surface was generated using the Gwyddion software - Version 2.47 (Czech Metrology Institute, Brno, Czech Republic).

Polishing

The specimens were then manually polished with the Vita Suprinity Polishing Set clinical kit (Vita Zahnfabrik). The rubber polishing tips were used in decreasing abrasive order. The preliminary polishing was carried out using the pink diamond rubbers, followed by the gray tips for the high gloss polishing. Each tip was used for 30 seconds, totaling 60 seconds,²⁰ and the procedures were performed using light hand pressure by only one operator (previously trained) using a handpiece that operated at a speed of 20,000 rpm. After polishing, all specimens were inspected and the surface roughness was calculated as mentioned above.

Residual Stresses and Vickers Hardness

Residual stresses were calculated using the microhardness indenter (Clark CM - 400AT, - SunTec Corporation, Novi, MI, USA). After polishing, 12 specimens from each group were selected, six with cracks (found during the inspection with an optical microscope) and the other six without cracks. The buccal surface of the ceramic veneer was indented using a Vickers' diamond with a load of 0.3 kgf for 5 seconds. For the specimens with cracks, the indentations were performed 50 µm away from the crack.

The length of the diagonals of the indentation was measured, and the residual stresses were calculated using equation 1^{21, 22}:

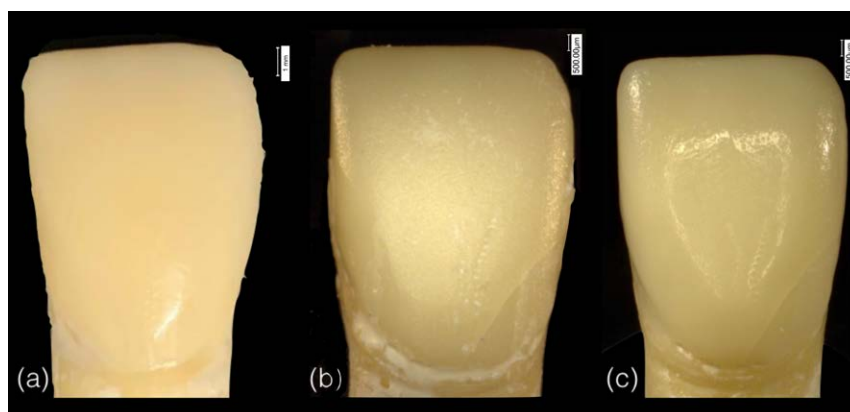


Figure 1. Suprinity ceramic veneers observed using (A) a digital camera before polishing; (B) an optical microscope before polishing; and (C) an optical microscope after polishing.

$$\sigma_R = K_{Ic} \left[\frac{1 - (c_0/c_1)^{3/2}}{\psi c_1^{1/2}} \right], \quad (1)$$

where K_{Ic} is the fracture toughness, c_0 and c_1 are the indentation crack lengths in unstressed (uncracked) and stressed (cracked) materials, respectively, and ψ is a crack geometry factor ($\psi = 1.24$).

The hardness of the ceramics was calculated using equation 2:

$$HV = 1.8544 \left(\frac{F}{d^2} \right), \quad (2)$$

where HV is the Vickers' hardness (kgf/mm²), F is the indentation force (kgf), and d is the mean diagonal of the indentation (mm).

Statistical Analysis

The normal distribution was tested using the Shapiro-Wilk test. The surface roughness was analyzed using a three-way analysis of variance (ANOVA), and a *post hoc*

Tukey test was performed to determine the differences between the groups. The Student *t*-test was used to determine significant differences between FE and SZ ceramic veneers in terms of residual stresses and hardness. A significance level of 5% was used for all the statistical tests.

RESULTS

Inspection of Veneers Before and After Polishing

No cracks or irregularities were observed in the specimens during visual inspection (Figure 1A). However, cracks were observed in 34.6% of the specimens in each group under the optical microscope (Figure 1B, C). Detailed information on the cracks is shown in Table 1.

After polishing, the percentage of specimens with cracks in each group increased to 42.3%. Polishing increased the number of cracks for each material by 7.7% (Table 2).

In most of the specimens, more than one crack was observed (Figure 2A). Initially, excess cement was

Table 1: Specimens with Cracks Discovered Pre-polishing (Number and Percentage)						
Region						
Material	Buccal Face N (%)			Lingual Face n (%)	Distal/Mesial Face n (%)	Total n (%)
	Cervical	Middle	Incisal	Incisal	Cervical	
FE	4 (15.3)	4 (15.3)	1 (3.8)	0	0	9 (34.6)
SZ	4 (15.3)	2 (7.6)	1 (3.8)	1 (3.8)	1 (3.8)	9 (34.6)

Abbreviations: FE, feldspathic ceramic; SZ, zirconia-reinforced lithium silicate ceramic.

Table 2: Specimens with Cracks Discovered Post-polishing (Number and Percentage)

Material	Region					Total n (%)
	Buccal Face n (%)			Lingual Face n (%)	Distal/Mesial Face n (%)	
	Cervical	Middle	Incisal	Incisal	Cervical	
FE	4 (15.3)	4 (15.3)	2 (7.6)	0	1 (3.8)	11 (42.3)
SZ	6 (23.0)	2 (7.6)	1 (3.8)	1 (3.8)	1 (3.8)	11 (42.3)

Abbreviations: FE, feldspathic ceramic; SZ, zirconia-reinforced lithium silicate ceramic.

observed in the margins of the veneers, but it was removed during polishing (Figure 2B, C).

Surface Roughness

The surface roughness (Ra) of the specimens was reduced significantly after polishing ($p < 0.001$). There were no differences in roughness between the cervical, middle, or incisal regions of the restoration. As shown in Table 3, the SZ ceramic showed lower Ra after polishing compared to FE ($p=0.011$).

For both ceramics, the AFM analysis showed sharp asperities and a significant increase in the surface roughness of un-polished specimens as compared to the ones that were polished, regardless of the region that was scanned (Figures 3 and 4).

Residual Stresses and Vickers Hardness

There was no significant difference in residual stresses ($p=0.782$), and hardness ($p=0.722$) between the two ceramics (Table 4).

DISCUSSION

Cracks were observed in both of the ceramic materials after using an optical microscope. The milling process may have resulted in the formation of these cracks. Some of the energy involved in the milling process is released in the form of heat, resulting in an increase in temperature at the cutting site. This high temperature and the cooling generated by irrigation create a thermal exchange that may contribute to the generation of residual stresses and cause surface damage.^{10,11,13,14}

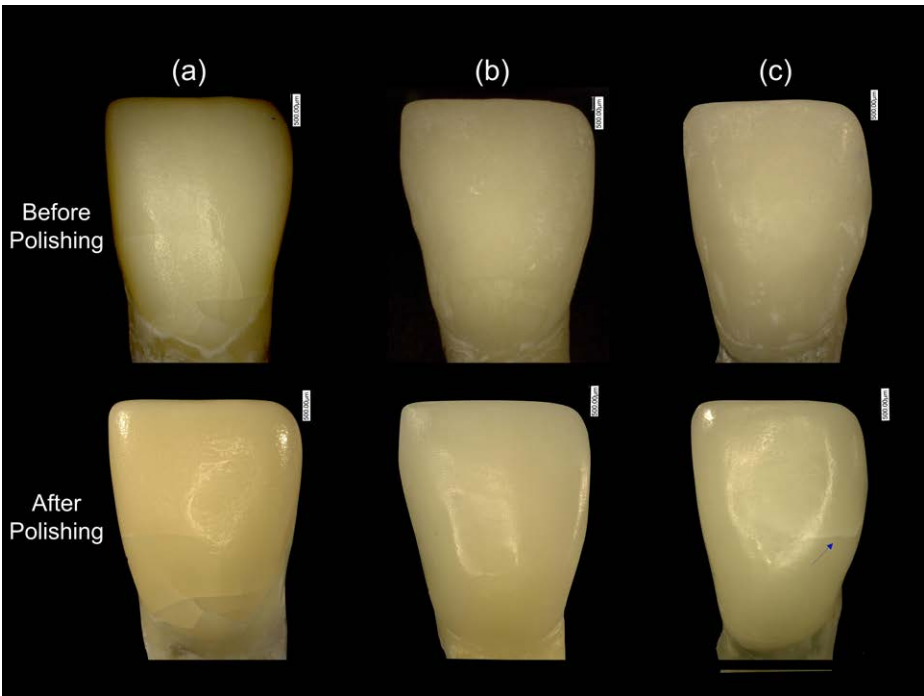


Figure 2. Buccal aspect of the specimens, before (top figures) and after polishing (bottom figures). (A) Multiple cracks in the cervical region; (B) Excess cement observed in the margins before polishing; (C) New cracks observed after polishing (blue arrow).

Table 3: Surface Roughness (μm) of FE and SZ Ceramic Veneers Before and After Polishing ^a		
Polishing	Ceramic	
	FE	SZ
Before	1.33 ± 0.01 Aa	1.23 ± 0.01 Aa
After	0.56 ± 0.01 Ba	0.38 ± 0.01 Bb

Abbreviations: FE, feldspathic ceramic; SZ, zirconia-reinforced lithium silicate ceramic.
^aDifferent upper case letters in the same column indicate statistical difference within the same column, and different lower case letters in the same row indicate statistical difference among different ceramics.

These cracks are difficult to visualize and can be missed by the dentist. Indeed, the cracks found on the specimens were not noticeable with visual inspection and could only be seen under an optical microscope on a 500-μm scale, using transillumination. Such surface damage could have been observed with the use of medium or high magnification dental microscopes (8x to 30x)²³; however, they are not commonly used in most dental offices due to their high cost.²⁴ A handy option to visualize the

cracks would be the use of dental loupes that, according to their classification in Galilean and Keplerian loupes (prismatic), have a magnification ranging from 2.5x to 6x.²⁵ The use of white light for transillumination is also recommended for this inspection since cracks and subsurface flaws redirect the light and form a dark shadow, making them more evident to the naked eye.²⁶ In the present study, the location of several cracks seemed to be related to the location of the sprue on

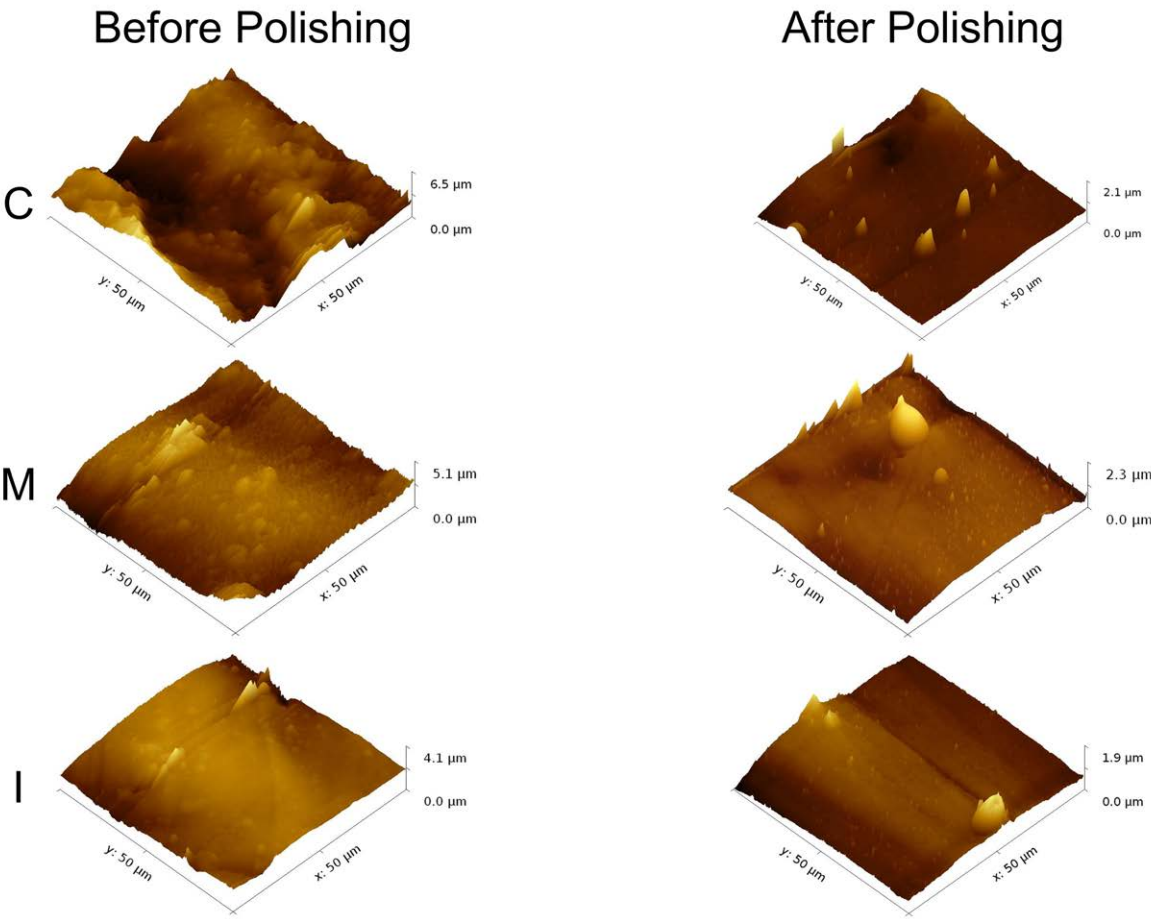


Figure 3. A 3D image of feldspathic ceramic before and after polishing. The letters indicate the regions that were scanned, where C: cervical; M: middle; and I: incisal.

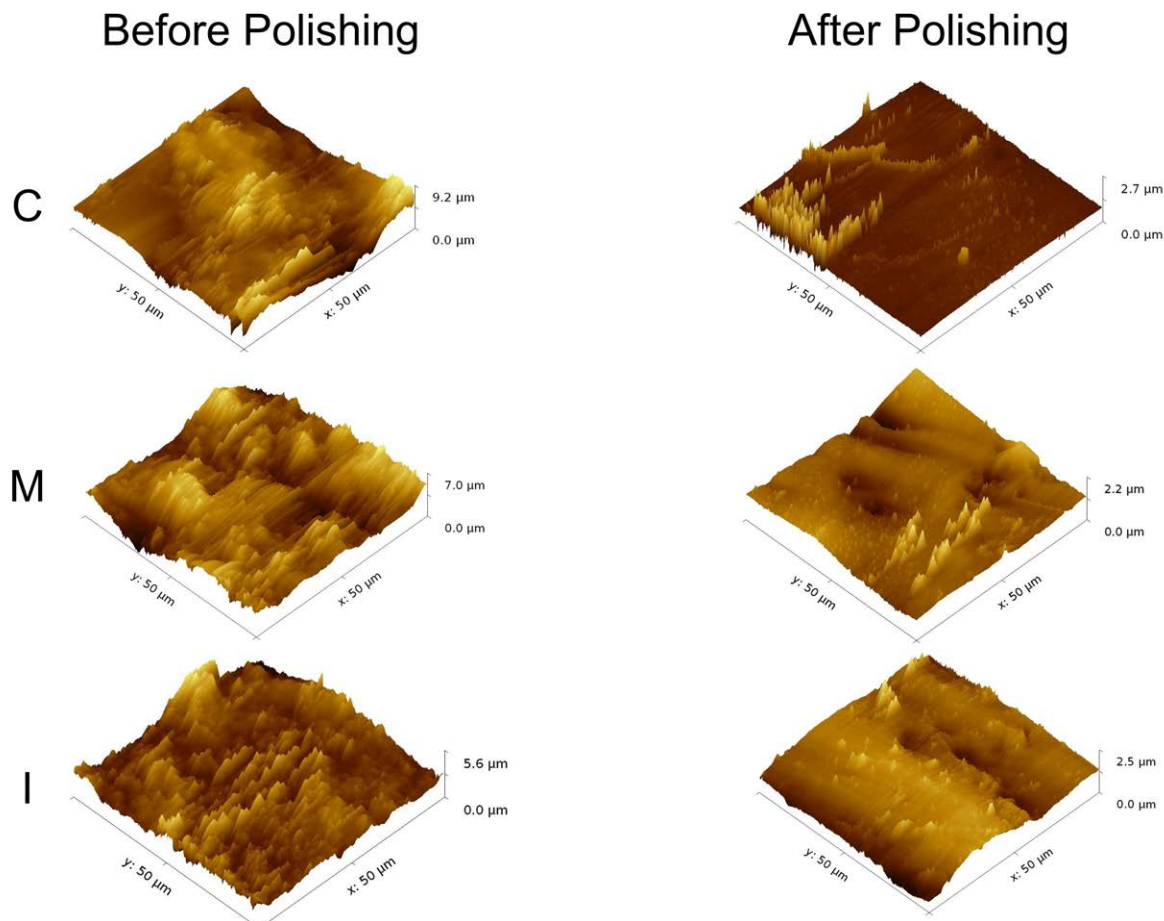


Figure 4. A 3D image of the zirconia-reinforced lithium silicate ceramic before and after polishing. The letters indicate the regions that were scanned, where C: cervical; M: middle; and I: incisal.

the veneer surface left after the milling process. The hypothesis that the topographic evaluation will identify the presence of surface defects was accepted.

The diamond burs used during the milling can result in rougher surfaces that may require finishing and polishing. In the pre-polishing analysis, a rough surface was seen on both of the ceramics, as also observed by Mota and others,¹² who reported a higher Ra value before polishing in all the evaluated ceramics. The hypothesis that the polishing would reduce the roughness of

ceramics was accepted because all specimens showed lower Ra after polishing. The SZ ceramics had a lower roughness compared to FE when polished. This may be due to the smaller crystal size and higher zirconium dioxide content of the SZ ceramic.²⁷ The polishing set used may have caused more considerable wear and tear on the vitreous structure of the FE ceramic, generating a more irregular surface compared to SZ.

The Vickers' indentation method can be used to estimate residual stresses and hardness in brittle materials.^{21,22}

Table 4: Mean and Standard Deviation (SD) of Residual Stresses and Vickers' Hardness^a

Group	Residual Stresses		Vickers' Hardness (kgf/mm ²)	
	Mean	SD	Mean	SD
FE	25.49 a	7.98	670.26 A	47.16
SZ	23.31 a	17.03	649.89 A	128.13

Abbreviations: FE, feldspathic ceramic; SZ, zirconia-reinforced lithium silicate ceramic

^aThe same case letters within the same column indicate no statistical difference between the FE or SZ groups.

For ceramic materials without residual stresses, a well-defined symmetrical indentation and cracks of similar lengths (c_0) emanating from the four corners of the indent without crack branching are observed.^{21,22} However, in specimens with cracks, residual stresses contributed to the formation of radial cracks after indentation.²¹ The FE and SZ ceramics showed similar values of residual stresses. In SZ, the pre-existing cracks may have promoted a transformation zone of the zirconia crystals²⁸; however, the volume fraction of transformation may have been non-uniform within the zone, leading to the development and propagation of new cracks²⁹ and the extrusion of grains.²⁸ This may have caused degradation of the material strength to a level comparable to that of FE ceramics. For residual stresses, the hypothesis of similarity between FE and SZ ceramics was accepted.

Surface hardness is defined as the material's ability to resist indentation and is generally associated with the material's stiffness. It was expected that both materials, FE and SZ, would show similar hardness values since both of them belong to the glass-ceramics family and were produced and polished using the same protocol. In 2015 Lebon and others³⁰ reported that the greater the hardness of the ceramic, the greater the surface roughness. The average hardness values for FE obtained by Sen and Us³ in 2018 (658.69 ± 69 kgf/mm²) were close to those found in the present study (670.26 ± 47.1 kgf/mm²). For SZ, the result obtained in this study (649.89 ± 128.13 kgf/mm²) is similar to the one determined by Elsaka and Elnaghy⁴ in 2016 (665.8 ± 46.9 kgf/mm²) and reported by the manufacturer (713.8 kgf/mm²). Hardness measurement provides information about the abrasiveness of materials when they interact with natural dentition, which is important when choosing dental materials.

This study was limited by the presence of cracks in the specimens, which decreased the sample size for some of the tests but warned of the need for a careful inspection of the veneers. These cracks may have been introduced by milling or cementation since inspection under an optical microscope was carried out after the veneers were cemented. In this regard, future studies should be conducted in order to identify other potential factors responsible for the formation of cracks observed in both the materials, as well as to determine the influence of the cracks on the ultimate strength of the veneer-tooth set.

CONCLUSION

Subsurface cracks were observed in both glass-ceramic veneers made of feldspathic and zirconia-reinforced lithium silicate ceramics. The polishing decreased the

surface roughness of the veneers. Zirconia-reinforced lithium silicate veneers had the lowest roughness after polishing. The residual stresses and hardness values were similar between the two ceramics studied.

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Regulatory Statement

This study was conducted in accordance with all provisions of the human subjects oversight committee guidelines and policies of the Unioeste Research Ethics Committee. The approval code issued for this study is CAAE number 79435217.1.0000.5515.

Conflict of Interest

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

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Errata

Operative Dentistry apologizes for the errors in the following manuscripts.

IF Leão, N Araújo, CK Scotti, RFL Mondelli, MM de Amoêdo Campos Velo, JFS Bombonatti; The Potential of a Bioactive, Pre-reacted, Glass-Ionomer Filler Resin Composite to Inhibit the Demineralization of Enamel *in Vitro*. *Oper Dent* 1 January 2021 46 (1): E11-E20. doi: <https://doi.org/10.2341/19-151-L>

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DM De Paula, AD Loguercio, A Reis, S Sauro, AH Alves, PR Picanço, K Yoshihara, VP Feitosa; Lack of Neutralization of 10-MDP Primers by Zirconia May Affect the Degree of Conversion of Dual-cure Resin Cement. *Oper Dent* 1 January 2021 46 (1) 107-115. doi: <https://doi.org/10.2341/18-189-L>

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There are errors in the corresponding author information and in paragraph 1 under Treatment Planning and Tooth Preparation in the Methods and Materials section (p6), and in the legend for Figure 10 (p11). They should read (corrections are underlined):

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Digital smile design was performed using Apple's Keynote Software to obtain veneer proportions and to enable communication and increase predictability. Standardized extraoral photographs were taken with a Nikon D5300 digital reflex camera using the following parameters: manual mode 1/125, f22, and ISO 125, coupled with Sigma Macro 105mm DX lens; twin manual 1/1 flash (Nikon R1C1 Wireless Close-UP Speedlight System) equipped with Watson CR123A Rechargeable Lithium Battery (3V, 400mAh); and a flash holder (Agnòs, Italy). The analysis of the face thirds was made according to the participant's smile. Initial impressions were taken using a heavy and light condensation silicone (Xantopren/Optosil, Heraeus Kulzer, Germany) onestep technique. The study casts were obtained, and the wax-up was performed according to digital planning.

Figure 10. *Means and standard deviation of the manufacturing process at the study periods (baseline, 6 months, and 12 months of follow-up) for the topics marginal adaptation (MARA), marginal discoloration (MARD), restoration fracture (RESF), and postoperative sensitivity (POSTS).*

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Flexural Properties and Polished Surface Characteristics of a Structural Colored Resin Composite

K Mizutani • T Takamizawa • R Ishii • S Shibasaki • H Kurokawa • M Suzuki • A Tsujimoto • M Miyazaki

Polishing the structural colored resin composite Omnicroma with an aluminum oxide flexible disk after finishing with a tungsten carbide bur significantly improved its surface properties when compared with the other methods.

<http://doi.org/10.2341/20-154-L>

Post-Space Treatment Influences the Bond Strength In Endodontically Treated Teeth: A Systematic Review and Meta-Analysis of *In Vitro* Studies

TC Bohrer • PE Fontana • RO Rocha • OB Kaizer

Several factors can influence the retention of posts to root canal dentin. Post-space treatment is one of these factors, which can improve the bond strength of the post to dentin.

<http://doi.org/10.2341/19-277-LIT>

Intrapulpal Concentration of Hydrogen Peroxide of Teeth Restored With Bulk Fill and Conventional Bioactive Composites

DP Silva • BA Resende • M Kury • CB André • CPM Tabchoury • M Giannini • V Cavalli

Using a 35% hydrogen peroxide bleaching agent in-office increases the concentration and diffusion of hydrogen peroxide into the pulp chamber compared to a low-concentration (9.5%) hydrogen peroxide gel.

<http://doi.org/10.2341/20-091-L>

Flexural Properties and Polished Surface Characteristics of a Structural Colored Resin Composite

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H Kurokawa • M Suzuki • A Tsujimoto • M Miyazaki

Clinical Relevance

Polishing the structural colored resin composite Omnicroma with an aluminum oxide flexible disk after finishing with a tungsten carbide bur significantly improved its surface properties when compared with the other methods.

SUMMARY

Objective: The aim of this study was to determine the flexural properties and surface characteristics of a structural colored resin composite after different finishing and polishing methods, in comparison to those of conventional resin composites.

Methods and Materials: A structural color resin composite, Omnicroma (OM, Tokuyama Corp, Chiyoda City, Tokyo, Japan), and two comparison resin composites, Filtek Supreme Ultra (FS, 3M, St Paul, MN, USA) and Tetric EvoCeram

(TE, Ivoclar Vivadent, Schaan, Liechtenstein), were used. The flexural properties of the resin composites were determined in accordance with the ISO 4049 specifications. For surface properties, 70 polymerized specimens of each resin composite were prepared and divided into seven groups of 10. Surface roughness (Sa), gloss (GU), and surface free energy (SFE) were investigated after the following finishing and polishing methods. Three groups of specimens were finished with a superfine-grit diamond bur (SFD), and three with a tungsten carbide bur (TCB). After finishing, one

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of the two remaining groups was polished with a one-step silicone point (CMP), and the other with an aluminum oxide flexible disk (SSD). A group ground with SiC 320-grit was set as a baseline.

Results: The average flexural strength ranged from 116.6 to 142.3 MPa in the following order with significant differences between each value: FS > TE > OM. The average E ranged from 6.8 to 13.2 GPa in the following order with significant differences between each value: FS > TE > OM. The average R ranged from 0.77 to 1.01 MJ/mm³ in the following order: OM > FS > TE. The Sa values of the OM groups polished with CMP and SSD were found to be significantly lower than those of the other resin composites, regardless of the finishing method. The GU values appeared to be dependent on the material and the finishing method used. The OM specimens polished with SSD showed significantly higher GU values than those polished with CMP. Most of the resin composites polished with SSD demonstrated significantly higher γ S values compared to the other groups. Extremely strong negative correlations between Sa and GU in the combined data from the three resin composites and each resin composite and between Sa and γ S in the OM specimens were observed; GU showed a strong positive correlation with γ S in the same material.

Conclusion: These findings indicate that both flexural and surface properties are material dependent. Furthermore, the different finishing and polishing methods used in this study were observed to affect the Sa, GU, and SFE of the resin composites.

INTRODUCTION

In order to achieve esthetic dental restorations, the color matching ability of resin composites used to restore teeth is considered to be of utmost importance. However, in some instances, it is difficult to color match the restoration to the tooth as the latter's color depends on the location and the optical properties of the tooth substrate.¹ In order to mimic the color of the restored tooth, different shades of resin composites are mixed using the layering technique.^{2,3} This technique consists of several filling steps, which require a certain amount of clinical skill to obtain the desired color.⁴

It is important to take into account both the esthetic and mechanical properties of the resin composite restoration and its durability in the oral environment.⁵⁻⁷ The mechanical properties of a resin composite are

closely related to its fracture resistance and wear behavior.^{8,9} Changes in the surface properties of a restoration lead to staining, plaque accumulation, restoration degradation, and gingival inflammation.^{10,11} Therefore, to obtain the desired esthetics and at the same time ensure its longevity, the polishing ability of the resin composite should be determined. Ishii et al.¹² have examined the surface properties of resin composites and reported that the surface free energy (SFE) might reflect some of the important characteristics of the material, as with surface topography evaluation.

Structural color is thought to be a chromogenic phenomenon in which the visible color is derived from the structural features of the substance at a scale comparable to or smaller than the wavelength of visible light.¹³ In contrast to colorants such as pigments or dyes, substances that produce structural color do not have a color of their own, but they can display visible colors owing to light interferences generated by their ultrastructure.¹⁴ These materials can be classified into two categories, iridescent and non-iridescent, in accordance with their optical properties. The iridescent color arises from photonic crystals, which have periodic structures with regular lengths of the order of the wavelength of visible light.¹⁵ On the other hand, non-iridescent materials have angle-independent characteristics wherein the color impression is the same for different illuminations and observation angles.¹⁶

A new type of resin composite has been developed based on the structural color concept and the bottom-up nanotechnology used in making unique filler particles.¹⁷ These fillers are in the form of spherical particles, having an average diameter of 260 nm, which produce the yellow to red color shades required to match the natural tooth color.^{17,18} The refractive index of the uniformly sized spherical filler exceeds that of the resin matrix, leading to the expression of a stronger structural color due to the scattering of the incident light.¹⁹ Using the structural colored resin composite has been seen to simplify the shade matching process and render it more cost-effective as it only requires a single universal shade to be used. Saegusa and others,¹⁷ who evaluated the color-matching ability of the structural colored resin composite and compared it with conventional ones using artificial teeth, have confirmed the excellent color-matching ability of the structural colored material. In addition, they suggested that these might have the potential to fix any color mismatch caused by using conventional materials. However, little information is available about the mechanical and surface properties of this structurally colored resin composite. As the color of the composite is achieved through modification of the filler structure, there is a

possibility that these properties will differ from those of conventional resin composites, and the properties of these composites must be taken into account in clinical usage. Therefore, it is important to measure them.

This study aims to determine the mechanical properties of the structural colored resin composite based on a flexural strength test, which should help to understand the effects of different finishing and polishing procedures on the surface properties of this material. The surface properties were then examined in terms of surface free energy (SFE), surface roughness, and gloss measurements; morphological assessments were made via scanning electron microscopy (SEM). The null hypotheses were as follows: 1) the flexural properties of the structural colored resin composite would not differ from those of conventional resin composites, and 2) the surface properties of the structural colored resin composite would not be affected by the finishing and polishing methods and would not differ from those of the conventional resin composites.

METHODS AND MATERIALS

Study Materials

The structural colored resin composite, Omnichroma (OM, Tokuyama Dental, Tokyo, Japan), and two other conventional resin composites, Filtek Supreme Ultra (FS, 3M Oral Care, St. Paul, MN, USA) as a nanofilled resin composite and Tetric EvoCeram (TE, Ivoclar Vivadent, Schaan, Lichtenstein) as a nanohybrid resin composite, were used in this study (Table 1). A halogen-quartz-tungsten curing unit (Optilux 501; SDS Kerr, Danbury, CT, USA) was used to avoid any effects of the reported non-uniformity of light-emitting diode curing units.²⁰ The light irradiance (above 600 mW/cm²) of the curing unit was confirmed using a dental radiometer (Model 100; SDS Kerr).

Flexural Strength Test

The flexural properties of the tested resin composites were examined as per the ISO 4049 specifications.²¹ A transparent polymer matrix tape (Matrix tape and Dispenser, 3M Oral Care) was placed on a glass slide, and a stainless-split mold (25 × 2 × 2 mm) was positioned on it. The resin composites were then inserted into the mold and covered with the matrix tape. Pressure was manually applied to the composites using another glass plate. The mold was then positioned on a glass slide. The middle third of the specimen was irradiated for 30 seconds after which the remaining thirds were irradiated for 30 seconds each. The polymerized specimen was removed from the mold, and all the sides were polished using a 1200-grit SiC (Fuji Star type

DCCS; Sankyo Rikagaku, Saitama, Japan) paper. The prepared specimens were stored in distilled water at 37 °C in the dark for 24 hours. Twelve specimens per test resin composite were subjected to the three-point bending test (span length = 20 mm) using a universal testing machine (model 5500R; Instron, Canton, MA, USA) at a crosshead speed of 1.0 mm/min until breaking point. The flexural strength (σ_F) and elastic modulus (E) were determined from the stress-strain curve created using built-in computer software (Bluehill ver. 2.5; Instron) connected to the testing machine. In addition, the modulus of resilience (R) was calculated using the following equation²²:

$$R = \sigma_F^2 / 2E$$

Specimen Preparation for Surface Property Evaluation

The specimens were prepared in cylindrical Teflon molds (height = 2.0 mm, diameter = 10.0 mm). One end of the mold was sealed using the matrix tape, and the resin paste was condensed into the mold from the open end. The open end was then covered with the matrix tape, and pressure was applied, followed by light irradiation for 30 seconds with a curing unit. The polymerized specimen was removed from the mold and was later stored in the dark at 25 °C for 24 hours before finishing and polishing. Seventy specimens were prepared for each resin composite.

Finishing and Polishing Procedures

The specimens were randomly divided into seven groups (n=10 each). All specimens in the seven groups were ground flat with a 320-grit SiC paper under tap water. The specimens in three groups were finished using a superfine-grit diamond bur (SFD; SF102R, ISO #017; Shofu, Kyoto, Japan), and those from another three groups were finished using a tungsten carbide bur (TCB; FG7714, ISO #014; Kerr, Orange, CA, USA). Those in the remaining group were ground with SiC 320-grit grinding paper and set as the baseline (BAS).

The finishing procedures were performed using a high-speed handpiece (TwinPower Turbine; J. Morita Mfg, Kyoto, Japan) with water spray. Light hand pressure was applied in multiple directions, and the burs were changed after five uses. Three specimens, each from the three groups (SFD, TCB, and BAS), were set aside for measurements. Two specimens, one each from the SFD and TCB groups, were polished using the one-step point-type polishing system comprising a silicone polisher impregnated with a diamond particle (CMP; CompoMaster, Shofu). Likewise, two specimens (one each from the SFD and TCB groups)

Table 1: <i>Materials Used in this Study</i>				
Code	Resin Composite (Lot No.)	Main Components	Type of Resin Composite (Filler Content)	Manufacturer
OM	Omnichroma (18B28)	UDMA, TEGDMA, silica-zirconia filler (260 nm)	Supra-nano filled (79 wt%, 68 vol%)	Tokuyama Dental, Tokyo, Japan
FS	Filtek Suprem Ultra (Shade; A2: N870378)	bis-GMA, UDMA, TEGDMA, bis-EMA, PEGDMA, zirconia/silica clusters (0.6-10 μm) silica (20 nm silica filler), zirconia (4-11 nm)	Nano filled (78.5 wt%, 63.3 vol%)	3M Oral Care, St. Paul, MN, USA
TE	Tetric EvoCeram (Shade; A2: T21387)	bis-GMA, UDMA, bis-EMA barium glass, ytterbium trifluoride, mixed oxide and pre-polymer (range: 40 nm-3 μm, average: 550 nm)	Nano hybrid (75-76 wt%, 53-55 vol%)	Ivoclar Vivaden, Schaan, Lichtenshtein
Code	Finishing Bur	Model	Manufacturer	
SFD	Super fine grit diamond bur	SF102R (ISO#017, particle size less than 25 μm)	Shofu, Kyoto, Japan	
TCB	Tungsten carbide bur	FG7714 (ISO#014, 12 blades)	Kerr, Orange, CA, USA	
Code	Polishing System	Model	Manufacturer	
CMP	Compomaster (one step system)	One step diamond polisher (6 μm) silicone base (25%), diamond particles (75%)	Shofu	
SSD	Super-Snap (multi step system)	SSD G: Fine, green: σ12-mm disk; 20- μm aluminium oxide SSD R: Superfine, red: σ12-mm disk; 7-μm aluminium oxide	Shofu	
Abbreviations: UDMA, urethane dimethacrylate, TEGDMA: triethyleneglycol dimethacrylate; bis-GMA, 2,2-bis[4-(2-hydroxy-3-methacryloyloxypropoxy) phenyl] propane; bis-EMA, bisphenol A polyethylene glycol diether dimethacrylate; PEGDMA: poly ethylene glycol diether dimethacrylate.				

were polished using the multistep polishing system comprising aluminum oxide-impregnated disks (SSD; Super-Snap Rainbow Technique Kit, Shofu). All the polishing procedures were performed using a slow-speed handpiece (TorqTech CA-DC; J. Morita Mfg.) at 5,000 rpm and contact pressure of 1.0 N, which was monitored with a digital balance (AT200; Mettler-Toledo, Greifensee, Switzerland) underneath the specimen. All specimens were finished and polished by a single operator to reduce variability between samples.

The final groups of specimens from each type of composite were as follows: ground with 320-grit SiC paper (BAS); finished with SFD (SFD); finished with TCB (TCB); SFD polished with CMP (SFD+CMP); TCB polished with CMP (TCB+CMP); SFD polished

with SSD (SFD+SSD); and TCB polished with SSD (TCB+SSD).

Measurement of Surface Area Roughness

Before the *Sa* measurements, the finished and polished specimens were cleaned with distilled water in an ultrasonic bath (Quantrex 301; L&R Ultrasonics, Kearny, NJ, USA) for 3 minutes and dried in oil-free air. The surfaces of all the specimens were observed using a three-dimensional laser scanning microscope (LSM, VK-8700; Keyence, Osaka, Japan). The spectral maximum of the excitation light was observed to be at 658 nm; the intensity of the excitation light and the amplification of the photomultiplier were kept constant during the observation period. Profilometric measurements were conducted in a region (1.0 mm ×

1.0 mm) at the center of the specimen. The Sa value was obtained using the built-in computer software (VK Analyzer; Keyence) connected to the LSM. Three measurements were taken, and the means were then determined for each group.

Measurement of Surface Gloss

The GU of each group was measured using a gloss meter (GM-26D; Murakami Color Research Laboratory, Tokyo, Japan) after the Sa measurements were obtained. The gloss meter was calibrated with a blackboard of known gloss value. Subsequently, the GU measurements were taken with an incident angle of 60 degrees, and the values for each group were determined.

Measurement of Surface Free Energy (SFE)

The contact angles of the specimens were measured in order to evaluate the surface characteristics. The contact angles of the three test liquids with known SFE parameters, 1-bromonaphthalene, di-iodomethane, and distilled water were measured using a contact angle meter (Drop Master DM500; Kyowa Interface Science, Saitama, Japan) with a built-in charge-coupled device camera.¹² The equilibrium contact angle (θ) of each test liquid on the specimens was then measured using the sessile-drop method at room temperature ($23 \pm 1^\circ\text{C}$). Sessile liquid drops (1.0 μL) were dispensed with a micropipette, and the surface characteristics were calculated based on the fundamental concepts of wetting. The Young-Dupré equation has associated contact angle to the work of adhesion for a solid (S) and liquid (L) that are in contact (W_{SL}), the interfacial free energy between the S and the L (γ_{SL}), and the free energies of the L and S (γ_{L} and γ_{S} , respectively) and is expressed as follows:

$$W_{\text{SL}} = \gamma_{\text{L}} + \gamma_{\text{S}} - \gamma_{\text{SL}} = \gamma_{\text{L}} (1 + \cos\theta).$$

An extension of the Fowkes equation following the Kitazaki-Hata approach²³ yields the following equations:

$$\gamma_{\text{SL}} = \gamma_{\text{L}} + \gamma_{\text{S}} - 2(\gamma_{\text{L}}^{\text{d}} \gamma_{\text{S}}^{\text{d}})^{1/2} - 2(\gamma_{\text{L}}^{\text{p}} \gamma_{\text{S}}^{\text{p}})^{1/2} - 2(\gamma_{\text{L}}^{\text{h}} \gamma_{\text{S}}^{\text{h}})^{1/2},$$

$$\gamma_{\text{L}} = \gamma_{\text{L}}^{\text{d}} + \gamma_{\text{L}}^{\text{p}} + \gamma_{\text{L}}^{\text{h}}, \gamma_{\text{S}} = \gamma_{\text{S}}^{\text{d}} + \gamma_{\text{S}}^{\text{p}} + \gamma_{\text{S}}^{\text{h}},$$

where, γ^{d} , γ^{p} , and γ^{h} are the components of the SFE (γ) arising from the dispersion force, the polar (permanent and induced) force, and the hydrogen-bonding force, respectively. The θ values were determined for the three test liquids, and the surface-energy parameters of the treated resin composites were obtained using

the above equations using add-on software (FAMAS, Kyowa Interface Science).

SEM Observations

To visualize the morphological features of the fillers in the resin composites, the polymerized specimens were polished using abrasive disks and a series of diamond pastes (DP-Paste; Struers, Ballerup, Denmark) down to a particle size of 0.25 μm . The mirror-polished surfaces were subjected to argon-ion beam etching (IIS-200ER; Elionix, Tokyo, Japan) for 40 seconds, with the ion beam directed perpendicular to the polished surface (accelerating voltage = 1 kV, ion current density = 0.4 mA/cm^2). The surfaces were then coated with a thin film of Au in a vacuum evaporator (Quick Coater Type SC-701; Sanyu Denchi, Tokyo, Japan). Images were obtained using an SEM (FE-8000; Elionix, Vienna, Austria) at an operating voltage of 10 kV at magnifications of 5,000 $\times$ and 30,000 $\times$.

In order to understand the surface texture of the finishing and polishing instruments before use, Au-coated surfaces were observed by SEM at magnifications of 50 $\times$ and 1,000 $\times$. Furthermore, SEM observations of representative specimens from the three resin composites were performed after the different finishing and polishing procedures. The coated surfaces were visualized by SEM at a magnification of 2,500 $\times$.

Statistical Analysis

A power analysis has indicated that at least 10 samples for flexural properties and eight samples for surface properties and SFE measurements were needed. Thus, this study was initially performed with 12 specimens for flexural property testing and 10 for other measurements. After gathering the data, *post hoc* power tests were performed using two statistical software systems (G Power calculator and SigmaPlot ver. 13.0; Systat Software, Inc, Chicago, IL, USA).

After confirming that the distribution was normal using the Kolmogorov-Smirnov test, data from each experiment were subjected to the analysis of variance (ANOVA) test; this was followed by the Tukey honest significant difference test at a significance level of 0.05. Significant differences in flexural properties were observed using the one-way ANOVA test, whereas differences in surface roughness, surface gloss, and total SFE were assessed using the two-way ANOVA test; the type of resin composite and the polishing method were used as factors for the two-way ANOVA. The statistical analyses were carried out using a commercially available statistical software program (SigmaPlot ver. 13.0).

The Pearson product-moment correlation coefficient was also used to perform pairwise comparisons, in

Table 2: Flexural Properties of the Tested Resin Composites ^{a,b}			
	Flexural Strength; σ_F (MPa)	Elastic modulus; E (GPa)	Resilience; R (MJ/mm ³)
OM	116.6 (4.8) c	6.8 (0.6) c	1.01 (0.11) a
FS	142.3 (5.8) a	13.2 (0.6) a	0.78 (0.06) b
TE	125.3 (5.2) b	9.3 (0.8) b	0.85 (0.11) b
Abbreviations: FS, Filtek Supreme Ultra; OM, Omnicroma; TE, Tetric EvoCeram.			
^a Values in parentheses indicate standard deviation.			
^b Same small case letter in vertical columns indicates no difference at 5% significance level.			

order to understand the relationships between the tested parameters of the surface properties (SigmaPlot version 13.0, Systat).

RESULTS

Flexural Properties

The flexural properties of the resin composites are presented in Table 2. The average σ_F ranged from 116.6 to 142.3 MPa in the following order with significant differences between each value: FS > TE > OM. The average E ranged from 6.8 to 13.2 GPa in the following order with significant differences between each value: FS > TE > OM. FS showed significantly higher E and σ_F values compared to the other resin composites. The average R ranged from 0.78 to 1.01 MJ/mm³ in the following order: OM > TE > FS. Although no significant difference was determined between FS and TE, OM showed a significantly higher R than the other resin composites, in contrast to σ_F and E .

Surface Area Roughness

The influence of different finishing and polishing methods on the Sa values is shown in Table 3. A two-way ANOVA revealed that the finishing and

polishing methods and the type of resin composite can significantly affect the Sa values ($p < 0.001$). The two-way interaction between these two factors was also found to be significant ($p < 0.001$). The groups finished with SFD showed significantly higher Sa values when compared with the other groups, regardless of the type of resin composite used. On the other hand, the TCB+SSD group showed the lowest Sa values compared to the other groups, and significant differences in FS and TE were observed between the TCB+SSD group and the other groups. In addition, most groups polished with SSD showed significantly lower Sa values compared to the groups polished with CMP, regardless of the type of finishing used (SFD or TCB).

Among the tested resin composites, no significant differences were observed between the BAS and TCB groups. However, the Sa values of the OM groups polished with CMP and SSD were found to be significantly lower than those of the other resin composites, regardless of the finishing method.

Gloss

The effects of the different finishing and polishing methods on the GU values are shown in Table 4. The two-way ANOVA test revealed that both factors, ie, finishing and polishing methods and the type of resin

Table 3: Influence of Finishing and Polishing Methods on Surface Area Roughness (Sa , μm) ^{a,b}							
	BAS	SFD	TCB	SFD+CMP	TCB+CMP	SFD+SSD	TCB+SSD
OM	1.32 (0.02) aB	1.51 (0.02) bA	1.05 (0.02) aC	0.92 (0.03) cD	0.85 (0.01) cE	0.78 (0.02) cF	0.78 (0.02) cF
FS	1.31 (0.02) aB	1.60 (0.05) aA	1.05 (0.02) aC	1.00 (0.02) bD	0.99 (0.04) bD	0.93 (0.04) bE	0.88 (0.02) bF
TE	1.30 (0.01) aB	1.46 (0.03) cA	1.03 (0.02) aCD	1.07 (0.05) aC	1.01 (0.03) aD	1.00 (0.02) aD	0.85 (0.04) aE
Abbreviations: BAS, baseline; CMP, diamond particle; FS, Filtek Supreme Ultra; OM, Omnicroma; SFD, superfine grit diamond bur; SSD, aluminum oxide-impregnated disks; TCB, tungsten carbide bur; TE, Tetric EvoCeram.							
^a Values in parentheses indicate standard deviation.							
^b Same small case letter in vertical columns indicates no difference at 5% significance level. Same capital letter in horizontal rows indicates no difference at 5% significance level.							

Table 4: Influence of Finishing and Polishing Methods on Surface Gloss (GU)^{a,b}

	BAS	SFD	TCB	SFD+CMP	TCB+CMP	SFD+SSD	TCB+SSD
OM	3.7 (0.2) bF	1.8 (0.1) cG	22.9 (0.6) aE	34.1 (1.0) bD	44.3 (0.4) bC	50.6 (1.0) aB	53.3 (1.2) aA
FS	7.4 (0.2) aF	2.7 (0.1) aG	12.4 (0.2) bE	53.7 (0.6) aB	65.2 (0.2) aA	31.8 (0.3) bD	40.7 (0.5) cC
TE	3.4 (0.1) cF	2.0 (0.1) bG	22.6 (0.2) aE	35.5 (0.4) bC	44.1 (0.8) bB	32.8 (0.8) bD	48.5 (0.3) bA

Abbreviations: BAS, baseline; CMP, diamond particle; FS, Filtek Supreme Ultra; OM, Omnicroma; SFD, superfine grit diamond bur; SSD, aluminum oxide-impregnated disks; TCB, tungsten carbide bur; TE, Tetric EvoCeram.

^aValues in parentheses indicate standard deviation.

^bSame small case letter in vertical columns indicates no difference at 5% significance level. Same capital letter in horizontal rows indicates no difference at 5% significance level.

composite used, have significantly affected the GU ($p < 0.001$). In addition, a significant two-way interaction between these two factors was observed ($p < 0.001$). The GU values of the BAS, SFD, and TCB groups were significantly lower than those of the groups polished with CMP and SSD. Furthermore, the specimens in the groups finished with TCB had significantly higher GU values compared to those finished with SFD. In addition, the specimens finished with TCB demonstrated significantly higher GU values when compared with those finished with SFD. The GU values also appeared to be dependent on the material and the finishing method used. The OM specimens polished with SSD showed significantly higher GU values than those polished with CMP. However, the FS specimens that had been polished with SSD showed significantly lower GU values compared to those polished with CMP, regardless of the finishing method. On the other hand, the TE specimens polished with SSD showed a different trend in their GU values when compared with the specimens finished with SFD and TCB.

Surface Free Energy

The effects of the different finishing and polishing methods on the SFE values are shown in Table 5

and Figure 1. A two-way ANOVA revealed that the finishing and polishing method, as well as the type of resin composite used, significantly influenced the γ_s value ($p < 0.001$). The two-way interaction between the factors was also found to be significant ($p < 0.001$).

The specimens in most of the groups polished with SSD showed significantly higher γ_s values compared to those in the other groups. The polished OM specimens showed significantly higher γ_s values compared to those in the BAS and other finished groups. In the case of the FS specimens, although the specimens in the TCB + SSD group presented with significantly higher γ_s value than those in the other groups, no significant differences were observed among the specimens in the other groups. The γ_s values of the TE specimens polished with CMP were found to be lower than those in the other groups. FS tended to have higher γ_s values when compared with the other resin composites, regardless of the finishing and polishing methods.

With regard to each component of the γ_s (Figure 1), although the dispersion force (γ_s^d) was constant at approximately $40 \text{ mN} \cdot \text{m}^{-1}$ in all the groups, variations in the polar force (γ_s^p) and hydrogen-bonding force (γ_s^h) were observed among the groups. However, all three resin composites tended to have higher γ_s^p values when

Table 5: Influence of Finishing and Polishing Methods on Total SFE (γ_s)^{a,b}

	BAS	SFD	TCB	SFD+CMP	TCB+CMP	SFD+SSD	TCB+SSD
OM	45.2 (2.0) bC	43.5 (1.9) bD	44.6 (2.2) cCD	48.4 (1.8) bB	48.2 (0.9) bB	50.8 (1.2) aA	50.6 (1.2) bA
FS	51.2 (1.8) aB	51.8 (1.5) aB	51.0 (0.9) aB	51.2 (1.1) aB	51.7 (1.5) aB	51.4 (1.2) aB	53.9 (2.2) aA
TE	49.4 (1.4) aBC	50.5 (1.6) aAB	48.2 (1.4) bCD	47.0 (1.5) bD	46.6 (1.2) cD	51.8 (1.0) aA	51.4 (1.6) bA

Abbreviations: BAS, baseline; CMP, diamond particle; FS, Filtek Supreme Ultra; OM, Omnicroma; SFD, superfine grit diamond bur; SFE, surface-free energy; SSD, aluminum oxide-impregnated disks; TCB, tungsten carbide bur; TE, Tetric EvoCeram.

^aValues in parentheses indicate standard deviation.

^bSame small case letter in vertical columns indicates no difference at 5% significance level. Same capital letter in horizontal rows indicates no difference at 5% significance level.

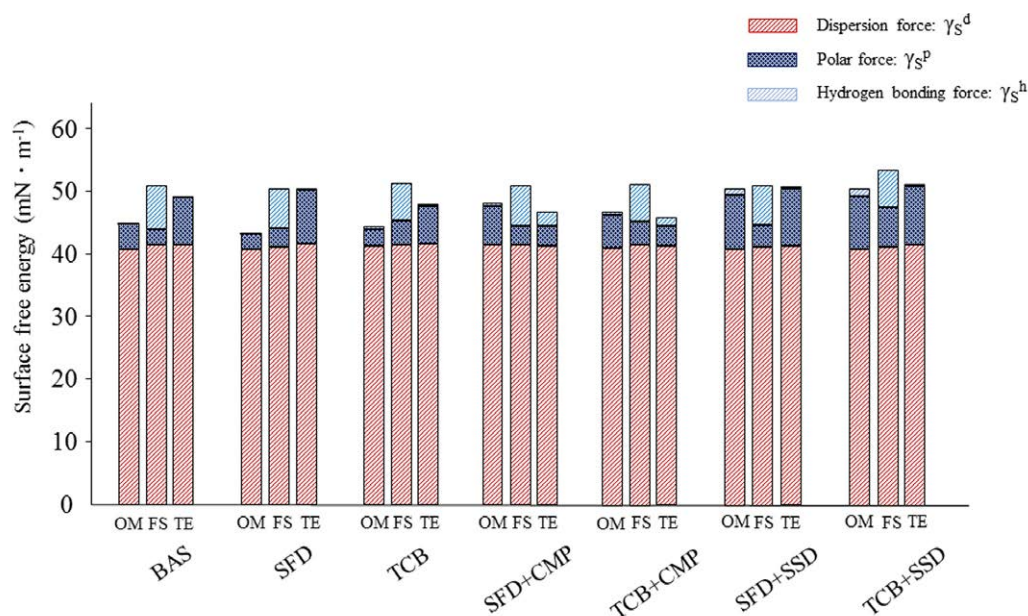


Figure 1. The total SFE (γ_s) values and the three corresponding parameters of the resin composites. Abbreviations: γ_s , total surface free energy; BAS, baseline; CMP, diamond particle; FS, Filtek Supreme Ultra; GU, surface gloss; OM, Omnicroma; SFD, superfine grit diamond bur; SSD, aluminum oxide-impregnated disks; TCB, tungsten carbide bur; TE, Tetric EvoCeram.

polished with SSD when compared with the other finishing and polishing methods. The FS specimens had higher γ_s^h components than the other resin composites, regardless of the finishing and polishing methods.

Interrelations Between the Tested Parameters of the Surface Properties

The Pearson product-moment correlation coefficient (r) and p values for the relations between the tested parameters of the surface properties are presented in Table 6. Extremely strong negative correlations between Sa and GU in the combined data from the three resin composites and each resin composite and between Sa and γ_s in the OM specimens were observed; GU showed a strong positive correlation with γ_s in the same material, and those correlations were revealed to be individually statistically significant. However, the other comparisons showed weak correlations or no correlations.

SEM Observations

SEM images of the mirror-polished surfaces after argon-ion etching are illustrated in Figures 2 through 4. The shapes, sizes, and distributions of the inorganic fillers are found to be resin composite dependent. OM consisted of nanosized spherical fillers (approximately 0.25 μm) and round pre-polymerized fillers that employ the same nanosized spherical fillers (Figure 2). FS consisted of spheroidal aggregates (0.5-5.0 μm)

of nanosized filler particles (Figure 3), whereas TE consisted of irregular fillers (0.5-2.0 μm) made up of nanosized filler particles that were packed into pre-polymerized fillers at a high density (Figure 4).

Representative SEM images of the surfaces of the instruments are shown in Figure 5. SFD consisted of embedded irregular diamond particles that were less than 20 μm in size. On the other hand, TCB consisted of sharp uniform blades. The one-step polishing instrument CMP consisted of impregnated irregular diamond particles, and the interfaces between the particles and matrix appeared to be loose. In the case of the multiple polishing system, SSD, the sizes of the aluminum oxide particles were found to be varied in the different disks (SSD G and SSD R). The particles in SSD R were tightly packed when compared to those in CMP and SSD G.

Representative SEM images of the resin composite surfaces after the different finishing and polishing methods are shown in Figures 6-8. All the resin composites exhibited smoother surfaces after finishing with TCB when compared to those finished with SFD. For FS and TE, scratches and plucked-out fillers were observed following polishing with SFD. In particular, plucked-out aggregated fillers were seen in the FS specimens, whereas large glass fillers were observed in the TE specimens.

When comparing the different polishing methods (CMP and SSD), smoother surfaces were observed in the

Table 6: Relationships Between the Parameters of Surface Properties			
		GU	γ_s
Combined data of three resin composites			
Sa	<i>r</i>	-0.847	-0.274
	<i>p</i> -value	<0.001	0.230
GU	<i>r</i>		0.318
	<i>p</i> -value		0.160
OM			
Sa	<i>r</i>	-0.972	-0.897
	<i>p</i> -value	<0.001	0.006
GU	<i>r</i>		0.930
	<i>p</i> -value		0.002
FS			
Sa	<i>r</i>	-0.713	-0.265
	<i>p</i> -value	0.072	0.566
GU	<i>r</i>		0.222
	<i>p</i> -value		0.632
TE			
Sa	<i>r</i>	-0.921	0.026
	<i>p</i> -value	0.003	0.956
GU	<i>r</i>		-0.145
	<i>p</i> -value		0.756
Abbreviations: γ_s , total surface free energy; BAS, baseline; CMP, diamond particle; FS, Filtek Supreme Ultra; GU, surface gloss; OM, Omnichroma; <i>r</i> , correlation coefficient; Sa, surface roughness; SFD, superfine grit diamond bur; SSD, aluminum oxide-impregnated disks; TCB, tungsten carbide bur; TE, Tetric EvoCeram			

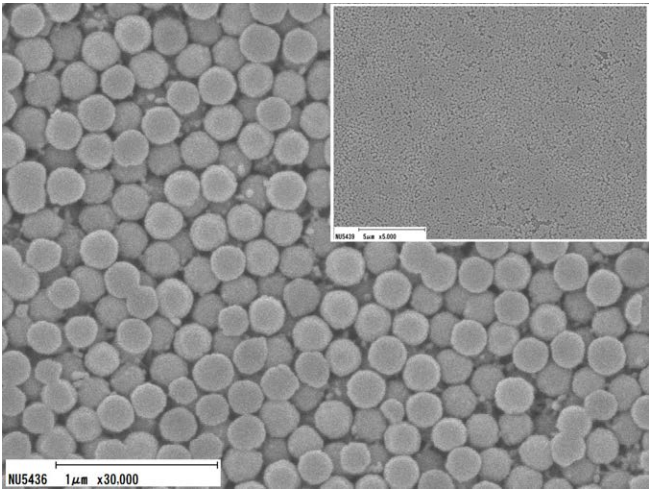


Figure 2. SEM images of resin composite surfaces after argon-ion etching Omnichroma (OM) – 5000× and 30,000×. Abbreviation: SEM, scanning electron microscopy.

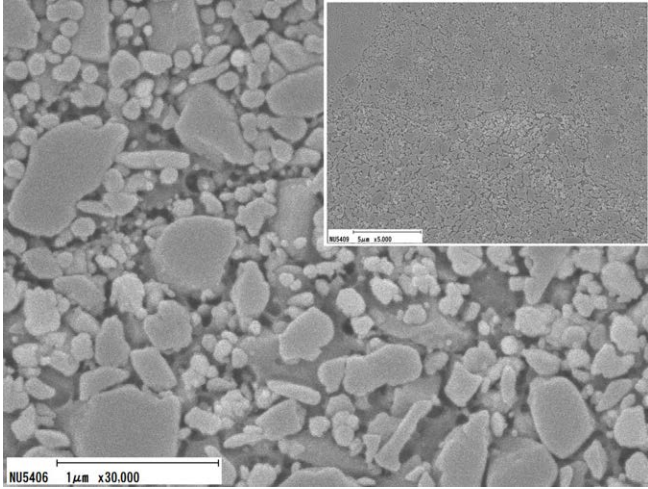


Figure 3. SEM images of resin composite surfaces after argon-ion etching. Filtek Supreme Ultra (FS) – 5000× and 30,000×. Abbreviation: SEM, scanning electron microscopy.

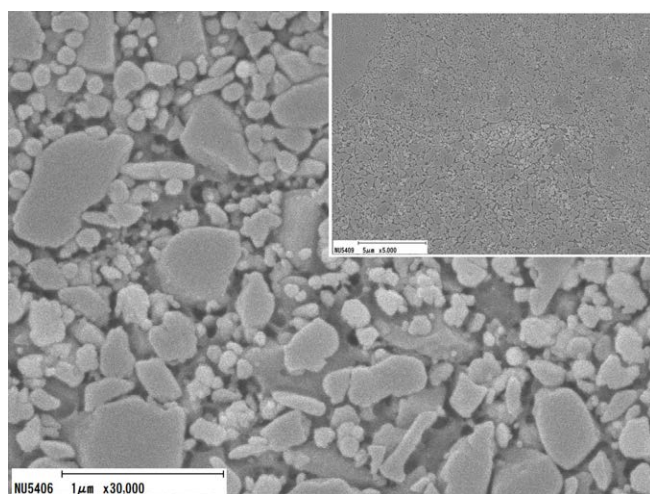


Figure 4. SEM images of resin composite surfaces after argon-ion etching Tetric EvoCeram (TE) – 5000 $\times$ and 30,000 $\times$. Abbreviation: SEM, scanning electron microscopy.

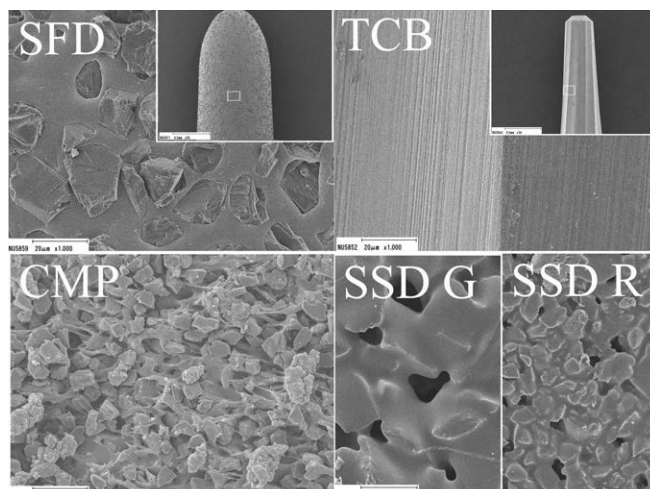


Figure 5. SEM images of resin composite surfaces after argon-ion etching. Representative SEM images of the instruments' surfaces. CMP, One-step diamond polisher, Compomaster (1,000 $\times$); SEM, scanning electron microscopy; SFD, Super fine grit diamond bur (50 $\times$ and 1,000 $\times$); SSDG, Multistep polishing system, Super-Snap fine green (1,000 $\times$); SSDR, Multistep polishing system, Super-Snap super fine red (1,000 $\times$); TCB, Tungsten carbide bur (50 $\times$ and 1,000 $\times$). Abbreviation: SEM, scanning electron microscopy.

SSD groups in the case of the OM and FS specimens, regardless of the finishing method. On the contrary, in the case of the TE specimens, there exists no difference in surface smoothness between the SSD and CMP groups.

DISCUSSION

Understanding the various properties of resin composites before clinical use will aid in selecting the optimum resin composite, which will in turn lead to ideal outcomes in the intraoral environment.^{7,8} In this study, the flexural

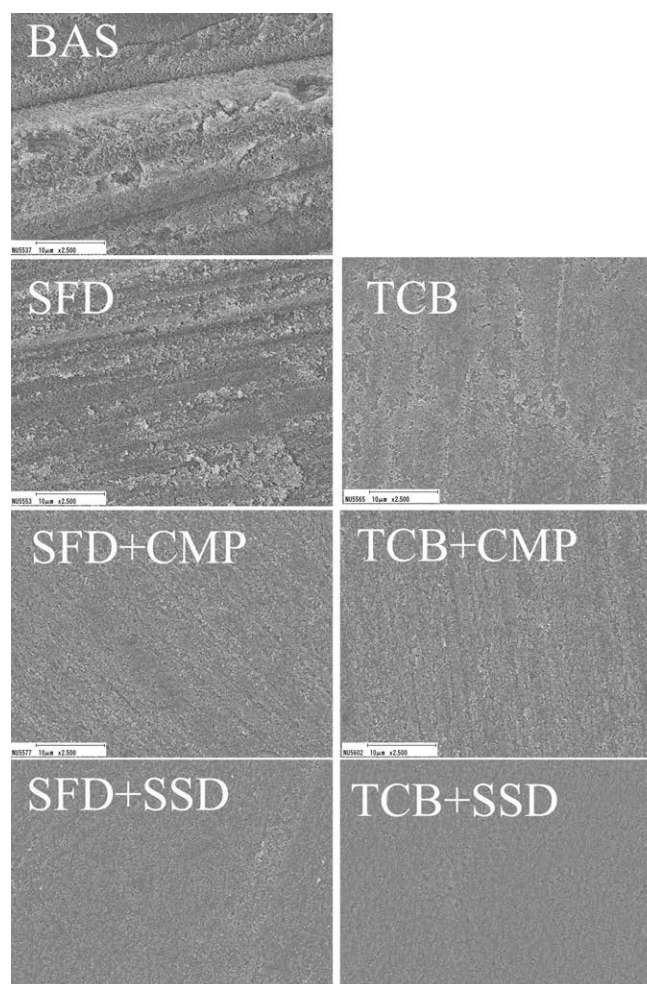


Figure 6. Representative SEM images of OM after different finishing and polishing methods. BAS, Ground with SiC #320 (2,500 $\times$); SEM, scanning electron microscopy; SFD, Finished with Super-fine grit diamond (2,500 $\times$); SFD+SSD, Polished with Super-Snap after finishing with Super-fine grit diamond bur (2,500 $\times$); SFD+SSD, Polished with Super-Snap after finishing with Super-fine grit diamond bur (2,500 $\times$); TCB, Finished with Tungsten carbide bur (2,500 $\times$); TCB+SSD, Polished with Super-Snap after finishing with Tungsten carbide bur (2,500 $\times$). Abbreviation: SEM, scanning electron microscopy.

and surface properties of the structural colored resin composite OM were investigated and compared with those of the conventional resin composites FS and TE.

When considering the longevity of resin composite restorations in intraoral conditions, fracture-related material properties are important. Flexural strength testing is a well established standardized method, and it is preferred as a way to screen the mechanical properties of materials due to ease of testing. These values are helpful in comparing materials under controlled conditions and also provide some help

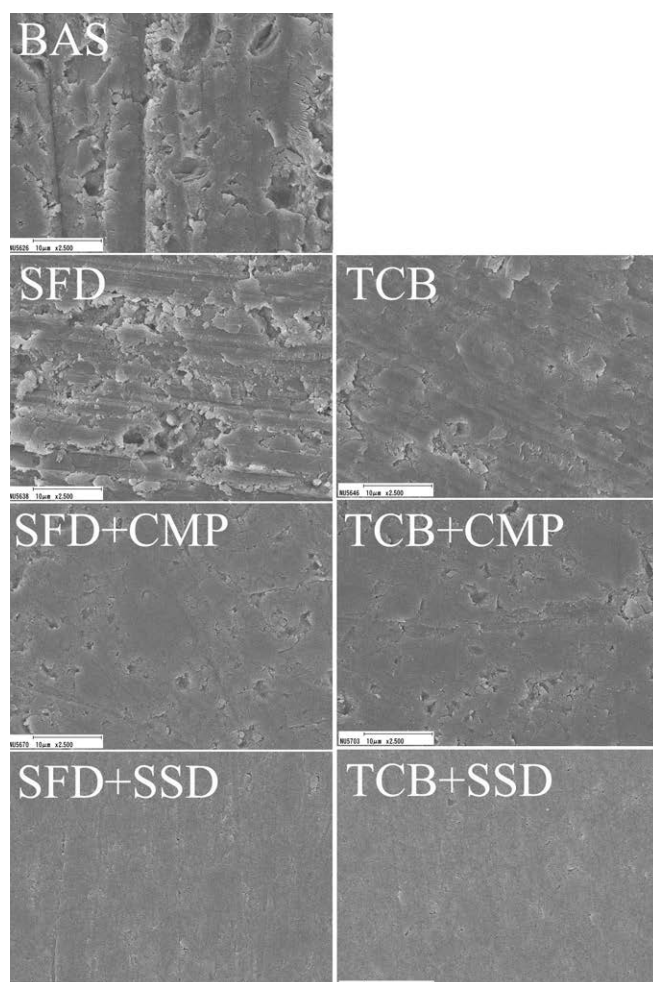


Figure 7. Representative SEM images of FS after different finishing and polishing methods. BAS, Ground with SiC #320 (2,500 $\times$); SEM, scanning electron microscopy; SFD, Finished with Super-fine grit diamond bur (2,500 $\times$); SFD+SSD, Polished with Super-Snap after finishing with Super-fine grit diamond bur (2,500 $\times$); TCB, Finished with Tungsten carbide bur (2,500 $\times$); TCB+SSD, Polished with Super-Snap after finishing with Tungsten carbide bur (2,500 $\times$). Abbreviation: SEM, scanning electron microscopy.

in predicting restoration longevity. The mechanical properties of resin composites are influenced by the resin monomers, filler characteristics, and surface treatment of the fillers. The findings of this study were found to be consistent with the results of the previous studies, which investigated the flexural properties of nanohybrid and nanofilled resin composites, including the resin composites used in this study.^{24,25} FS showed significantly higher σ_F and E values compared to TE in the current study. Thus, it can be speculated that the fine nanosized spherical fillers and the aggregated

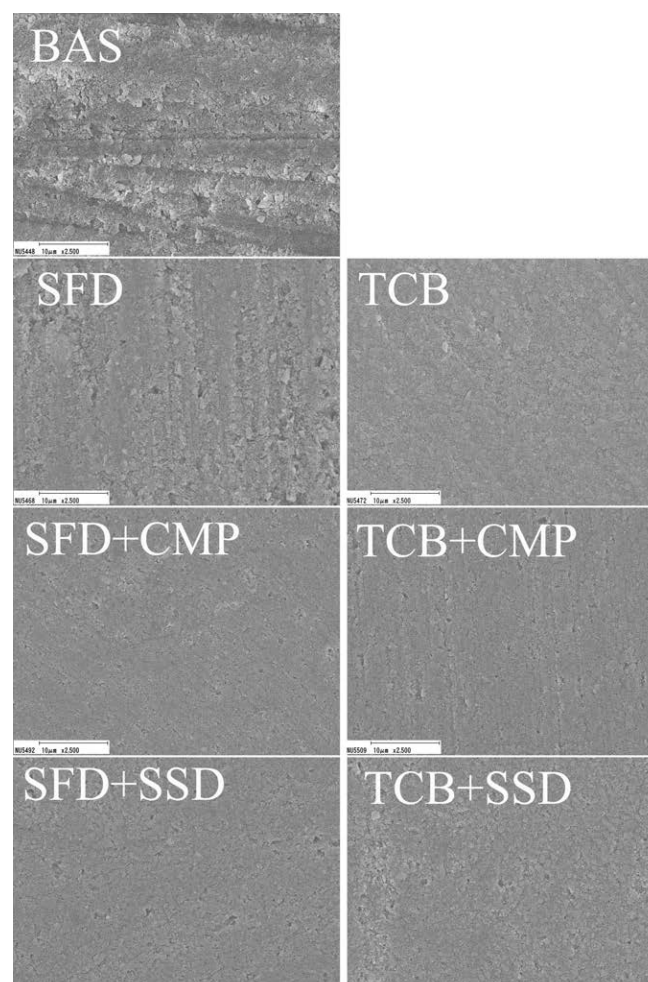


Figure 8. Representative SEM images of TE after different finishing and polishing methods. BAS, Ground with SiC #320 (2,500 $\times$); SEM, scanning electron microscopy; SFD, Finished with Super-fine grit diamond bur (2,500 $\times$); SFD+SSD, Polished with Super-Snap after finishing with Super-fine grit diamond bur (2,500 $\times$); TCB, Finished with Tungsten carbide bur (2,500 $\times$); TCB+SSD, Polished with Super-Snap after finishing with Tungsten carbide bur (2,500 $\times$). Abbreviation: SEM, scanning electron microscopy.

fillers with a wide range of sizes in FS might contribute to higher fracture resistance.

In general, materials with high flexural strength have high elastic moduli.^{26,27} OM presented with significantly lower E values compared to the other materials despite having a higher filler content. Of the monomers used in the tested composites, 2,2-bis[4-(2-hydroxy-3-methacryloyloxypropoxy)phenyl] propane (bis-GMA) has a relatively higher molecular weight and lower mobility compared to urethane dimethacrylate (UDMA) and triethyleneglycol dimethacrylate (TEGDMA).

Izabela and others,²⁸ who examined the mechanical properties of three common homopolymers, have reported that UDMA had a lower E than bis-GMA and TEGDMA. UDMA is the resin monomer used in OM. However, although the type of resin monomer used can influence the flexural properties of a resin composite, it is difficult to identify the exact resin monomer and its effects on σ_f and E due to the various types present in resin composites; moreover, the interactions between resin monomers and inorganic fillers may differ between composites. OM has been known to consist of uniformly sized spherical fillers with constant interparticle spacing. FS consists of non-aggregated silica (20 nm) and zirconia fillers (4 to 11 nm), whereas OM consists of silica-zirconia fillers (260 nm). The fillers in OM were found to have greater interparticle spaces (Figures 2 and 3) than those in FS. Therefore, crack propagation in OM tended to be simple, leading to lower fracture resistance. On the other hand, R is thought to be the ability of a material to absorb energy when it is elastically deformed under external stress without failing.²⁶ OM showed a significantly higher R value compared to the other resin composites. This may be attributed to the presence of UDMA, which acts as a very flexible backbone with weak hydrogen-bonding due to the urethane groups. Therefore, the first null hypothesis, which indicates that the flexural properties of OM would not differ from those of other resin composites, was rejected.

The surface characteristics of resin composites, in addition to the mechanical properties, must be understood to predict their longevity in the intraoral environment, because the surfaces of restorations are directly subjected to various degradation factors.^{10,11} From the results of this study, the two factors, ie, finishing and polishing procedure and type of resin composite used, have significantly influenced the Sa values. In particular, the groups finished with SFD showed significantly higher Sa values compared to those finished with TCB, regardless of the type of resin composite. This result was in line with a previous study that investigated the surface roughness of bulk-fill resin composites after different finishing and polishing procedures.¹² This finding may be explained by the different surface textures of the finishing instruments (Figure 5) resulting in different finishing mechanisms. The tungsten carbide burs cut away the surface, whereas diamond burs grind the surface with many abrasive diamond particles.^{29,30} SEM observations clearly showed that some filler particles were plucked from the surfaces in the case of SFD, whereas in the case of TCB polishing, the filler particles remained embedded in the surface, resulting in a smoother surface (Figures 6 and 7). Furthermore, the finishing methods have

significantly affected the polished groups, because most of the specimens in the TCB group showed lower Sa values compared to those in the SFD group, regardless of whether CMP or SSD was used.

The multiple-step polishing system (SSD) created smoother surfaces compared with the one-step polishing system (CMP; Figures 6 through 8). This might be attributed to the distribution (Figure 5) and the hardness of the particles in the different polishing instruments. Watanabe and others³¹ indicated that, although the one-step polishing system has the capacity to polish resin composites as effectively as multistep polishing systems, the smoothest surface was obtained with multistep polishing systems. Among the resin composites, OM has showed significantly lower Sa values compared to the other resin composites for all the polishing methods. It can be inferred that the superior polishability of OM is probably due to the uniform nanoscale spherical fillers and the constant interspaces between them.

The surface gloss of restorations has been considered an important parameter for esthetics.³² Gloss is defined based on the degree of specular reflection of light.³³ The finishing and polishing methods and type of resin composite used have significantly affected the GU in the current study. The GU obtained after polishing is known to be dependent on the type of material and the finishing method used. Although the OM specimens polished with SSD showed significantly higher GU values compared to those polished with CMP, the opposite findings were observed in the FS specimens, regardless of the finishing method used. Cazzaniga and others³⁴ obtained similar results wherein FS specimens polished with aluminum oxide disks showed lower surface roughness compared to those polished with one-step rubber points; however, a significantly higher surface gloss was obtained when polished with the one-step rubber points. In general, surface roughness and gloss are thought to have a negative correlation.^{35,36} Nonetheless, a smoother surface is not necessary to obtain a high surface gloss, and the relationship depends on the polishing procedures and materials used.³⁴ Although 40 to 60 GU was identified as the typically desired gloss in an American Dental Association professional product review,³⁷ Cook and Thomas³⁸ reported that a finish and polish below 60 GU was generally considered as poor; the acceptable values lie between 60 and 70 GU. However, a systematic review on surface gloss reported that few investigations showed a gloss of over 60 GU, even when the final polishing was performed.³² Therefore, if the clinically acceptable GU is assumed to be 40 to 60 GU, SSD groups for OM and CMP groups for FS may be acceptable.

The SFEs were determined to understand the surface changes wrought by the different finishing and polishing methods from the perspective of surface chemistry. The finishing and polishing methods and the type of resin composite used significantly influenced the γ_s in this study. Therefore, the second null hypothesis, which implies that the surface properties of OM would not be affected by the finishing and polishing methods and would not differ from the other resin composites, was rejected. For all the resin composites, the groups polished with SSD showed significantly higher γ_s values when compared with the other groups. Fundamentally, the wettability of a substance increases with the increase in the γ_s value.^{39,40} In composite resins, inorganic fillers are hydrophilic, whereas the resin matrix is hydrophobic.¹² The increase in the γ_s values in the SSD groups may be attributed to the high level of inorganic filler exposure on the surface due to the polishing method. A flexible disk coated with aluminum oxide might be able to cut the filler particles effectively, leaving parts of the filler particles exposed at the surface. This process produces uniform surface conditions without the plucking of the fillers, improving its resistance to various degradation factors.

γ_s^h represents the water and hydroxyl components of the substrate, whereas γ_s^p is related to the electronic and metallic interactions and the dipolar interactions.^{39,40} Although the γ_s^p and γ_s^h values in each group showed wide variations, some trends were observed between the materials or the finishing and polishing methods. FS had a higher number of γ_s^h components than the other resin composites in all the groups. This trend is likely brought about by the different surface chemistries between the exposed fillers and the resin matrix. The reasons why FS showed higher γ_s^h might be related to the relatively higher vol% of inorganic filler components and the somewhat larger nanofiller clusters, in addition to the presence of relatively hydrophilic resin monomers. In a previous study, which investigated the water sorption of common homopolymers, the descending order of water sorption was reported as TEGDMA > bis-GMA > UDMA.⁴¹ The study suggested that these differences could be attributed to the presence of hydrophilic ether linkages in TEGDMA, hydroxyl groups in bis-GMA, and urethane linkages in UDMA. Although the parts of resin monomers related to hydrophilicity might increase the γ_s^h , it is difficult to determine the details of the interactions between γ_s^p or γ_s^h and the inorganic fillers or resin matrix due to the complexity of the resin composites.

Regarding the interrelations between the tested parameters of the surface properties, extremely strong correlations were observed between *Sa* and *GU* in all the

resin composites, as reported previously.^{35,36} Therefore, in order to obtain an esthetic and smooth surface on the restoration, it is important to conduct appropriate finishing and polishing procedures. On the other hand, extremely strong correlations were observed between *Sa* and γ_s and *GU* and γ_s in the OM specimens only, indicating that finishing and polishing methods may have a larger impact on the surface properties of OM when compared to the other resin composites.

Structural colors depend on the refractive index distribution and the differences in the refractive indices of the resin matrix and the inorganic filler.^{17,19} Although appropriate finishing and polishing procedures may be necessary to generate a structural color in OM, further studies are needed to determine the influence of the different finishing and polishing procedures on color matching.

CONCLUSION

Although the structural colored resin composite OM showed significantly lower σ_f and *E* values, it had a significantly higher *R* compared to the other resin composites. These results suggest that cavity status should be taken into consideration when using OM in clinical situations. The finishing and polishing methods along with the type of resin composite used have significantly affected the surface properties of the resin composite, as measured by the *Sa*, *GU*, and SFE values. SEM observations demonstrated that the shapes, sizes, and distributions of the fillers varied among the resin composite, and different surface appearances were observed with the different finishing and polishing methods used. In the case of the OM specimens, the use of the multiple polishing system (SSD) after finishing with a TCB may improve its surface properties when compared with the other finishing and polishing methods.

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Conflict of Interest

The authors have no financial interest in any of the companies or products mentioned in this article.

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Post-Space Treatment Influences the Bond Strength In Endodontically Treated Teeth: A Systematic Review and Meta-Analysis of *In Vitro* Studies

TC Bohrer • PE Fontana • RO Rocha • OB Kaizer

Clinical Relevance

Several factors can influence the retention of posts to root canal dentin. Post-space treatment is one of these factors, which can improve the bond strength of the post to dentin.

SUMMARY

Objectives: This systematic review of *in vitro* studies investigated the influence of the post-space treatment used to remove the smear layer on the bond strength of the post to root canal dentin.

Methods and Materials: *In vitro* studies included in this study were identified from PubMed/MEDLINE, Lilacs, and Scopus databases up until March 2019, without limits on publication year or

language. Two reviewers independently selected the studies based on the inclusion and exclusion criteria, extracted the data, and evaluated the risk of bias of all studies. A random effects model was used for pairwise meta-analyses (control vs. post-space preparation groups) at a significance level of $p < 0.05$.

Results: Of the 2,832 potentially eligible studies, 453 studies were selected for full-text analysis, and 75 were included in this systematic review. Only

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Conclusion: Post-space treatment has a positive influence on the bond strength of the post to root canal dentin. In this review, the post-space treatments that improve the adhesive resistance of the post were ethanol, sodium hypochlorite, and ethylene diamine tetra-acetic acid (NaOCl + EDTA), NaOCl + EDTA + ultrasound, erbium-doped yttrium aluminium garnet laser (Er:YAG laser), neodymium-doped yttrium aluminium garnet laser (Nd:YAG laser), and diode laser.

METHODS AND MATERIALS

Therefore, although several studies have attempted to point out the best treatment to be used in the post-space, some controversy remains. Thus, this study aimed to systematically review the literature to verify the influence of the post-space treatments on the bond strength of posts to root canal dentin. The hypothesis tested was that there would be no difference in bond strength to root canal dentin when the post-space is or is not treated.

This study was conducted and reported according to the Cochrane Handbook and the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) statement.^{23,24} The protocol of this systematic review was not registered in any platform, because no platforms exist at this time to register reviews of *in vitro* studies.

The systematic review was performed by compiling all available *in vitro* studies to answer the following question: Is there an influence of the post-space treatment on the bond strength of post to root canal dentin in endodontically treated teeth?

Thus, the population, intervention, comparison, and outcomes (the PICOs) for this review included: tooth (population); post-space treatment (intervention); no treatment (comparison), and bond strength (outcome).

Studies have been performed to find the ideal treatment for the post-space, promoting better retention of the intraradicular retainer.^{5,11-16} Among the post-space treatments, ethylenediaminetetraacetic acid (EDTA) is a valid option for smear layer removal.¹⁷ Sodium hypochlorite (NaOCl) is the most common irrigating solution used and can dissolve organic matter in the canal.¹⁷

Moreover, Zhang and others¹⁸ suggested the use of 35% phosphoric acid as a post-space treatment as the increased bond strength is associated with its potential to remove the smear layer in the post-space. Also, some studies have shown that the use of ultrasound and Nd:YAG, Er:YAG, Er, Cr:YSGG, and diode lasers within the post-space can contribute to disinfecting this space and eliminating the smear layer, thus improving the retention of the intraradicular post.¹⁹⁻²²

The PubMed/MEDLINE, Lilacs, and Scopus databases were searched to identify relevant studies up to March 2019 with no limits on publication year or language.

The search strategy used in PubMed/MEDLINE and adapted for other databases was a combination of specific medical subject headings (MeSH) and keywords, as follows: (((((((((((((((((((((((Tooth, Endodontically Treated) OR Endodontically-Treated Tooth) OR Tooth, Endodontically-Treated) OR Teeth, Endodontically Treated) OR Endodontically-Treated Teeth) OR Teeth, Endodontically-Treated) OR Nonvital Teeth) OR Teeth, Nonvital) OR Devitalized Teeth) OR Teeth, Devitalized) OR Pulpless Teeth) OR Teeth, Pulpless) OR Pulpless Tooth) OR Tooth, Pulpless) OR Devitalized Tooth) OR Tooth, Devitalized) OR Nonvital Tooth) OR root canal dentin) OR dentin) OR root canal) OR endodontic) OR post

space)) AND (((((((((((((((((((Canal Irrigants, Root) OR Irrigants, Root Canal) OR Root Canal Medicaments) OR Canal Medicaments, Root) OR Medicaments, Root Canal) OR Acid, Ascorbic) OR Sodium Ascorbate) OR Ascorbate, Sodium) OR citric acid) OR qmix) OR edta) OR chlorhexidine) OR lasers) OR Hypochlorite, Sodium) OR Sodium Hypochlorite (Solution)) OR Pretreatment) OR Ethanol) OR post space irrigation) OR ultrasonic activation) OR diode laser) OR irrigation protocol)) AND (((((((push out bond strength) OR push-out bond strength) OR dislocation*) OR push-out) OR push out) OR adhes*) OR bond strength). All the identified studies were then imported into Mendeley software (Elsevier Inc, New York, United States) to remove duplicates.

Study Selection

Two reviewers (TB and PF) independently assessed the titles and abstracts of studies that were included if the following inclusion criteria were fulfilled: 1) studies that evaluated the influence of any post-space treatment; 2) studies in which the post-space treatment was applied to root canal dentin; and 3) *in vitro* studies.

The final decision about the study selection was made after a full-text reading of the previous selected studies, according to the following exclusion criteria: 1) studies in which the treatment was not in the post-space; 2) studies which did not present a control group (solution that has no interference in the adhesion; for example, water); 3) studies that did not provide bond strength values as mean and standard deviation in megapascals (MPa); 4) studies that used experimental materials; 5) studies with contaminated specimens; 6) studies that did not present immediate bond strength data. If any data were not described or were unclear in the primary study, it was requested of the authors by e-mail (at least twice), and the study was excluded if they did not reply. In the case of multiple publications with the same data, only one study was considered. The group data were excluded from studies in which the aged group was stored in a solution other than water. Reference lists of all included studies were also manually checked in order to retrieve all relevant papers.

Disagreements between the reviewers were resolved by consensus or arbitration by an independent review (OBK). The inter-examiner agreement regarding the inclusion criteria was excellent (kappa coefficient=0.88).

Data Extraction

Data extraction was independently performed by two researchers using standardized extraction sheets. The extracted information included the study characteristics

(title, authors, year and country), study methodology (sample size, type of tooth, endodontic sealer used, post-time waiting for post luting, post-space treatment used, type of post used, resin cement used, post-time waiting for bond strength test and type of bond strength test) and the outcome (mean bond strength [MPa] and standard deviation).

Risk of Bias

The risk of bias assessment was evaluated according to the description of the following parameters suggested by previous studies:^{25,26} randomization of the teeth, sample size calculation, materials used according to the manufacturer's instructions, specimens (roots) with similar dimensions, endodontic treatment performed by a single operator, post-space treatment performed by a single operator, post luting procedures performed by a single operator, blinding of the operator to the testing machine, and failure analysis.

If the study presented a clear description of the parameter, it received a "yes"; if not, it received a "no." Studies that reported 1 to 3 items were classified as high risk of bias, 4 to 6 as medium risk, and 7 to 9 as low risk. Disagreements between the reviewers were solved by consensus for the final risk of bias classification.

Data Analyses

Meta-analyses were performed using Review Manager software (RevMan version 5.3 software, Cochrane Collaboration; Copenhagen, Denmark). The mean difference with a 95% confidence interval was calculated for the bond strength means from each included study, taking into account two groups: experimental (post-space treatment) and control (no post-space treatment). The pooled-effect estimates were obtained using an inverse variance method and the random effect model (Z-test; $p < 0.05$).

The overall analysis was performed by comparing any post-space preparation with the control group. For studies that evaluated more than one post-space treatment, the type of endodontic sealer, post-time waiting for post luting, type of post, type of cement, thirds of the root, test time, or type of drills, one bond strength mean of each group (experimental and control) was calculated using a formula according to the Cochrane Statistical Guidelines.²³

Prespecified subgroup analyses by type of post-space treatment, type of endodontic sealer, post-time waiting for post luting, type of post, type of cement, thirds of the root, test time and type of drills used to prepare the post-space were performed to assess whether these variables modify the bond strength of post to root canal dentin.

Forest plots were created to illustrate the meta-analyses. A modified chi-squared test (Cochran Q test) and the inconsistency I^2 test was used to calculate the statistical heterogeneity of the treatment effect among studies.

RESULTS

Search and Selection

The study selection process, conducted according to the PRISMA statement, is depicted in Figure 1. From 2832 potentially eligible studies, 2379 were not included for full-text reading, mainly because the post-space treatment was not applied to root dentin. Thus, 75 studies from 453 screened for full-text analysis were included in the systematic review.^{5,8,11-16,18,27-92} The main reasons for the exclusion of studies were: studies in which the treatment was not in the post-space and studies that did not present a control group.

Descriptive Analysis

Descriptive analysis of the included studies is shown in Table 1. All studies were published between 2005 and 2018, with the majority of studies being performed in Brazil ($n=35$) and Turkey ($n=13$).

Regarding language, 70 studies were published in English, two studies in Chinese, two studies in Portuguese and one study in Spanish. Among the included studies, 56 used human teeth and 19 used bovine teeth.

Nine different endodontic sealers were used in the included studies, including epoxy resin-based sealers ($n=37$), calcium hydroxide-based sealers ($n=17$), and zinc oxide and eugenol-based sealers ($n=6$). Most of the studies used AH Plus sealer ($n=30$), while 14 studies had no information about the endodontic sealer used.

Forty-three (43) different post-space treatments were evaluated in this review, with chlorhexidine being the most used solution ($n=28$). All post-space treatments in studies included in this systematic review that filled the root canal with epoxy resin-based sealer were evaluated, while only 19 post-space treatments were evaluated in studies using calcium hydroxide sealer. Only 10 post-space treatments were evaluated for studies using zinc oxide and eugenol-based sealer.

Regarding the storage time before post luting, most of the studies stored the specimens for one week ($n=32$), while the maximum storage period was two weeks and the minimum was 24 hours. Moreover, 16 studies did not have any information about the storage time before post luting.

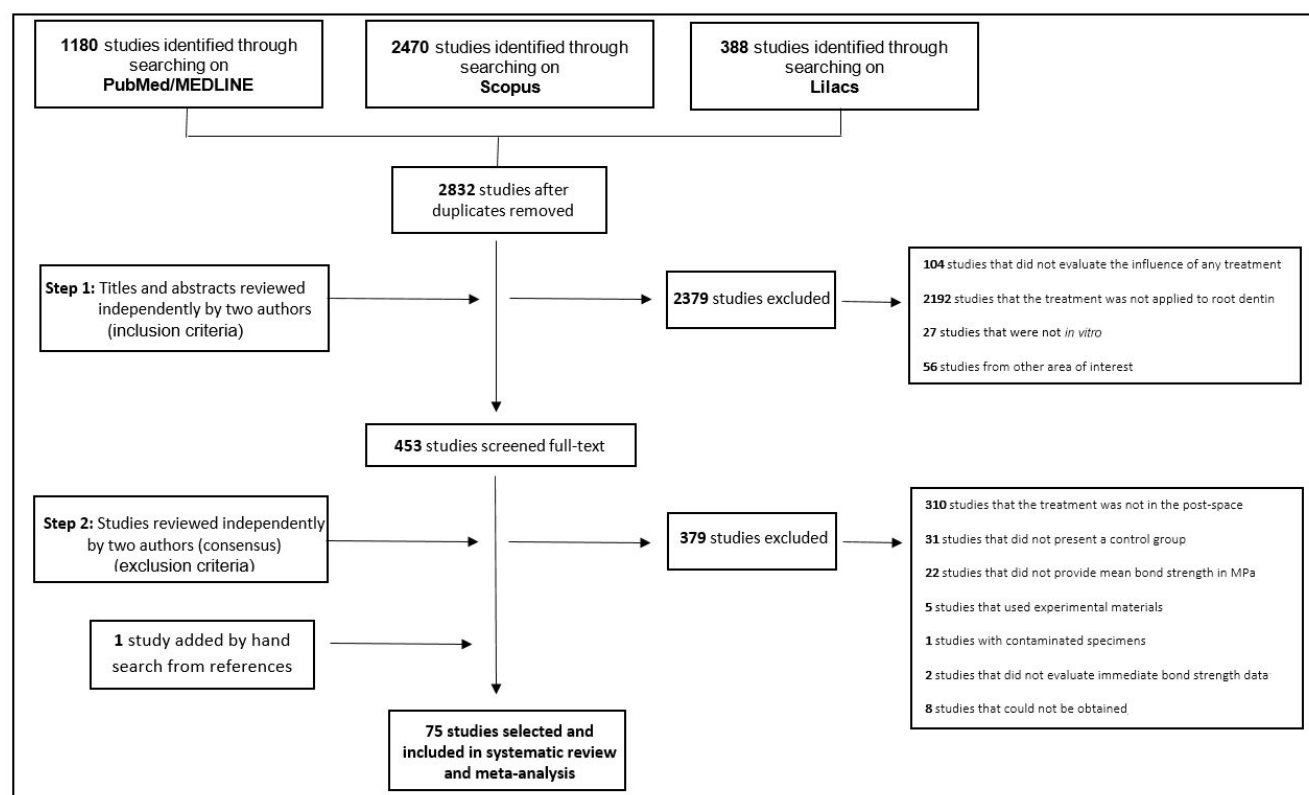


Figure 1. Flow diagram of study selection according to PRISMA statement. Abbreviations: MPa, megapascals.

Table 1: Description of Included Studies

Authors/Year	Country ^a	Language	Type of Teeth	Endodontic Sealer	Storage Time Before Luting	Post Space Treatments	Drills Used to Make Post Space	Type of Post	Cement	Storage Time Before Test	Bond Strength Test
Alaghemand & others ²⁷	Iran	English	Human upper central incisors & canine teeth	AH Plus	24 h	0.1 M EDTA; 99.6% Ethanol; 0.1 M EDTA + 99.6% Ethanol	2 DT light drill	DT light-post system	Panavia F 2.0	24 h	Push-out test
Alfredo & others ²⁸	Brazil	English	Human maxillary permanent canines	Sealer 26	2 d	17% EDTA + 1.0% NaOCl; Er:YAG laser irradiation	No. 6 Largo burr (1.7 mm diameter)	Cast post	Panavia F or zinc phosphate cement	3 d	Tensile strength test
Alkhudairy & others ¹¹	Saudi Arabia	English	Human maxillary permanent central & lateral incisors	AH 26	—	5.25% NaOCl; 2.5% NaOCl	Sequential reamers (3M ESPE)	RelyX Fiber Post, size # 3	RelyX-Unicem or MultiCore Flow	—	Push-out bond
Angeloni & others ²⁹	Italy	English	Human incisors	AH Plus	—	2% CHX	Calibrated burs (3M ESPE or Voco)	RelyX Fiber Post, size: yellow or Rebuilda Post, size: green	RelyX Unicem or Bifix SE	24 h/6 mo/1 y	Micro-push-out bond strength test
Arana & others ³⁰	Brazil	Spanish	Human mandibular premolar	AH Plus	1 wk	24% EDTA	Gates Glidden #2 & drill #2 provided by the post system's manufacturer	Exacto, size n° 2	Rely X U100 or Para Core Automix	24 h or Thermo-cycling 5000 cycles	Expulsion test
Arisu & others ³¹	Turkey	English	Human mandibular premolar	AH 26	24 h	2.25% NaOCl; 2.25% NaOCl+ 17% EDTA; diode laser (1.25 W)	Low-speed drill provided by the post system's manufacturer (Mirafit White Reamer)	Mirafit White, 1.35 mm in diameter	Panavia F 2.0	1 wk	Push-out test
Arslan & others ³²	Turkey	English	Human mandibular premolar	AH Plus	1 wk	5% NaOCl; 5% NaOCl + Ultrasonic irrigation; 5% NaOCl + Er:YAG laser (0.3 W, 15 Hz); EDTA + Er:YAG laser (0.3 W, 15 Hz); Er:YAG laser (0.3 W, 15 Hz)	Gates-Glidden drills & 1.4-mm size drill (Cytec Carbon)	Cytec Carbonsize 2 (1.4 mm diameter)	RelyX U200	24 h	Push-out test
Baena & others ³³	Spain	English	Single-rooted human teeth	AH Plus	1 wk	35% H3PO4; 17% EDTA; 25% Polyacrylic acid	Gates-Glidden drills 2, 3 & calibrated drills corresponding to the conical RelyX glass Fiber Post size #1 or #2	RelyX glass Fiber Post size 1 or 2	RelyX Unicem 2	1 wk	Push-out test
Bitter & others ³⁴	Germany	English	Human maxillary central incisors	AH Plus	24 h	5.25% NaOCl + ultrasonic irrigation; 1% NaOCl + ultrasonic irrigation; 5.25% NaOCl + EDTA; 2% CHX	Drill provided by the manufacturer of the fiber post system X Post size 4, or drill of the system FRC Post size 3	Fiber post system X Post size 4 or FRC Post size 3	Multicore Flow or SmartCem2 or CoreX Flow	-	Push-out test
Bordim & others ³⁵	Brazil	English	Bovine incisors	—	—	100% ethanol	—	White Post DC, size 4	AllCem dual-cure	24 h or 1 y	Push-out test
Carvalho & others ³⁶	Brazil	English	Human single-rooted & single-canal premolars	AH 26	24 h	99.6% ethanol	Drill recommended for RelyX Fiber Post size 2	RelyX Fiber Post, size 2	Dual Link	24 h	Push-out test

Table 1: Description of Included Studies (cont.)

Carvalho & others ³⁷	Brazil	English	Bovine incisor	AH Plus	1 wk	2.5% NaOCl; 100% ethanol; 2.5% NaOCl +100% ethanol	Largo burrs 3 & 4	Reforpost RX 2	RelyX ARC or RelyX U200	1 wk	Push- out test
Cecchin & others ⁵	Brazil	English	Bovine incisors	—	—	2% CHX in gel; 100% ethanol; 2% CHX in gel + 100% ethanol	—	Fiber post relining with resin composite was made with a fiber- glass post (Angelus) & composite resin (B0.5, Z250)	Rely X ARC	24 h or 1 y	Push- out test
Cecchin & others ³⁸	Brazil	English	Bovine incisors	—	—	2% CHX	—	Fiberglass posts no. 3 (Angelus) relined with composite resin (B 0.5, Z250)	Rely X ARC	24 h or 1 y	Push- out test
Cecchin & others ⁸	Brazil	English	Bovine incisors	—	—	2% CHX in a gel; 100% Ethanol; 2% CHX in a gel +100% ethanol	—	Fiber posts relined with resin composite was achieved with a fiber- glass post (Angelus 3) & composite resin (B0.5, Z250)	Rely X ARC	24 h or 250,000 cycles of me- chanical fatigue (1 y of clinical function)	Push- out test
Cintra & others ³⁹	Brazil	Portu- guese	Human premolars	Seala- pex	1 wk	2.5% NaOCl; 2% CHX; 17% EDTA	Drill 2 of fiber glass post sys- tem (Exacto)	Exacto 2	RelyX Unicem Aplicap	1 wk	Push- out test
Clavijo & others ⁴⁰	Brazil	English	Bovine incisors	Sealer 26	3 d	17% EDTA	Drills designated for the quartz coat- ed carbon fiber post Aestheti Post	Aestheti Post	RelyX ARC or RelyX U100 or Multilink	—	Push- out test
Crispim da Silveira & others ⁴¹	Brazil	English	Bovine incisors	Sealer 26	24 h	5.25% NaOCl + 17% EDTA; 5.25% NaOCl; 17% EDTA; 2% CHX in gel; 70% ethanol; polyacrylic acid;	Gates Glidden 4 drill & Largo drill 5	Reforpost	RelyX U100	24 h	Push- out test
Culhaoglu & others ⁴²	Turkey	English	Human incisors	—	—	2% CHX; 5.25% NaOCl+17% EDTA; 5% boric acid; 10% boric acid	—	Panavia Post (18 mm long & 1.44 mm in diameter)	Panavia F 2.0 or Pana- via SA	1 wk	Push- out test
da Cunha & others ¹⁴	Brazil	English	Bovine incisors	Sealer 26	1 wk	5.25% NaOCl; 5.25% NaOCl + 10% ascorbic acid	Drills supplied by the manufacturer of the fiber posts (Exacto 3)	Exacto 3	RelyX U100 or RelyX ARC	24 h	Push- out test
Da Silva & others ⁴³	Brazil	English	Human maxillary canines	Sealer 26	3 d	2% CHX in gel; 20.3% EDTA +1% NaOCl; Xylene	First (1) & second (2) drills of the 2 C-Post carbon fiber post system	C-Post #2	Hi-X cement	24 h	Tensile- bond- strength test
De Araújo & others ⁴⁴	Brazil	English	Bovine roots	Sealer 26	1 wk	2% CHX; 11.5% polyacrylic acid; 11.5% polyacrylic acid + 2% CHX	Gates-Glid- den drill 2 & low-speed drill provided by the post system's manufacturer	Exacto 2	RelyX ARC or RelyX Luting 2	1 wk or 6 mo	Push- out test

Table 1: Description of Included Studies (cont.)

de Oliveira & others ⁴⁵	Brazil	English	Bovine incisors	Endofill	1 wk	70% ethanol; acetone; 70% isopropyl alcohol	Using a heated Rhein instrument (1) followed by Largo burs 3	Glass fibre posts (Angelus) were relined with composite resin (Z250)	RelyX ARC	1 wk	Push-out test
Duski & others ⁴⁶	USA	English	Human premolars	AH Plus	—	2% CHX	A series of sequential reamers provided for the post (Rely-X Fiber Post 2)	Rely-X Fiber Post 2	RelyX ARC or RelyX Unicem	Immediate or Thermo-cycling 20,000 cycles or 40,000 cycles	Push-out test
Ekim & Erdemir ⁴⁷	Turkey	English	Human maxillary central teeth	AH Plus	1 wk	2.5% NaOCl + 17% EDTA; 2.5% NaOCl + 17% EDTA + ULTRASONIC; 2.5% NaOCl + 17% EDTA + apical negative pressure; 2.5% NaOCl + 17% EDTA + diode laser; 2.5% NaOCl + 17% EDTA + Nd:YAG laser; 2.5% NaOCl + 17% EDTA + Er:YAG laser; 2.5% NaOCl + 17% EDTA + Er:YAG laser + photon-induced photoacoustic streaming	Post drills (White Post DC, drill, 1)	White Post DC, 1	Panavia F 2.0	24 h	Push-out test
Elnaghy & others ⁴⁸	Egypt	English	Human teeth	AH Plus	1 wk	5.25% NaOCl; 2% CHX; 17% EDTA; 17% EDTA + 2% CHX; Qmix	Drill provided with the post system (Rebilda post)	Rebilda post, Ø 1.5	i Cem	1 wk	Micro-push-out bond strength
Ertas & others ⁴⁹	Turkey	English	Single-rooted human teeth	AH Plus	24 h	5.25% NaOCl; 2% CHX; 100% ethanol; 5.25% NaOCl + 17% EDTA; 5.25% NaOCl + 17% EDTA + 2% CHX; 5.25% NaOCl + 17% EDTA + 100% ethanol; 5.25% NaOCl + 17% EDTA + PAD (FotoSan Agent, photoactivated disinfection).	Post drill	UniCore, 1.5-mm	Bifix SE	—	Push-out test
Fan & others ⁴⁹	China	English	Human single-canal premolars	AH Plus	1 wk	2.5% NaOCl; 17% EDTA + 2.5% NaOCl; 7% maleic acid + 2.5% NaOCl	Drill provided with the post system until size 3	Fiber posts (3M ESPE)	Rely X U200	1 wk	Micro-push-out
Faria-e-Silva & others ⁵⁰	Brazil	English	Bovine incisors	Sealer 26	3 d	5% NaOCl; 17% EDTA; 11.5% polyacrylic acid	Drills available in the post kit	White Post DC3	RelyX Unicem or BisCem	1 wk	Push-out test
Feng & Gao ⁵¹	China	Chinese	Human mandibular canines or premolars	—	3 d	35% H3PO4; primer Clearfil SE Bond; 35% H3PO4 + Single Bond 2; primer Clearfil SE Bond + bond Clearfil SE Bond	Drills of post	Macro-Lock Post 3	Embrace Core Resin Cement	24 h	Push-out test

Table 1: Description of Included Studies (cont.)

Furuse & others ⁵²	Brazil	English	Bovine incisors	Sealer 26	1 wk	5.25% NaOCl; 5.25% NaOCl + 10% ascorbic acid	3 Largo & burs provided by the post manufacturer (Exacto)	Exacto 3	RelyX ARC	24 h	Push-out test
Garcia & others ⁵³	Brazil	English	Human maxillary canines	EndoFill	2 d	Diode laser (power of 1.5 W & a frequency of 100 Hz)	Low-speed post preparation bur was used (FibreKor Post System)	FibreKor Post System 2	Rely-X Unicem or Cement-Post	—	Push-out test
Garcia & others ⁵⁴	Brazil	English	Human maxillary canines	Endofill	2 d	Diode laser (1.5 W/100 Hz); diode laser (1.5 W/continuous wave); diode laser (3.0 W/100 Hz); diode laser (3.0 W/continuous wave);	Post preparation bur (FibreKor Post System)	Parallel fiber-glass posts 2 (Angelus)	Cement-Post	—	Push-out test
Garcia & others ⁵⁵	Brazil	English	Human mandibular premolars with single canals	Sealer 26	1 wk	5% NaOCl; 17% EDTA +5% NaOCl; 17% EDTA	Low-speed drill provided by the post system manufacturer	White Post - DC 2	RelyX U100	24 h	Push-out test
Gomes França & others ⁵⁶	Brazil	English	Bovine roots	—	—	2% CHX; 100% ethanol	Largo Peeso Reamers at increasing diameters until reaching 4	Reforpost 2	Rely X ARC	2 d or 6 mo	Push-out test
Gorus & others ⁵⁷	Turkey	English	Single-rooted & single-canaled human teeth	—	—	Er: YAG laser (15 Hz/0.6 W) + 0.5% NaOCl	Drill of the post system (Snow-fiber post-drill, 1.0)	Snowpost	Clearfil SA	24 h	Push-out test
Jain & others ⁵⁸	India	English	Single-rooted human teeth	AH Plus	24 h	10% sodium ascorbate; 10% hesperidin; 1% riboflavin 5 phosphate	Drill for Hi-Rem posts size #1	Hi-Rem, size #1	Rely X ARC	—	Push-out test
Kirmali & others ⁵⁹	Turkey	English	Single-rooted human maxillary incisors	AH Plus	1 wk	Er,Cr:YSGG laser (20 Hz/1W); Er,Cr:YSGG laser (20 Hz/2W); Er,Cr:YSGG laser (20 Hz/3W)	Drill by the manufacturer with a 1.5 mm tip diameter.	Rebilda, 15	Grandio Core Dual Cure	1 wk	Push-out test
Kul & others ⁶⁰	Turkey	English	Mandibular premolar human teeth	AH Plus	1 wk	5.25% NaOCl+17% EDTA; 2% CHX; 35% H3PO4	1 Peeso reamer, & preparation of the post was completed with a number 1 drill (DT Light-Post System)	DT Light-Post System	RelyX U200	24 h	Push-out test
Lacerda & others ⁶¹	Brazil	English	Bovine teeth	Sealer 26	1 wk	2% CHX; 2.5% NaOCl; ultrasound; 2% CHX + ultrasound; 2.5% NaOCl + ultrasound	Burs of the system of glass fiber post (White Post DC3 & DC4)	White Post DC3 & DC4	Bifix QM	1 wk	Push-out test
Lacerda & others ⁶²	Brazil	English	Single-rooted human premolar teeth	—	—	1% NaOCl; 2% CHX gel	Largo burs 2, 3 & 4	Reforpost	RelyX ARC or RelyX U100	1 wk or 6 mo	Push-out test
Leitune & others ⁶²	Brazil	English	Human upper central incisor teeth	—	—	0.2% CHX; 2% CHX	2 drill from the Exacto post system	Exacto	RelyX ARC	24 h or 6 mo	Push-out test
Lima ⁶³	Brazil	English	Bovine incisors	AH Plus	2 d	17% EDTA; 11.5% Polyacrylic acid; NaOCl	Gates-Glidden 3 & post drill 3	White post DC 3	Variolink II or RelyX U100 or Maxcem Elite	24 h	Push-out test

Table 1: Description of Included Studies (cont.)

Mao & others ⁶⁴	China	English	Human maxillary central incisors	AH 26	1 wk	10% NaOCl; 17% EDTA + 5.25% NaOCl	D.T. Pre-Shaping Drills 3	D.T. light-post 3	Duo-Link or LuxaCore Dual	1 wk	Push-out test
Martinho & others ⁶⁵	Brazil	English	Bovine incisors	Sealer 26	1 wk	2% CHX; 2.5% NaOCl; ultrasound; Nd:YAG laser (15 Hz/ 1.5 W); 2% CHX + ultrasound; 2% CHX + Nd:YAG laser (15 Hz/ 1.5 W); 2.5% NaOCl+ ultrasound; 2.5% NaOCl + Nd:YAG laser (15 Hz/ 1.5 W)	—	White Post DC4	Bifix QM	1 wk	Push-out test
Mathew & others ⁶⁶	India	English	Uniradicular human teeth	AH Plus	24 h	5% NaOCl + 17% EDTA; diode laser (3W)+5% NaOCl	(0.70 mm) peeso reamer 1, & preparation was completed using drill number 1 (Hi Rem Endod Drill 201)	Hi Rem Over, size 1	G Cem or GC Pro	24 h	Push-out test
Mohammadi & others ⁶⁷	Iran	English	Human maxillary central incisors	AH 26	24 h	Er,Cr:YSGG laser (0.5W+ 20% water & air level) +(2.5W + 50% air & water level)	Peeso reamers 4, 3, 2 & he special drills provided by the manufacturer fiber posts (Endolight Post)	Endolight Post	Maxcem Elite	24 h	Push-out test
Neelakantan & others ⁶⁸	India	English	Human single-rooted maxillary central incisors	AH Plus	1 wk	3% NaOCl; 3% NaOCl + 17% EDTA; 6% NaOCl + 18% etridronic acid; 3% NaOCl + Qmix	This was accomplished using a warm plugger (E&Q Plus). Post-space preparation was performed using the post-specific drill (Rely X fiber post)	RelyX fiber post	Rely X Unicem or Fusion Ultra DC	24 h or 4 mo	Push-out test
Oral & others ⁶⁹	Turkey	English	Human single-rooted maxillary anterior teeth	—	—	2.5% NaOCl + Er:YAG Laser; 2% CHX + Er:YAG Laser; Slurry Bioactive Glass Granules; Silane-based Primer+ Er:YAG Laser; Slurry Bioactive Glass Granules + Silane-based Primer + Er:YAG Laser	ParaPost up to diameter of 1.75 mm with increasing drills of 1.14, 1.25, 1.40, 1.50 & 1.75 mm from 1 mm coronal level of apices.	EverStick POST (1.5mm)	ParaCem	—	Push-out test
Parčina Amižić & others ⁷⁰	Croatia	English	Single-rooted human premolars	AH Plus	1 wk	Er:YAG laser with photon-induced photoacoustic streaming (PIPS) tip; Er,Cr:YSGG laser with radial-firing (RFT2) tip	Gates Glidden 4 burs	everStick POST, diameter 1.2 mm	G-Cem	—	Micro push-out bond strength
Ramos & others ⁷¹	Brazil	English	Human canines	AH Plus	1 wk	Photodynamic therapy	2 bur (White Post DC System)	White Post DC System 2	Relyx ARC or Relyx U200	24 h	Push-out test

Table 1: Description of Included Studies (cont.)

Ramos & others ⁷²	Brazil	English	Human canines	AH Plus	1 wk	Photodynamic therapy	# bur (White Post DC System)	White Post DC System #2	RelyX U200 Automix or Gold Label 1	24 h	Push-out test
Santos & others ⁷³	Brazil	English	Bovine incisors	—	—	2% CHX; 100% Ethanol; 100% Ethanol+ 2% CHX	—	Reforpost	Rely X U200	1 wk after obtain slices, the specimens were tested in time intervals of 2 d & 6 mo	Push-out test
Scotti & others ⁷⁴	Italy	English	Human single-rooted teeth	Pulp Canal Sealer EWT	24 h	32% H ₃ PO ₄	—	Fiber post	Bisfill 2B	1 wk	Push-out test
Scotti & others ⁷⁵	Italy	English	Single-rooted human teeth	Pulp Canal Sealer EWT	1 wk	10% EDTA; 10% EDTA + Teethmate Desensitizer; Teethmate Desensitizer	Largo drills 1 & also dedicated drills (EasyPost 3)	Radix 3	Panavia SA	1 wk	Push-out test
Seballos & others ¹⁶	Brazil	English	Single-rooted premolars human	AH Plus	1 wk	2%CHX; 1% NaOCl; 2.5% NaOCl; 5% NaOCl; 1% CaOCl; 2.5% CaOCl; 5% CaOCl	2, 3, 4 Largo drills & fiber post bur	Exacto Translúcido N2	RelyX U200	48 h	Push-out test
Shafiei & others ⁷⁶	Iran	English	Human maxillary central incisors	AH26	1 wk	EDC (1-ethyl-3-(3-dimethylaminopropyl) carbodiimide pretreatment was included in the adhesive; 18%EDTA; 18%EDTA +EDC;	Drills (2) from the respective post manufacturer	FRC Postec Plus No. 2	Variolink II or Panavia F2.0 or Clearfil SA	1 wk or 1 y	Push-out test
Shafiei & others ⁷⁷	Iran	English	Human maxillary central incisors	—	1 wk	2% CHX; Chlorhexidine diacetate added to a mixture of ED primer; 2% CHX; Chlorhexidine diacetate incorporated Clearfil SE Bond	Drills provided by the post manufacturer	Glassix Post	Panavia F2.0	1 wk or 2 y	Push-out test
Shafiei & others ⁷⁸	Iran	English	Human maxillary central incisors	AH26	1 wk	1% NaOCl; 17%EDTA	Drills from the post manufacturer	Fiber posts	Duo-link	1 wk	Push-out test
Silva ⁷⁹	Brazil	Portuguese	Bovine incisors	Sealer 26	24 h	2% CHX	Drill with 1.5 mm diameter from post manufacturer	Exacto 2	RelyX ARC	1 wk or 6 mo or 1 y	Push-out test
Simões & others ⁸⁰	Brazil	English	Single-rooted human premolars	Sealer 26	24 h	17% EDTA; 35% H ₃ PO ₄	Exacto drill 2	Exacto 2	RelyX ARC or RelyX U200 Automix	24 h or 6 mo	Push-out test
Simões & others ⁸¹	Brazil	English	Single-rooted human premolars	Sealer 26	24 h	11.5% polyacrylic acid	Drill number 2 was used (Angelus)	Exacto # 2	RelyX ARC or RelyX U200 Automix	24 h or 6 mo	Push-out test

Table 1: Description of Included Studies (cont.)

Tuncdemir & others ⁸²	Turkey	English	Human maxillary central incisors	AH Plus	1 wk	5.25% NaOCl; 17% EDTA; 37% orthophosphoric acid; Diode laser (wave-length of 660 nm, output power of 75 mW)	Matching drill	Snowlight Post 14	Clearfil SA	—	Push-out test
Uzun & others ⁸³	Turkey	English	Human mandibular premolars	AH Plus	2 d	Er:YAG laser (1.5-W, 15-Hz)	(1) Oval fiber post + Ellipson tip group: An oval sectioned ultrasonic tip (Ellipson tip) mounted in Suprasson; (2) Circular fiber post + Unicore drill group: A dedicated drill (Unicore)	Oval posts (Ellipson posts), circular posts (Unicore posts size 2)	RelyX Unicem	24 h	Push-out test
Victorino & others ⁸⁴	Brazil	English	Human canines	AH Plus	1 wk	1% CHX diacetate; 1% CHX diacetate + 99% ethanol; 99% ethanol; 2% CHX	Unicore Drill 2	Unicore Post	PermaFlo DC	24 h	Push-out test
Wang & others ⁸⁵	Brazil	English	Bovine roots	Sealer 26	1 wk	2% CHX	Gates drill 2 & drill provided by the manufacturer of the post-system	Exacto posts, (2)	Rely X ARC	1 wk	Push-out test
Wu & others ⁸⁶	China	English	Human incisors & premolars	—	—	Irradiation unit in conjunction with a transparent light-guiding attachment; 17% EDTA + 5% NaOCl + irradiation unit in conjunction with a transparent light-guiding attachment	Diameter of 1.5mm using preparation drills (Para Post Drill #6)	Para Post Fiber White	DC Core Automix Dentin	24 h	Microtensile bond strength
Xia & Cheng ⁸⁷	China	English	Human premolars	RealSeal SE	3 d	2.5% NaOCl; 17% EDTA + 2.5% NaOCl; 17% EDTA+2.5% NaOCl+ ultrasound	Size 3 universal drill (RelyX Fiber Post system)	RelyX Fiber Post system	RelyX Unicem	24 h	Push-out test
Yaman & others ⁸⁸	Turkey	English	Permanent human lower premolars	AH Plus	24 h	Clearfil SE Primer; 37% H ₃ PO ₄ ; ≥99.5% Ethanol; 2% CHX	Largo Peeso Reamer & drill corresponding to the size of the FP (ICELight reamer)	ICELight, 1.4 mm	Clearfil SA Cement Automix	24 h	Microtensile bond strength
Yu & others ⁸⁹	China	English	Human premolars	AH Plus	3 d	5.25% NaOCl; 5.25% NaOCl + EGCG irrigant; 5.25% NaOCl + anhydrous ethanol *EGCG was dissolved in anhydrous ethanol at the concentration of 400 µg/mL to prepare the EGCG irrigants	Rely X Fiber Post drill 3	Rely X Fiber Post	Clearfil DC Core Auto-mix	24 h or thermo-cycling for 10,000 cycles	Push-out test
Zhang & others ¹⁸	China	English	Human premolars	AH Plus	3 d	35% H ₃ PO ₄ ; 17% EDTA+ 5.25% NaOCl; 17% EDTA+ 5.25% NaOCl + ultrasound	#2 Peeso reamer & #3 DT drill from DT Light-Post system	#3 DT Light posts	Clearfil SE Bond or Clearfil DC Bond	—	Push-out test

Table 1: Description of Included Studies (cont.)

Zhou & others ⁹⁰	China	English	Human maxillary anterior teeth	VitaPex	—	0.5% CHX; 1% CHX Different amounts of 20% chlorhexidine digluconate were added directly into ED primer to prepare mixtures containing three different concentrations of chlorhexidine: 0%, 0.5% & 1.0%	Gates-Glidden drills #2 & post drills provided by the post manufacturer	LuxaPost, 1.5 mm diameter	Panavia F	24 h or 18 mo	Push-out test
Zhu & others ⁹¹	China	Chinese	Human mandibular premolars	AH 26 or AH Plus	1 wk	17% EDTA + 5.25% NaOCl; 17% EDTA + 5.25% NaOCl + ultrasound	—	Fiber posts	RelyX Unicem	1 wk	Push-out test
Çökük & others ¹³	Turkey	English	Human maxillary central incisors	MM Seal	1 wk	5% NaOCl; 2% CHX; 1.5W Er, Cr: YSGG laser; 1.25W Er, Cr: YSGG laser	Exacto drill 2 of fiber glass post system	Exacto	Panavia F2.0	1 wk	Push-out test
Šimundić Munić & others ⁹²	Croatia	English	Anterior single-rooted permanent human teeth	AH Plus	2 wk	Er:YAG (pulse energy 20 mJ, pulse duration 50 µs, pulse repetition rate 15 Hz, energy density 2.06 J/cm ² .); Er:YAG + QMiX solution; Er,Cr:YSGG (power 1.25 W, repetition rate 20 Hz, pulse duration 140 µs, pulse energy 62.5 mJ); Er,Cr:YSGG + QMiX solution; Nd:YAG laser (pulse energy 100 mJ, repetition rate 10 Hz, medium power 1.5W, pulse duration: 100 µs, energy density 140.85 J/cm ²)	Drill, size 1 (diameter 0.8 mm at the tip), provided by the post system's manufacturer	FRC Postec Plus size #1	Speed CEM	1 wk	Push-out test

^aCountry of the first author. Abbreviations: EDTA, ethylene diamine tetra acetic acid; NaOCl, sodium hypochlorite; CHX, chlorhexidine digluconate; H3PO, phosphoric acid; EGCG, flavonoid produced in large amounts as a secondary metabolite by the *Camellia sinensis* plant, green tea; Er:YAG, erbium-doped yttrium aluminium garnet laser; Er,Cr:YSGG, erbium, chromium-doped:yttrium, scandium, gallium, & garnet; Nd:YAG, neodymium-doped yttrium aluminium garnet; CaOCl, calcium hypochlorite. "—" signifies information is unclear in the paper.

In analyzing the type of drills used to make the post-space, most of the studies only used the drill of the post systems (n=43), and nine studies did not have this information. Sixty-eight studies (68) used fiber post, four studies used fiber post relining, two studies used carbon fiber post, and one study used cast post.

In total, 41 commercial cements were used, and three of them were not resin cement, as follows: one zinc phosphate cement, one glass ionomer cement, and one resin-modified glass ionomer. The resin cement most used was RelyX ARC (3M Oral Care, St Paul, MN, USA) resin cement (n=19).

The maximum storage time before the bond strength test was two years, and minimum storage time was 24 hours. The most commonly employed method for evaluating bond strength was the push-out test (n=66).

Meta-Analyses

Post-space treatment improved the bond strength of posts to root canal dentin, as significant differences were found between the control and experimental groups ($p < 0.00001$) (Figure 2). A subgroup meta-analysis also showed improved bond strength when post-space treatment was done using ethanol ($p < 0.0001$), NaOCl

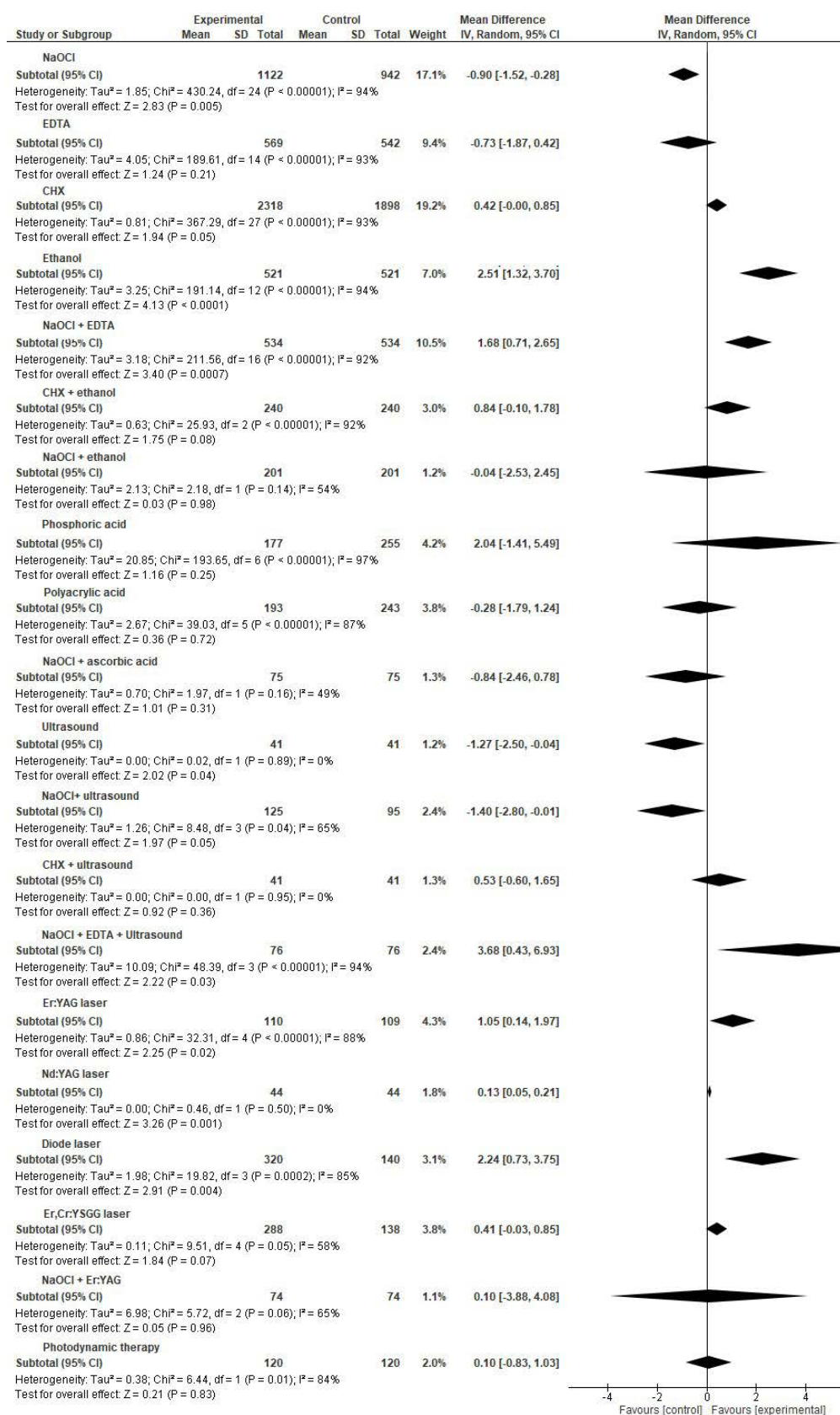


Figure 2. Forest plot of global meta-analysis. Abbreviations: CI, confidence interval.

+ EDTA ($p=0.0007$), NaOCl + EDTA + Ultrasound ($p=0.03$), Er:YAG laser ($p=0.02$), Nd:YAG laser ($p=0.001$), and diode laser ($p=0.004$) (Figure 3).

Moreover, subgroup analyses (endodontic sealer, post-time for post luting, type of post, drills used to make post-space, resin cement, post-waiting time for the test, and thirds of root) were performed (Figure 4). Most factors in the subgroup analyses affected the results of the meta-analysis, except for resin cement, post-waiting time for tests, and different thirds of the root canal.

High heterogeneity was found in the global meta-analysis and subgroup meta-analyses ($I^2>50\%$).

Risk of Bias

The majority of the included studies were scored as having a high risk of bias ($n=52$),^a whereas only one study was scored as low risk of bias.¹⁶ The items which were not described in the majority of studies were blinding of the operator of the test machine (97.33%), sample size calculation (97.33%), post luting procedures performed by the same operator (94.67%), and post-space treatment performed by a single operator (90.67%) (Table 2).

DISCUSSION

This systematic review and meta-analysis aimed to verify whether post-space treatments would improve the bond strength of posts to root canal dentin. In general, the post-space treatment has a positive influence on the bond strength of intraradicular posts compared to the control group. A meta-analysis of the data leads to rejecting the null hypothesis, as bond strength to root canal dentin was higher when the post-space was treated.

The formation of debris and residues in the canal during the post-space preparation can affect intraradicular posts adhesion.^{5,6,8-10} In addition, endodontic sealer residues might also interfere on degree of conversion of cement used for post luting.^{26,97} Moreover, the presence of the smear layer impairs adequate contact between adhesive systems/cement used for bonding the post and the root canal.⁹⁴ In this sense, the use of post-space treatment can improve the post adhesion in root canal dentin, removing partial or total debris of the root canal, and promoting the opening of dentinal tubules.¹⁸

In total, 43 post-space treatments were evaluated by studies included in this systematic review, but not all treatments increased the bond strength values. Among the post-space treatments analyzed, the treatments that improved the bond strength values were: ethanol

(in concentrations ranging between 70% and 100%), NaOCl (1% to 5.25%) + EDTA (17% to 20.3%), NaOCl (2.5%) + EDTA (17%) + Ultrasound, Er:YAG laser, Nd:YAG laser, and diode laser.

Ethanol was used in 13 studies. It is considered a bipolar solvent and may be a good option for dentin cleaning because it dissolves both polar and non-polar compounds.⁴⁵ Furthermore, this substance acts in controlling humidity in the depth of the root canal, making the collagen matrix from the post-space more hydrophobic due to the substitution of water by ethanol, and thus can improve the adhesive strength of the post and reduce the degradation of the adhesive layer.¹⁰ Moreover, the combination of NaOCl + EDTA treatment was evaluated in 17 studies, and this treatment is indicated for smear layer removal due to the intrinsic properties of these two solutions. NaOCl is an excellent proteolytic agent promoting a greater dissolution of organic compounds, thereby cleaning the root canal.¹⁷ In addition, EDTA has also shown to be effective in removing this smear layer. EDTA is a demineralizing agent, and has the ability to chelate calcium ions, to dissolve inorganic material such as hydroxyapatite, and it has little or no effect on the organic material.¹⁷ The use of ultrasound activation associated with NaOCl + EDTA in this study does not seem to affect the efficacy of this treatment, and the dentist may choose to use or not use this additional treatment.

The post-space preparation with lasers could be able to improve bonding to root canal dentin compared to the control group; however, few studies evaluated laser treatment; only four studies considered Er:YAG laser, two considered Nd:YAG laser, and four compared the diode laser. The treatment with Er:YAG laser increased dentinal permeability, had a thermomechanical effect on the hydrated component of surface dentin leading to ablation and water evaporation, and micro explosions eject organic and inorganic tissue, promoting clean dentinal walls and open tubule orifices.^{83,95} Studies in the literature showed that Nd:YAG laser irrigation promoted morphological alterations such as melting, resolidification, and formation of small globules in dentin surface.^{92,96} Furthermore, the diode laser has been recommended in the literature because it is efficient in removing the smear layer and debris from root canals.^{97,98}

Despite not increasing the bond strength of the post to root dentin, chlorhexidine was the most used treatment among the studies included in this meta-analysis. Chlorhexidine has antibacterial action, substantivity, and biocompatibility.^{29,38,42,44} Also, it is a non-toxic MMP inhibitor, intending to preserve the stability of the bond strength over time.^{29,56} However,

^a 11-15, 18, 28, 30-32, 34, 36, 38, 40-44, 46-52, 55-63, 66-71, 73-75, 80-82, 86, 88-92

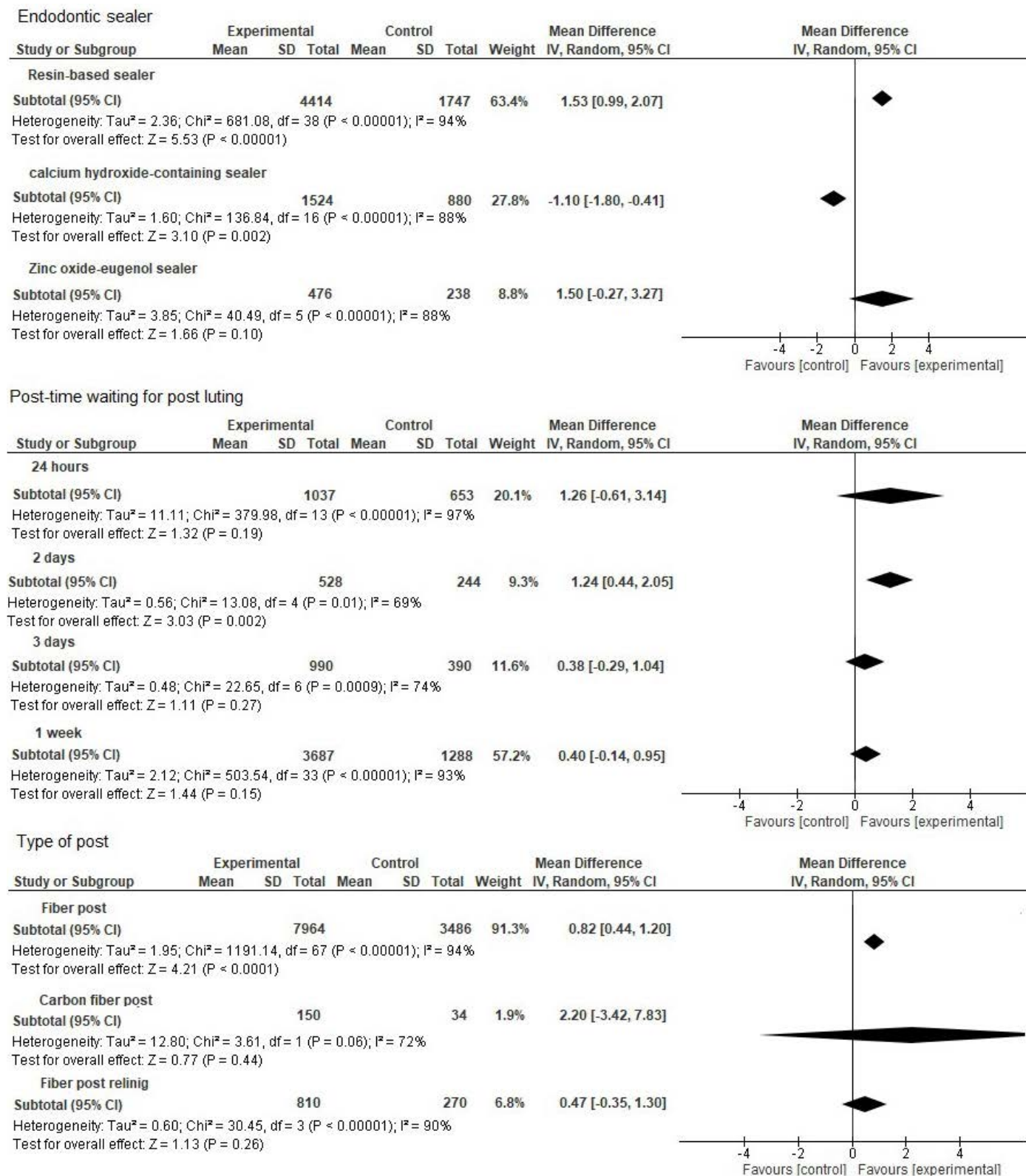


Figure 3. Forest plot of post space treatments analyzed separate. Abbreviations: CI, confidence interval.

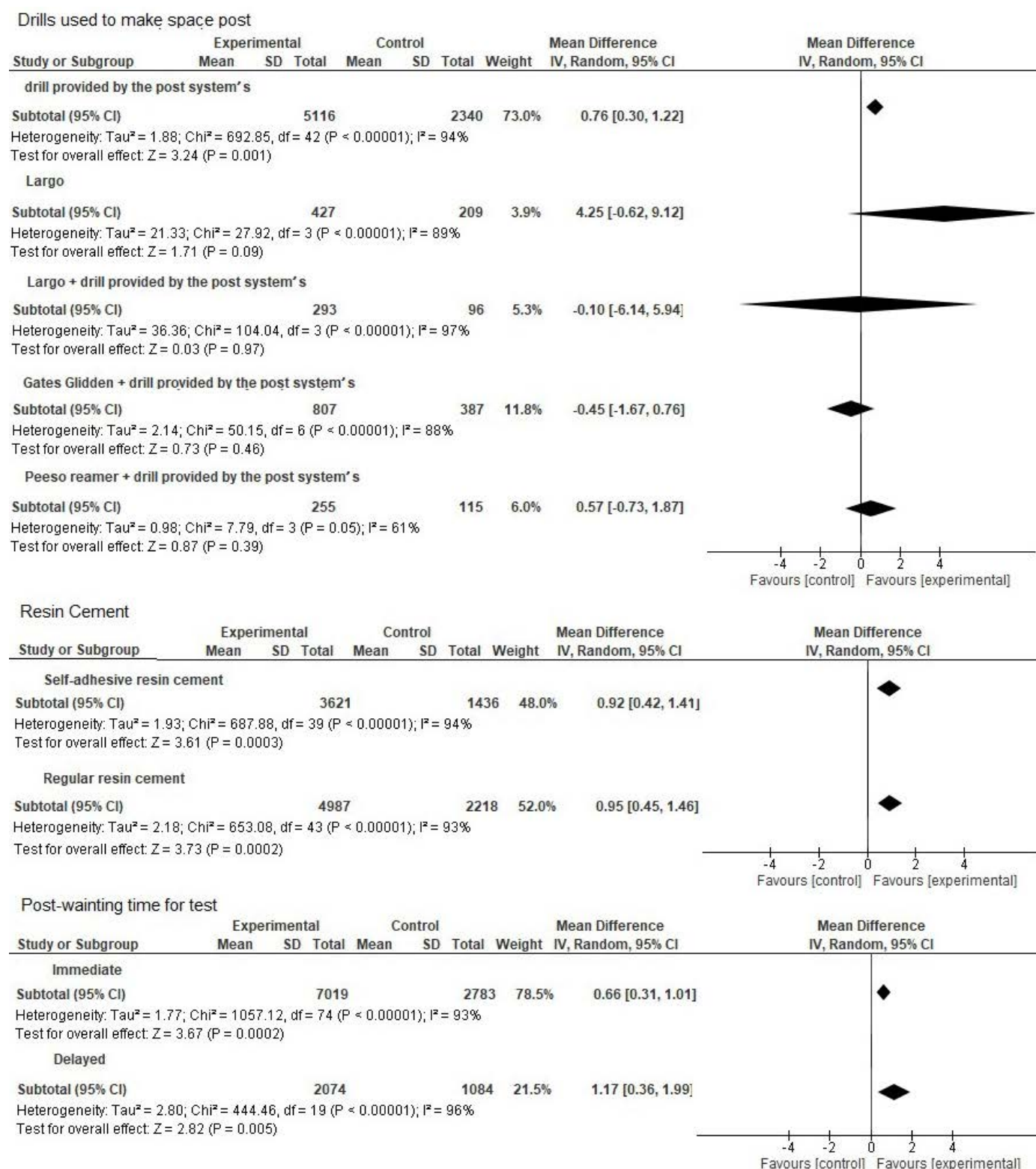


Figure 3. Forest plot of post space treatments analyzed separate. Abbreviations: CI, confidence interval. (cont.)

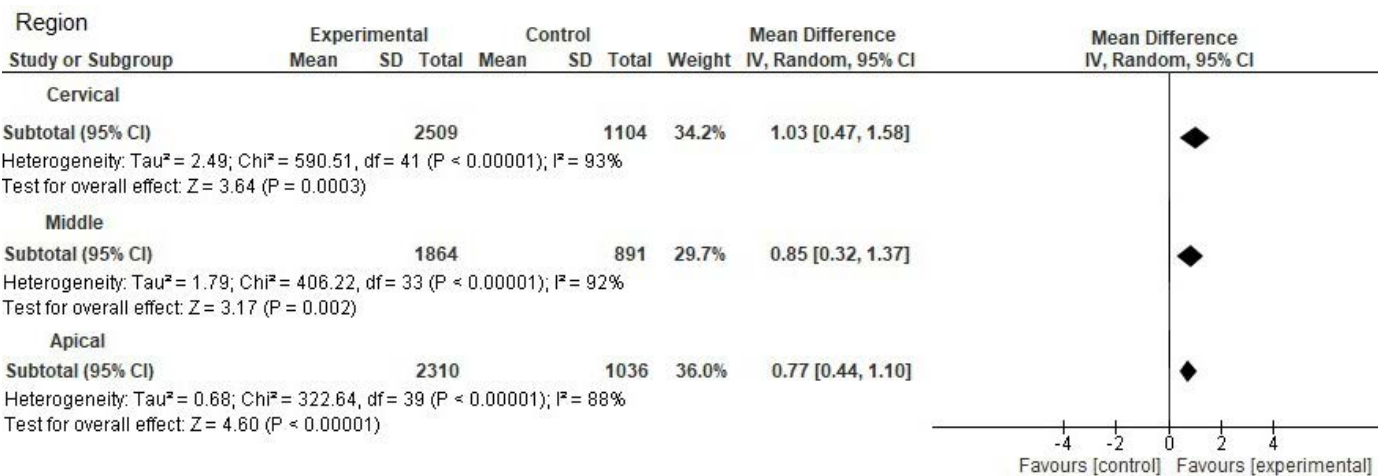


Figure 3. Forest plot of post space treatments analyzed separate. Abbreviations: CI, confidence interval. (cont.)

for the post-space treatment, chlorhexidine does not seem to be effective.

Moreover, subgroup analyses were performed evaluating different factors that can affect the efficiency of post-space treatments. For the overall data, the type of endodontic sealer used seems to affect the treatment action. Also, other studies in the literature showed that the type of canal sealer can affect the bond strength of the fiber post.^{26,93} For the resin-based sealers, the post-space treatments are effective in improving the post bond strength. The resin-based sealer is considered in the literature as the gold standard because this sealer does not affect the post retention.⁹⁹

On the other hand, different treatments decreased or showed no difference in the bond strength for calcium hydroxide sealers and zinc oxide-eugenol sealers, respectively. In contrast, the literature showed higher bond strength values of a post in root canals filled with a sealer containing calcium hydroxide compared with other sealers; this can be explained by the isobutyl salicylate present in this sealer, which reacts with calcium creating a physiochemical barrier that may have influence on cement adhesion.^{93,100} However, this sealer seems to affect the post-space treatment because the control group achieved the highest bond strength values of the post. Eugenol-based sealers have lower bond strength values than other sealers because they interfere with polymerization of cement used for post luting.⁹⁹ The post-space treatment evaluated with this sealer does not seem to affect the post retention. However, this result should be evaluated with caution since only 10 treatments were evaluated for this sealer.

Regarding the storage time before post luting, there is no difference between post-space treatment and the control group, except for the two-days subgroup. However, it should be considered that they do not have

a long storage period, and only five studies used two days of storage. This analysis is essential because the prolonged contact of endodontic sealer with dentin walls may affect the adhesion of the post through the penetration of molecules of endodontic sealer in dentinal tubules.^{101,102} A more extended storage period and more endodontic sealer molecules would be able to penetrate dentin walls, and post-space treatments would be necessary for the removal of these molecules. Therefore, the post-time waiting for post luting is influenced by the type of endodontic sealer used for filling the root canal.¹⁰³

In the subgroup analysis of the type of post, the fiber post showed that the post-space treatment improved the post retention. In the literature, one systematic review found the same result for fiberglass posts; this study shows that the root canal cleaning can affect the bond strength of the fiberglass post and that NaOCl + EDTA was recommended.¹⁰⁴ Other types of posts should be analyzed with caution, as there are few studies included in this present review that used carbon fiber post (n=2), fiber post relining (n=4), or cast post (n=1).

Post-space preparation may interfere in the post retention due to the effect of the drill used, which may remove variable amounts of gutta-percha and dentin, and generate a temperature increase on the root surface, which may form cracks or fractures in the intraradicular dentin.¹⁰⁵⁻¹⁰⁸ In this systematic review, the post-space treatment was only efficient for drills provided by the post system's subgroup. Other types of drills should be considered with caution due to the presence of few studies that used each of the following drills: Largo drill (n=4), Largo drill + drill provided by the post system (n=4), Gates Glidden drill + drill provided by the post system (n=7) and Peeso Reamer drill + drill provided by the post system (n=4).

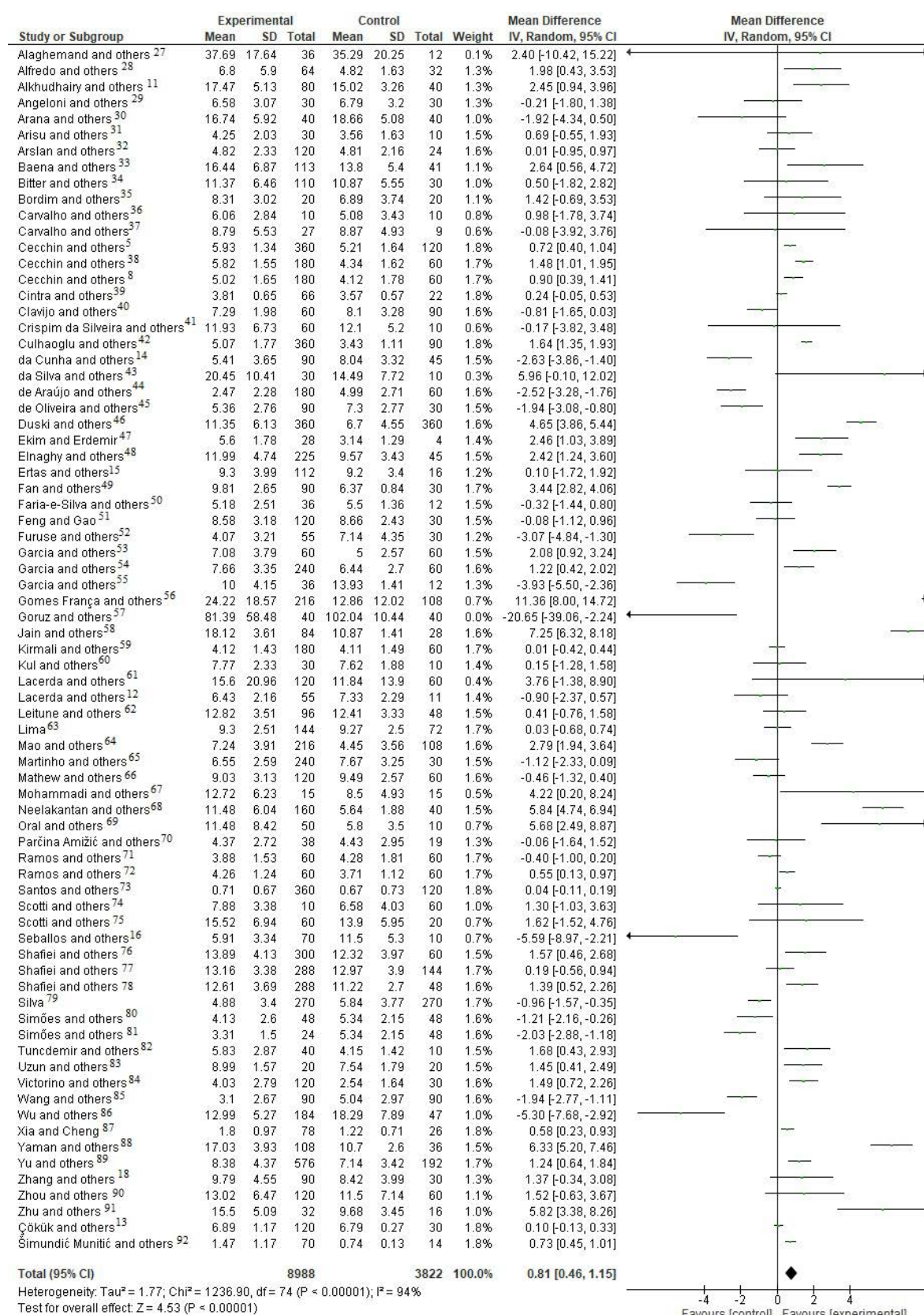


Figure 4. Forest plot of analysis subgroup of global data. Abbreviation: CI, confidence interval.

Table 2: Risk Bias of the Studies Considering Aspects Reported in Methods & Materials Section

Article	Randomization Teeth	Sample Size Calculation	Used Materials According to the Manufacturer's Instruction	Teeth with Similar Dimensions	Endodontic Treatment Performed by a Single Operator	Space of Post Treatment Performed by a Single Operator	Luting Post Procedures Performed by the Same Operator	Blinding of the Operator of the Test Machine	Failure Analysis	Risk of Bias
Alaghemand & others ²⁷	YES	NO	YES	NO	YES	NO	NO	NO	YES	MEDIUM
Alfredo & others ²⁸	YES	NO	YES	YES	NO	NO	NO	NO	NO	HIGH
Alkhudhairy & others ¹¹	YES	NO	YES	NO	NO	NO	NO	NO	YES	HIGH
Angeloni & others ²⁹	YES	NO	YES	NO	NO	NO	NO	NO	YES	MEDIUM
Arana & others ³⁰	NO	NO	YES	NO	NO	NO	NO	NO	NO	HIGH
Arisu & others ³¹	NO	NO	YES	YES	NO	NO	NO	NO	YES	HIGH
Arslan & others ³²	YES	NO	NO	NO	NO	NO	NO	NO	YES	HIGH
Baena & others ³³	YES	NO	YES	NO	YES	NO	NO	NO	YES	MEDIUM
Bitter & others ³⁴	YES	NO	YES	NO	NO	NO	NO	NO	YES	HIGH
Bordin & others ³⁵	YES	NO	NO	YES	YES	NO	NO	YES	NO	MEDIUM
Carvalho & others ³⁶	YES	NO	NO	NO	NO	NO	NO	NO	YES	HIGH
Carvalho & others ³⁷	YES	NO	YES	YES	YES	NO	NO	NO	YES	MEDIUM
Cecchin & others ⁵	YES	NO	NO	YES	YES	NO	NO	NO	YES	MEDIUM
Cecchin & others ³⁸	NO	NO	NO	YES	NO	NO	NO	NO	YES	HIGH
Cecchin & others ⁸	NO	NO	YES	YES	YES	NO	NO	NO	YES	MEDIUM
Cintra & others ³⁹	YES	NO	YES	YES	NO	YES	NO	NO	NO	MEDIUM
Clavijo & others ⁴⁰	YES	NO	YES	NO	NO	NO	NO	NO	NO	HIGH
Crispim da Silveira & others ⁴¹	YES	NO	YES	YES	NO	NO	NO	NO	NO	HIGH
Culhaoglu & others ⁴²	YES	NO	NO	NO	NO	NO	NO	NO	YES	HIGH
da Cunha & others ¹⁴	NO	NO	YES	YES	NO	NO	NO	NO	NO	HIGH
Da Silva & others ⁴³	YES	NO	YES	NO	NO	NO	NO	NO	YES	HIGH
De Araújo & others ⁴⁴	YES	NO	YES	NO	NO	NO	NO	NO	YES	HIGH
de Oliveira & others ⁴⁵	YES	NO	YES	NO	YES	YES	NO	NO	YES	MEDIUM
Durski & others ⁴⁶	YES	NO	YES	NO	NO	NO	NO	NO	NO	HIGH
Ekim & Erdemir ⁴⁷	YES	NO	YES	NO	NO	NO	NO	NO	YES	HIGH
Elnaghy ⁴⁸	YES	NO	YES	NO	NO	NO	NO	NO	YES	HIGH
Ertas & others ¹⁵	NO	NO	YES	YES	NO	NO	NO	NO	YES	HIGH
Fan & others ⁴⁹	YES	NO	YES	NO	NO	NO	NO	NO	YES	HIGH
Faria-e-Silva & others ⁵⁰	NO	NO	NO	YES	NO	NO	NO	NO	NO	HIGH
Feng & Gao ⁵¹	YES	NO	NO	YES	NO	NO	NO	NO	YES	HIGH
Furuse & others ⁵²	NO	NO	YES	YES	NO	NO	NO	NO	YES	HIGH
Garcia & others ⁵³	YES	NO	YES	YES	NO	NO	NO	NO	YES	MEDIUM
Garcia & others ⁵⁴	YES	NO	YES	YES	NO	NO	NO	NO	YES	MEDIUM
Garcia & others ⁵⁵	YES	NO	NO	NO	YES	NO	NO	NO	NO	HIGH
Gomes França & others ⁵⁶	YES	NO	NO	YES	NO	NO	NO	NO	YES	HIGH
Gorus & others ⁵⁷	YES	NO	NO	NO	NO	NO	NO	NO	NO	HIGH
Jain & others ⁵⁸	NO	NO	NO	NO	NO	NO	NO	NO	NO	HIGH
Kirmali & others ⁵⁹	YES	NO	YES	NO	NO	NO	NO	NO	YES	HIGH
Kul & others ⁶⁰	NO	NO	YES	NO	NO	NO	NO	NO	YES	HIGH

Table 2: Risk Bias of the Studies Considering Aspects Reported in Methods & Materials Section (cont.)

Lacerda & others ⁶¹	NO	NO	YES	NO	NO	NO	NO	NO	NO	HIGH
Lacerda & others ¹²	YES	NO	NO	YES	NO	NO	NO	NO	NO	HIGH
Leitune & others ⁶²	YES	NO	NO	NO	YES	YES	NO	NO	NO	HIGH
Lima ⁶³	NO	NO	NO	YES	NO	NO	NO	NO	YES	HIGH
Mao & others ⁶⁴	YES	NO	YES	YES	NO	NO	NO	NO	YES	MEDIUM
Martinho & others ⁶⁵	YES	NO	YES	YES	YES	NO	NO	NO	YES	MEDIUM
Mathew & others ⁶⁶	YES	NO	YES	NO	NO	NO	NO	NO	YES	HIGH
Mohammadi & others ⁶⁷	YES	NO	NO	NO	NO	NO	NO	NO	YES	HIGH
Neelakantan & others ⁶⁸	YES	NO	YES	NO	NO	NO	NO	NO	YES	HIGH
Oral & others ⁶⁹	NO	NO	YES	NO	NO	NO	NO	NO	YES	HIGH
Parcina & others ⁷⁰	NO	NO	NO	YES	NO	NO	NO	NO	NO	HIGH
Ramos & others ⁷¹	YES	NO	NO	YES	NO	NO	NO	NO	YES	HIGH
Ramos & others ⁷²	YES	NO	YES	YES	NO	NO	NO	NO	YES	MEDIUM
Santos & others ⁷³	NO	NO	YES	NO	NO	NO	NO	NO	YES	HIGH
Scotti & others ⁷⁴	YES	NO	NO	NO	NO	NO	NO	NO	NO	HIGH
Scotti & others ⁷⁵	YES	NO	NO	NO	NO	NO	NO	NO	NO	HIGH
Seballos & others ¹⁶	YES	NO	YES	YES	YES	YES	YES	YES	YES	LOW
Shafiei & others ⁷⁶	YES	NO	YES	YES	NO	YES	NO	NO	YES	MEDIUM
Shafiei & others ⁷⁷	YES	NO	YES	YES	NO	NO	YES	NO	YES	MEDIUM
Shafiei & others ⁷⁸	YES	NO	YES	YES	NO	YES	YES	NO	YES	MEDIUM
Silva ⁷⁹	YES	NO	YES	YES	NO	NO	NO	NO	YES	MEDIUM
Simões & others ⁸⁰	YES	NO	NO	NO	NO	NO	NO	NO	YES	HIGH
Simões & others ⁸¹	YES	NO	NO	NO	NO	NO	NO	NO	YES	HIGH
Tuncdemir & others ⁸²	YES	NO	NO	NO	YES	NO	NO	NO	YES	HIGH
Uzun & others ⁸³	YES	NO	YES	NO	YES	YES	YES	NO	YES	MEDIUM
Victorino & others ⁸⁴	YES	NO	YES	YES	NO	NO	NO	NO	YES	MEDIUM
Wang & others ⁸⁵	YES	NO	YES	YES	NO	NO	NO	NO	YES	MEDIUM
Wu & others ⁸⁶	YES	NO	NO	NO	NO	NO	NO	NO	YES	HIGH
Xia & Cheng ⁸⁷	YES	NO	YES	NO	YES	NO	NO	NO	YES	MEDIUM
Yaman & others ⁸⁸	YES	YES	NO	NO	NO	NO	NO	NO	YES	HIGH
Yu & others ⁸⁹	YES	YES	NO	NO	NO	NO	NO	NO	YES	HIGH
Zhang & others ¹⁸	YES	NO	YES	NO	NO	NO	NO	NO	YES	HIGH
Zhou & others ⁹⁰	YES	NO	YES	NO	NO	NO	NO	NO	YES	HIGH
Zhu & others ⁹¹	YES	NO	NO	NO	NO	NO	NO	NO	YES	HIGH
Çökük & others ¹³	NO	NO	YES	NO	YES	NO	NO	NO	YES	HIGH
Šimundić Munitić & others ⁹²	YES	NO	NO	NO	NO	NO	NO	NO	YES	HIGH

The type of post most used in our systematic review was the fiber post. The main reason for the failure of this type of post is post debonding;¹⁰⁹ therefore, the type of cement used for post luting is important. Different types of cement have been analyzed in the literature; however, adhesive cementation achieves higher bond strength than other types of cement.^{110,111} All the

¹ 5, 51, 61, 70, 82, 88, 89, 91

included studies in this review used resin cement for post luting, and the post-space treatment improves the post retention for all types of resin cements. Regarding the post-treatment before luting, most of the papers included in the meta-analysis used silano for post-treatment. Some papers^b do not explain what was used for the post-treatment and one⁶⁷ paper used only alcohol for post-treatment.

For the post-waiting time for test analysis, the immediate (stored between 24 hours and one week) and delayed subgroups (stored between four months and two years) obtained higher results for post retention when the post-space treatment was used compared with the control group. Although there was no difference between the subgroups (immediate and delayed), it is important to take into account length of storage time because studies in the literature suggested the integrity of cement-dentin bonds over time decreased the post bond strength.¹¹² In addition, some treatments were available in the post-space to increase the bond strength value in the delayed condition.^{5,8,38}

The bond strength test most used among the included studies was the push-out test.⁹² One reason for this is promoting shear stresses at the interface between cement-root dentin and cement-post, and the push-out test generates the best evidence available in the literature.^{113,114}

It is reported in the literature that root thirds affected the bond strength of the post due to regional differences in the concentration, volume, and direction of dentinal tubules in different thirds,¹¹⁵ although others did not show any difference between thirds.^{44,84} In the present review, the use of post-space treatment was better than the control group, independent of tooth third.

High heterogeneity among studies was found in the meta-analyses, and heterogeneity is expected because this review only considered *in vitro* studies. There are many differences among experimental designs in *in vitro* studies such as bond strength test, type of teeth, number of specimens per group, and specific variables such as the endodontic sealers, type of post, type of cement, and post-space treatments. Moreover, a small number of samples and consequently high standard deviations also contribute to heterogeneity.^{25,116} Among the evaluated studies, only one¹⁶ had a low risk of bias. The parameters of sample size calculation, treatments performed by a single operator, and blinding the operator of the testing machine were the most frequently missed or unclear parameters. These findings usually occur in a systematic review of laboratory studies.^{25,26,97,116}

The present study is a systematic review of only *in vitro* studies, which impacts the interpretation of the findings, thus constituting a limitation of the study. The literature search only being conducted in the PubMed/MEDLINE, Scopus, and Lilacs electronic databases is also a limitation despite the number of obtained studies that can be considered as representative and reasonable. Nevertheless, the obtained results could be considered as a recommendation for clinicians regarding the post-space treatment.

Thus, despite the study limitation, the post-space treatment with ethanol should be preferred due to the simplicity of the technique and similar results as the more complex techniques, mainly in the situations that the root canal is filled with a resin-based sealer, post-waiting of 2 days using fiber post, and when the post-space preparation was done with the drill provided by post system.

CONCLUSION

This systematic review of laboratory studies indicates, under the limitations of the present meta-analysis, that post-space treatments improve the bond strength of posts to root canal dentin. The treatments with ethanol, NaOCl + EDTA, NaOCl + EDTA + ultrasound, Er:YAG laser, Nd:YAG laser, and diode laser provide higher bonding to root canal dentin. Thus, the clinician can choose the most appropriate treatment to be used among those described above.

Conflicts of Interest

The authors 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.

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Intrapulpal Concentration of Hydrogen Peroxide of Teeth Restored With Bulk Fill and Conventional Bioactive Composites

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Clinical Relevance

Using a 35% hydrogen peroxide bleaching agent in-office increases the concentration and diffusion of hydrogen peroxide into the pulp chamber compared to a low-concentration (9.5%) hydrogen peroxide gel.

SUMMARY

This study evaluated intrapulpal concentration and hydrogen peroxide (HP) penetration at the interface of teeth restored with bioactive composites, using conventional or bulk-fill composites. Cylindrical cavities were prepared on the buccal surface of bovine incisor crowns (n=20)

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and restored with: resin modified glass-ionomer (RMGI, Riva Light Cure, SDI), non-bioactive bulk-fill composite (FB, Filtek Bulk, 3M Oral Care), non-bioactive conventional composite (FZ, Filtek Z350, 3M Oral Care), bioactive bulk-fill composite (AC, Aactiva BioActive, Pulpdent), and bioactive conventional composite (BII, Beautifil II, Shofu). After 5,000 thermal cycles, restorations (n=10)

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were exposed to high (35% HP [4 applications of 8 min/session-4 sessions]) or low (9.5% HP [30 min/day-14 days]) concentration bleaching protocols. After the last bleaching application, the HP intrapulpal concentration was determined. Additional teeth were restored, pigmented with rhodamine B solution, and HP penetration around the interface was observed under laser scanning confocal fluorescence microscopy (LSCFM, $n=3$). The presence of gaps at the interface was observed on replicas of the cross-sectioned samples under scanning electron microscopy (SEM, $n=5$). Data were submitted to one-way (gap analysis) and two-way analysis of variance (ANOVA; HP intrapulpal concentration) and Tukey test ($\alpha=0.05$). The LSCFM images were qualitatively analyzed. The restored teeth submitted to 35% HP presented higher HP intrapulpal concentration than teeth submitted to 9.5% HP ($p<0.05$). No differences in HP intrapulpal concentration was observed among groups ($p>0.05$) when exposed to 9.5% HP. Lower HP intrapulpal concentration was observed for teeth restored with RMGI exposed to HP 35%, when compared with teeth restored with non-bioactive conventional (FZ; $p=0.004$) and bulk-fill composites (FB; $p=0.01$). No gap formation was observed at the outer enamel adhesive interface for all restorative materials. LSCFM images showed that 35% HP promoted greater degradation of rhodamine B at the enamel, except for RMGI. In this context, RMGI promoted lower HP intrapulpal concentration than non-bioactive conventional and bulk-fill composites.

INTRODUCTION

The excellent aesthetic results provided by the bleaching agents are based on the trans-dentinal diffusion and decomposition of hydrogen peroxide (HP) into free radicals.¹ The interaction of bleaching agents occurs mainly in dentin, due to the absence of organic chromophores in the enamel structure.^{1,2} Thus, the resulting free radicals of HP potentially reach the pulp chamber, causing inflammatory responses, morphological changes to pulp tissue, and postoperative sensitivity.^{2,4}

Tooth bleaching should be performed with caution, as the use of high concentrations of HP has shown to promote severe post-operative damages and cytotoxic effects.⁵ However, studies indicate that even at low concentrations, bleaching agents could reduce pulp cell viability.^{6,7} On the other hand, clinical studies

have observed sporadic or transitory sensitivity after treatment with high and low concentrations of hydrogen peroxide.⁸

Clinically, pulp damage manifests as dental sensitivity, frequently leading the patient to cease bleaching.⁹ Studies report that, in addition to the concentration, the length of time of an application directly influences the diffusion of the peroxide.^{3,4,10} Thus, different protocols and concentrations of HP have been investigated in order to avoid unnecessary exposure and to decrease the intrapulpal concentration of hydrogen peroxide.^{7,10,11} In this context, Marson and others⁴ have previously observed that HP diffusion is dependent on the concentration and bleaching gel application protocol.⁴

Literature shows that restored teeth submitted to tooth whitening present a greater amount of HP in the pulp chamber than sound, non-restored teeth.¹² This occurs because the restorative interface becomes a path for peroxide microleakage.¹² In this regard, restorative materials have been developed to promote adequate marginal sealing and mechanical properties.¹³ Although no restorative material completely blocks HP penetration, the diffusion of HP can be affected by polymerization shrinkage and the polymerization stress promoted at the adhesive interface of conventional composites.³ Thus, in an attempt to obtain greater marginal integrity and to reduce clinical time and the polymerization stress, bulk-fill composites were developed, allowing increments of up to 4 mm thickness.¹³

Bioactive composites containing pre-reacted glass ionomer (S-PRG-Beautifil II, Shofu) charge particles were created to allow interaction with the adjacent tissue by the release of fluoride by an ion exchange mechanism in the pre-reacted hydrogel.¹⁴ Studies have shown that the S-PRG-containing bioactive materials offer satisfactory biological properties, bacterial inhibition, biocompatibility, and good marginal sealing.¹³⁻¹⁵ To make bioactive materials even more applicable, a new bulk-fill composite (Activa BioACTIVE, Pulpdent) was formulated with an ionic resin matrix, allowing the release of not only fluoride but also calcium and phosphate.¹⁶

Bioactive or bulk-fill composites hypothetically present greater marginal sealing ability that may influence the diffusion of the HP into the pulp chamber.¹² Considering that these materials are used in posterior teeth (up to premolars with involvement of the buccal surface) that are possibly subjected to dental bleaching, the diffusion around existing restorations and concentration of HP into the pulp chamber must be evaluated. Therefore, this study evaluated the concentration and diffusion

of HP into the pulp chamber of teeth restored with a resin-modified glass ionomer (Riva Light Cure), a non-bioactive bulk-fill composite (Filtek Bulk Fill), a non-bioactive conventional incremental resin composite (Filtek Z350 XT), a bioactive bulk-fill composite (Activa BioACTIVE), and a bioactive conventional composite (S-PRG-based material-Beautifil II, Shofu). The null hypotheses tested were that 1) a higher concentration of the bleaching agent (35%) would not significantly influence the intrapulpal concentration of HP of restored teeth compared to a lower concentration (9.5%), and 2) the type of restorative material would not significantly influence the intrapulpal concentration of HP for both HP concentrations.

METHODS AND MATERIALS

Sample Preparation

Bovine incisors were collected, cleaned, and stored in a 0.1% thymol solution at 4°C for 30 days. All crowns were examined under a stereomicroscope in order to discard teeth with surface defects. After cleaning, teeth were stored in a 0.1% thymol solution at 4°C for 30 days. The roots were cut with diamond discs (KG Sorensen, Barueri, Brazil) up to 2 mm below the cemento-enamel junction. The pulp tissue was removed using files (Hedstrom files, Maillefer Dentsply, Ballaigues, Switzerland), and the pulp chamber was thoroughly rinsed with deionized water. The cervical pulp orifice was enlarged with a spherical diamond tip bur (#1016, KG Sorensen) to allow for the placement of the acetate buffer solution into the pulp chamber.¹² The buccal enamel-dentin thickness was assessed and 100 crowns with total thickness of 4.0 ± 0.1 mm were selected.

Cylindrical cavities (4 mm diameter x 3mm depth) were manually prepared in the buccal surface of the specimens with diamond burs (3053 and 3017, KG Sorensen) in a high-speed handpiece (Kavo, Joinville, SC, SP Brazil) under water-cooling. A periodontal probe and a specimeter were used to measure the depth and diameter of the cavity during preparation. Five cavities were prepared per discarded diamond bur. The application of the adhesive system and restorative materials followed the manufacturers' instructions (Table 1). The adhesive system was previously applied only in cavities restored with the resin composites and light-cured for 20 seconds with a LED device (Valo, Ultradent Products Inc, South Jordan, UT, USA). Irradiance was measured using a spectroradiometer (1200 mW/cm², USB 4000, Ocean Optics, Dunedin, FL, USA). For resin-modified glass ionomer restorations, Riva Conditioner was applied, followed by manipulation, insertion of the cement, and light-

curing for 20 seconds. The emitting end of the light source was placed parallel and as close as possible to the cavosurface margin, without touching the restorative materials. The operator used a blue-blocker eyeglass during the restoration procedure to correctly position the light-curing tip. The finishing and polishing of the restorations were performed with extra-thin tips (3118 FF, KG Sorensen), sandpaper discs (Sof-Lex, 3M Oral Care, St Paul, MN, USA) and each granulation was used for 15 seconds (medium, fine, and superfine). The specimens were stored in distilled water at 37°C for 48 hours prior to the thermal cycling procedure.

Thermal Cycling and Bleaching Procedure

To age the adhesive interface, the specimens were submitted to 5,000 thermal cycles (MCT2-AMM, São Paulo, SP, Brazil) in deionized water baths at 5° to 55°C $\pm 1^\circ\text{C}$, corresponding to six months of aging.¹² Twenty-four hours after thermal cycling, two layers of nail polish (Revlon Inc, New York, NY, USA) were applied, covering all exposed enamel except for a 1-mm space around the restorations. Then, the restored teeth were submitted to high- (35% HP) or low-concentration (9.5% HP) bleaching agents (Table 2). Therefore, each restorative material would be exposed to high- or low-bleaching therapy (n=10). The low-concentration agent (9.5% HP) was applied daily for 14 days, and 35% HP was applied in four sessions at intervals of seven days. Specimens were stored in artificial saliva in between treatments (20 mM Tris buffer, pH 7.0, 1.5 mM Ca, 0.9 mM P, 150 mM KCl, 0.05 μg F/mL),¹⁷ at 37°C, renewed every two days.

Concentration of Hydrogen Peroxide Into the Pulp Chamber

The bleaching agents (35% HP or 9.5% HP) were used following the manufacturer's instructions (Table 2). At the last bleaching application, the pulp chamber was dried and 150 μL of acetate buffer solution 2M (pH 4.5) was placed into the chamber in order to stabilize the HP that penetrated into the pulp throughout bleaching. Subsequently, 0.01 g of the high-concentration bleaching agent was applied on the buccal surface for 8 minutes in four consecutive applications, and 0.01 g of the low-concentration agent remained in contact with the enamel surface for 30 minutes.

After the bleaching procedure, the solution was removed and transferred to a glass test tube. The pulp chamber of each tooth was filled for a second time with 150 μL of the acetate buffer for 1 minute, and this solution was transferred to the same glass tube. Deionized water (2650 μL), leuco crystal violet (100 μL of 0.5 mg/mL, Sigma-Aldrich, St. Louis, MO,

Table 1: Composition and Manufacturer's Instructions of the Restorative Materials

Materials (Abbreviation)	Commercial Names and Manufacturer	Composition	Manufacturer's Instructions
Polyacrylic acid conditioner	Riva conditioner (SDI Limited)	26% polyacrylic acid	After tooth preparation, apply the conditioner to the prepared surfaces. Leave for 10 s and rinse thoroughly with water. Remove excess water and keep it moist.
Dental adhesive (SBU)	Single Bond Universal (3M Oral Care)	10-MDP, phosphate monomer, dimethacrylate resins, HEMA, Vitrebond copolymer, filler, ethanol, water, initiators, silane	1) Selective acid etching (37% phosphoric acid) of enamel for 15 s 2) Apply adhesive with a microbrush to the surface (20 s), followed by a gentle air-spray for 5 s and light cure for 10 s.
Resin-modified glass ionomer (RMGI)	Riva Light Cure (SDI Limited)	Powder: Fluoroaluminosilicate glass. Liquid: Polycyclic acid, tartaric acid, polyacrylic acid	After enamel etching for 10 s with polyacrylic acid, followed by abundant rinsing and air-drying, apply and light-cure for 10 s.
Non-bioactive bulk-fill composite (FB)	Filtek Bulk Fill Posterior (3M Oral Care)	AUDMA, UDMA, 1,12-dodecane-DMA.	Apply composite in increments of 4 mm and light cure (20 s).
Non-bioactive conventional composite (FZ)	Filtek Z350 XT (3M Oral Care)	Bis-GMA, Bis-EMA, UDMA, TEGDMA Nanoparticles of non-agglomerated silica, zirconia/silica nano-agglomerates, free-bound agglomerates	Apply composite in increments of 2 mm and light cure (20 s).
Bioactive bulk-fill composites (AC)	Activa BioACTIVE (Pulpdent)	Mixture of diurethane and other methacrylates with modified polyacrylic acid (44.6%) amorphosine (6.7%) sodium fluoride (0.75%).	Apply composite in increments of 4 mm and light cure (20 s).
Bioactive conventional composite (BII)	Beautifil II (Shofu)	Bisphenol-A glycidyl methacrylate (Bis-GMA), triethylene glycol dimethacrylate (TEGDMA), particles pre-reacted glass ionomer (S-PRG).	Apply composite in increments of 2 mm and light cure (20 s).
Abbreviations: AUDMA, aromatic urethane dimethacrylate; Bis-GMA, bisphenol A-glycidyl methacrylate; HEMA, 2-hydroxyethyl methacrylate; TEGDMA, triethylene glycol dimethacrylate; UDMA; urethane dimethacrylate; Bis-EMA; ethoxylate bisphenol-A-glycol dimethacrylate; s, second.			

USA), and horseradish peroxidase (50 μ L of 1 mg/mL; Sigma-Aldrich) were added to each tube.¹⁸

As a result, a colored solution was obtained, allowing the optical density measurement in a spectrophotometer (DU 800, Beckman Coulter Inc, Brea, CA, USA) at a wavelength of 596 nm. For this purpose, a standard curve with known HP concentrations was used to convert the optical density values into micrograms (μ g) of HP/mL of solution. The values were then converted into micrograms per milliliter.^{12,18}

Laser Scanning Confocal Fluorescence Microscopy (LSCFM)

To observe the HP diffusion at the adhesive interface and through enamel and dentin, additional specimens of each group were prepared as previously described, submitted to thermal cycles, and subsequently to either high- or low-concentration bleaching protocols ($n=3$). An additional control group, restored with a resin-modified glass ionomer, was added to this methodology and consisted of restored samples that

Table 2: Bleaching Agent Composition and Manufacturer's Instructions

Bleaching Agents	Commercial Name (Manufacturer, Location)	Composition	Manufacturer's Directions
35% hydrogen peroxide	Pola Office ^a (SDI Limited)	Liquid: 35% hydrogen peroxide, 65% water. Powder: 73.26% thickeners, 26.2% catalysts, 0.04% dye, 0.5% desensitizing agents (potassium nitrate). pH=3.7 ^b	Indicated for in-office bleaching therapy, in 4 sessions. Apply a mixture to the enamel for 8 minutes, 4 times.
9.5% hydrogen peroxide	Poladay ^a (SDI Limited)	Bleaching gel: hydrogen peroxide (9.5%). Activator: additives (47%), glycerol (30%), water (20%), flavorings (0.1%). pH=5.7 ^b	Indicated for at-home bleaching therapy, for 14 days. Apply the whitening gel to the tray 1 time for 30 minutes.

^aAccording to manufacturer's directions.
^bPreliminary pH results obtained by the authors.

remained unbleached, in order to confirm if rhodamine B solution would be able to diffuse through enamel and dentin.

The crowns were fully immersed in rhodamine B solution (Aldrich Chem. Co) for seven days at a concentration of 0.1 mM in 30 mL of deionized water. Subsequently, the in-office or at-home bleaching protocols were performed (except the control group). The center of the restorations was cross-sectionally cut with a diamond disc under vegetable oil irrigation (Isomet 1000, Buehler, Lake Bluff, IL, USA).

The inner face was polished (EcoMet 3000, Buehler) with abrasive papers (400, 600, and 1200 granulations), specimens were immersed in vegetable oil for 30 seconds and then immersed in an ultrasonic chamber for 15 minutes for the complete removal of the polishing residues. The interface was analyzed by an argon laser-scanning microscope (TCS SP5AOBS, Leica Microsystems CMS GmbH, Germany) with a wavelength of 543 nm (red channel-for rhodamine B) and 488 nm (green channel-dental tissues autofluorescence), with 20x objective lenses in scan mode, over the entire length from enamel to the bottom of the cavity. The green channel was used to confirm the focus of each image.

Internal Marginal Adaptation

Impressions of the polished cross-sectioned restored surfaces, regardless of the previous bleaching procedure, were taken using a polyvinyl siloxane material with

light and heavy consistency (Express XT, 3M ESPE, St. Paul, MN, USA). After 24 hours, the impressions were poured with an epoxy resin (EpoxiCure, Buehler Ltd), to obtain the restoration replicas (n=5). The polymeric replicas were sputter-coated with gold (SCD050, Bal-Tec AG, Balzers, Liechtenstein) in order to analyze the presence of gaps between the restorative material and enamel/dentin under a scanning electron microscope (SEM) (JEOL, JSM-5600LV, Tokyo, Japan). For each specimen, approximately 15 images (100 × magnification) were obtained to observe the entire length of the restored cavity. Software (ImageJ, National Institutes of Health, Bethesda, MD, USA) was used to determine the sum length of debonded segments and the entire perimeter of each restoration, which were calibrated by the SEM image scale bar. The percentage of the internal marginal gap was obtained for each sample according to the following formula:

$$\% \text{ gap} = \frac{100\% \times \text{length of gap}}{\text{total length of restoration}}$$

Statistical Analysis

The exploratory analyses of results were submitted to the SPSS software (SPSS Inc., Chicago, IL, USA). The normal distribution and homoscedasticity of the values were conducted by Shapiro-Wilk and Levene tests, and log-transformed data were required for intrapulpal concentration and square root for the percentage of internal gap values. The results were then submitted to

one-way analysis of variance (ANOVA) (gap analysis), and two-way ANOVA (intrapulpal concentration) followed by the Tukey test, with a significance level set at 5%.

RESULTS

According to the two-way ANOVA and Tukey test, the concentration of the bleaching agents and the restorative materials tested influenced the intrapulpal concentration of peroxide ($p=0.046$, Table 3). The HP intrapulpal concentration was higher when the high-concentration agent (35% HP) was applied compared to the low-concentration agent (9.5% HP), regardless of the restorative material used ($p<0.05$). No differences in the HP intrapulpal concentration were observed among restorative materials ($p>0.05$) when exposed to the low-concentration agent (9.5% HP). The intrapulpal peroxide concentration following bleaching with 35% HP was higher in teeth restored with non-bioactive conventional (FZ; $p=0.004$) and bulk-fill (FB; $p=0.01$) composite resins compared to RMGI. No differences were observed among groups restored with the bioactive composites (both conventional and bulk-fill) and the other materials ($p>0.05$).

Representative images of LSCFM of each group are presented in Figure 1. The control group, with no bleaching procedures, exhibited rhodamine B dye penetration through enamel and dentin. However, half of the top enamel (in-depth) remained without staining even after 7 days in rhodamine B solution. This same pattern was observed in all samples, although some

differences between restorative materials groups and bleaching agents were found. For both bleaching procedures, the RMGI pattern of rhodamine B staining remained similar to the unbleached control group, characterized by a bright red color. The amount of rhodamine B oxidized (loss of bright red) by 35% HP was higher compared to 9.5% HP for all other restorative materials tested. No difference was observed regarding rhodamine B oxidation by bleaching agents comparing non-bioactive and bioactive conventional and bulk-fill composites. No bleaching procedure was able to remove rhodamine B from dentin, possibly due to the degree of dye saturation in each tooth. The black spots in dentin, with no presence of green (dentin autofluorescence), captured during the scanning mode used, can indicate a lack of focus in this area. Regarding the bonding interface, no differences were observed between groups, and confocal images failed to identify gap formation with the parameters used.

The percentage of internal marginal gap formation is depicted in Table 4. AC presented the highest percentage of gap formation, except when compared to RMGI, which presented intermediate values. The gap formation for AC, however, was always set at the bottom of the cavity. Figure 2 shows that for all restorative materials, no gap formation was observed between the outer enamel and the bonding interface.

DISCUSSION

This study showed that high concentrations of bleaching agents influenced the amount of HP in the

Table 3: Mean (Standard Deviation) of Hydrogen Peroxide Concentration (HP) into the Pulp Chamber ($\mu\text{g/mL}$) of Restored Teeth, Submitted to Low- and High-concentration Bleaching Agents

Restorative Materials (Brand Name)	9.5% HP	35% HP
Resin-modified glass ionomer (RMGI - Riva Light Cure)	0.09 (0.06) Ba	0.27 (0.13) Ab
Non-bioactive bulk-fill composite (FB - Filtek Bulk-fill)	0.09 (0.03) Ba	0.51 (0.38) Aa
Non-bioactive conventional composite (FZ - Filtek Z350 XT)	0.07 (0.04) Ba	0.62 (0.55) Aa
Bioactive bulk-fill composites (AC - Activa BioACTIVE)	0.09 (0.04) Ba	0.42 (0.29) Aab
Bioactive conventional composite (BII - Beautifil II)	0.07 (0.02) Ba	0.43 (0.26) Aab

Abbreviations: HP, hydrogen peroxide.

Mean values followed by distinct letters differ statistically by 5%, according to two-way ANOVA and Tukey test. Uppercase letters compare bleaching agents (rows) and lowercase letters compare restorative materials (columns).

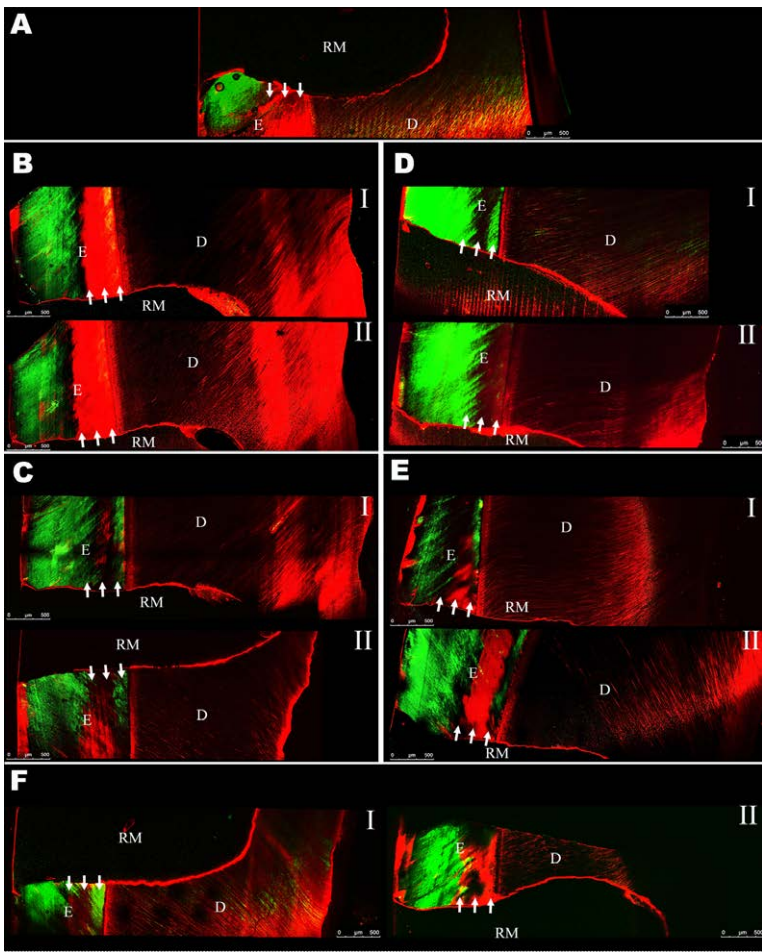


Figure 1. Representative images of hydrogen peroxide at the interface of restored teeth under laser scanning confocal fluorescence microscopy. (A): Control group (unbleached restored teeth). (B): Resin-modified glass ionomer - Riva Light Cure. (C): Bulk-fill composite - Filtek Bulk-fill. (D): Conventional composite - Filtek Z350 XT. (E): Bulk-fill bioactive composite - Activa BioACTIVE. (F): Conventional bioactive composite - Beautifil II. (i): Bleached with 35% HP. (ii) Bleached with 9.5% HP. White arrows: indicate the oxidation, or not, of rhodamine B in the enamel area). Abbreviation: HP, hydrogen peroxide.

Table 4: Mean (Standard Deviation) Percentage of Internal Gap Formation	
Material (Brand Names)	Gap (%)
Resin-modified glass ionomer (RMGI -Riva Ligh- Cure)	16.90 (6.36) ab
Non-bioactive Bulk-fill Composite (FB - Filtek Bulk-fill)	12.52 (2.95) bc
Non-bioactive Conventional Composite (FZ - Filtek Z350 XT)	11.75 (5.54) bc
Bioactive Bulk-fill Composites (AC - Activa BioACTIVE)	27.11 (12.11) a
Bioactive Conventional Composite (BII - Beautifil II)	6.09 (3.04) c
Means followed by the same letter are not statistically different (p>0.05). n = 5 specimens/ group.	

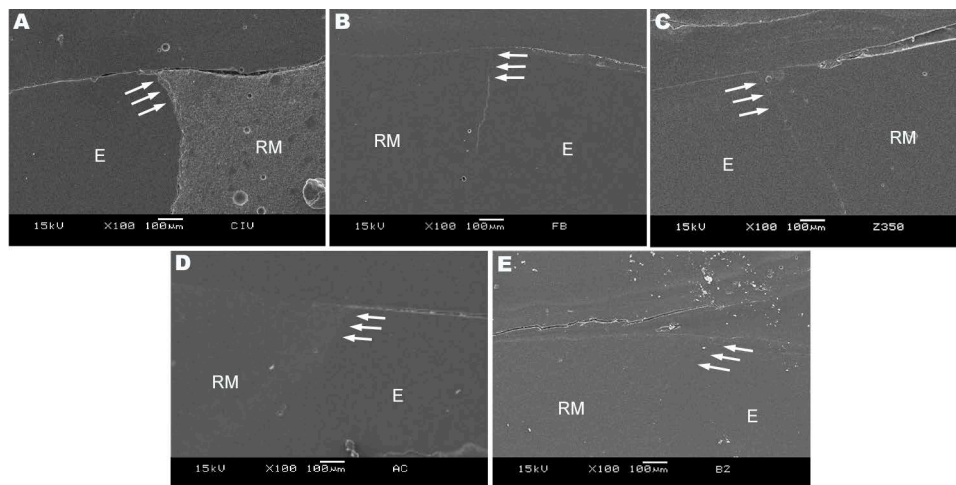


Figure 2. Representative SEM images of enamel-restorative material interface. (A): Resin-modified glass ionomer - Riva Light Cure. (B): Bulk-fill composite - Filtek Bulk-fill. (C): Conventional composite - Filtek Z350 XT. (D): Bulk-fill bioactive composite - Activa BioACTIVE. (E): Conventional bioactive composite - Beautifil II. Abbreviations: SEM, scanning electron microscope.

pulp chamber of restored teeth. Therefore, the first hypothesis was rejected. The results suggested that intrapulpal concentration of peroxide was directly related to the concentration of the bleaching agent, as observed previously.¹⁰ In fact, the LSCFM images demonstrated greater degradation of rhodamine B by the high-concentration bleaching agent (35% HP), which possibly displays similar clinical paths of HP penetration.

According to Kwon and others,¹⁹ the immersion of the specimens in rhodamine B for 7 days allowed adequate enamel, dentin, and dentinoenamel junction staining. Therefore, the black areas (interposed by the green channel) may display the paths of HP penetration, by the oxidation of rhodamine B. The spectrophotometry analysis indicated the presence of HP into the pulp chamber, but the images suggested degradation of rhodamine in enamel and low signs of degradation in dentin. This could be a limitation of the method, as the bleaching agent was not able to degrade the whole dye in dentin due to its saturation, but HP was able to reach the pulp chamber. Also, for 9.5% HP, the oxidation pattern of rhodamine B was different when comparing RMGI and the other resin composites tested. This difference can also suggest that RMGI may influence the HP penetration compared to the other materials when the lower concentration of HP is used, although no difference was observed spectrophotometrically.

Penetration of bleaching agents in the pulp chamber can be modulated according to peroxide concentration,^{3,4,6,10,18} composition,²⁰ pH of bleaching gels,²¹ presence of restorations,^{12,22} and enamel thickness and morphological characteristics.²³ Previous studies have emphasized that both the concentration and the

application time are able to influence the diffusion of HP.^{10,21} These results were confirmed by others, who observed that the longer the contact of the bleaching agent with enamel, the greater was the penetration into dental tissues.⁴

It has been observed that not only time, but the pH of bleaching agents influence the rate of HP dissociation. Alkaline bleaching gel increases the degradation rate of HP into reactive oxygen species (ROS), and this could reduce the risk of ROS penetration into the pulp tissue due to the short lifetime of oxygen species.^{24,25} Besides, a bleaching agent with an acidic pH may decrease enamel microhardness, increase roughness, and possibly increase clinical sensitivity.²⁶ The pH of the bleaching agents used hereby exhibited acidic values for both high (pH=3.7) and low (pH=5.7) agents. Therefore, the pH of these agents may increase the intrapulpal concentrations of HP.

The rheological properties of the bleaching agents are among the factors that influence its behavior.^{20,27} Kwon and others (2018) suggested that bleaching gels with higher viscosity promoted lower intrapulpal peroxide concentration than low and medium viscosity gels.²⁷ Therefore, in addition to the other positive aspects of the 9.5% HP agent (lower HP concentration, lower contact time, and higher pH), its greater viscosity could have contributed to the more favorable results.

The type of restorative material directly influenced the intrapulpal HP concentration, as RMGI showed lower penetration than the FB and FZ composites (non-bioactive), when exposed to the high-concentration agent. Based on this fact, the second null hypothesis was rejected. A previous study suggested that the presence of restorations and the use of high-concentration

bleaching agents allow the diffusion and greater amount of peroxide in the pulp chamber.³ Although no restorative material has been able to completely prevent the penetration of HP, the final concentration can be affected by the type, shape, and volume of the material, which influence the polymerization stress.^{3,13} Even though the literature is still controversial, previous reports observed that the presence of marginal microleakage in enamel restored with composite resin exposed to different concentrations of bleaching agents may favor the diffusion of the agent into the pulp.^{28,29}

In this study, RMGI restorations submitted to 35% HP promoted lower HP intrapulpal concentration when compared with non-bioactive materials (FB and FZ). The presence of metal ions in the composition of RMGI (Al^{3+} , SiO_3^{2-} , Ca^{2+}) could have interacted with HP, resulting in the formation of oxides and hydroxyl radicals ($\text{OH}\cdot$), increasing peroxide degradation immediately in the first contact of the restoration with HP.³⁰ In addition, previous studies have shown that RMGI (Riva Self Cure) presents good physical and mechanical properties due to the arrangement of its particles within the matrix, promoting good marginal integrity, thus lowering the risk of peroxide diffusion at the interface.³¹ Although bioactive composites also release metal ions (Ca^{2+} , BO_3^{3-} , Sr^{2+} , Si_3^{2-} , Na^+ , B^{3-}), these are trapped in charged particles inside a polymeric matrix, possibly impairing their releasing mechanism.

It should be noted that HP is able to alter the physical, mechanical, and esthetic properties of restorative materials. Contact with HP may influence the surface roughness and porosity of the composites,³² promote crack formation, microhardness reduction³³, and change interface integrity.³⁴ Bleaching on S-PRG (BII)-based bioactive composites led to an undesirable effect on microhardness and marginal sealing of restorations.³⁴ However, in another finding, the stable mechanical properties of BII was observed, and these results were attributed to the presence of greater amounts of fillers, including large pre-polymerized (besides S-PRG) fillers.³⁵ This finding corroborates the fact that bioactive composites exhibit similar behavior to traditional systems against bleaching protocols.

The restorations were submitted to thermal cycles in order to age the interface and simulate a restoration in use. Due to the temperature variation throughout the 5,000 cycles, differences in the coefficient of thermal expansion (CTE) of the materials may result in marginal misadaptation and microleakage.³⁶ Therefore, the use of materials with a CTE close to the dental structure could potentially reduce the HP penetration. In this context, Sidhu and others (2004) observed that RMGI showed low dimensional changes due to a compensatory effect

at high and low temperatures.³⁷ At high temperatures, a thermal contraction occurs due to dehydration; however, in the cooling there is an expansion and rehydration of the material. In composite resins, the authors showed significant thermal expansions only in heating,³⁷ and it was influenced by the amount of inorganic particles, matrix composition, and degree of polymerization.³⁶ Thus, RMGI possibly provided lower stress at the interface and, consequently, lower penetration of HP compared to other materials.

A self-etching multimode adhesive system (Single Bond Universal - SBU) was used for all the resin composites, which did not influence the material behavior. SBU provides adequate bond strength results due to the chemical interaction between the monomer (10-MDP) and the dental substrate.³⁸ Possibly, the formed adhesive layer prevented higher peroxide concentration from reaching the pulp chamber, confirmed by the integrity of enamel sealing in SEM images (Figure 2). Since enamel bonding is more reliable and durable than dentin bonding, and enamel is the site of interest of the present study, we believe that other adhesive systems could also provide similar results. In addition, the gap observed at the adhesive interface is more related to the resin composite shrinkage after polymerization than to the adhesive itself.^{39,40}

Regarding marginal adaptation, most authors evaluate the use of bulk-fill composites in Class II restorations. Clinically, stress distribution at the restorative interface, such as gap formation, depends on the C factor, bonding quality, restorative material volume, and cavity geometry.³⁹⁻⁴¹ The failures occur mainly in the pulpal floor or in the internal angle of the cavity, as the polymerization contraction vectors point to the occlusal surface.⁴²⁻⁴⁴ In this study, the bioactive bulk-fill composite (AC) indicated a higher gap percentage, which may be related to the fused consistency of this material, since it offers greater polymerization contraction and less inorganic content. In addition, the presence of low molecular weight monomers increases methacrylate group density and polymerization shrinkage.^{43,45} However, the integrity of the enamel sealing might have prevented the internal gaps to influence the HP penetration results.

It is important to emphasize that this study has the inherent limitation of an *in vitro* evaluation, and the several physiological conditions affecting the HP diffusion, such as intrapulpal pressure of the dentinal fluid, the presence of peroxidase and catalase enzymes, and cytoplasmic extensions of odontoblasts, were not reproduced.⁹⁻¹¹ Moreover, bovine teeth are thicker and present smaller dentin tubules in comparison to human

teeth.⁴⁶ Since the higher permeability of human teeth results in greater susceptibility to hydrogen peroxide penetration, the present results should be cautiously extrapolated to clinical conditions.⁴⁷

Still, within the limitations of this *in vitro* study, we recommend the use of low-concentration agents for bleaching purposes in order to prevent high HP-intrapulpal concentrations. Although restored teeth with resin-modified glass ionomer cement presented satisfactory results, the clinical applicability of this finding is restricted. Therefore, this study does not discourage the use of the other restorative materials tested.

CONCLUSION

In this study, the 35% HP in-office bleaching agent (HP) significantly increased the concentration of hydrogen peroxide into the pulp chamber compared to low-concentration HP gel (9.5%), regardless of the restorative material used. The intrapulpal concentration and diffusion of hydrogen peroxide at the interface of teeth restored with RMGI was significantly lower when exposed to 35% HP compared to the non-bioactive resin composites tested.

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Regulatory Statement

This research was conducted respecting the rules of the local Ethical and Research Committee and the policies of the University.

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.

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