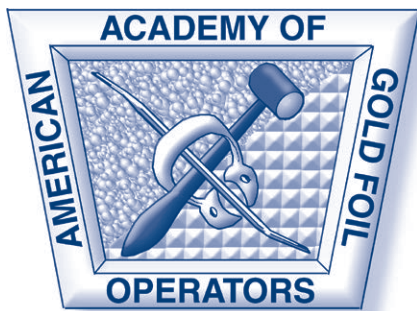


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Porcelain Veneers as an Alternative for Esthetic Treatment: Clinical Report

BT Rotoli • DANL Lima • NP Pini
FHB Aguiar • GDS Pereira • LAMS Paulillo

Clinical Relevance

This report is about veneers for functional and esthetic rehabilitation of the patient.

SUMMARY

This case report describes the restoration of the anterior dentition with porcelain laminate veneers. The advances in bonding of porcelain to tooth structure make this treatment a feasible alternative to restore teeth with alteration

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in shape and position in cases in which the esthetic demand is high. The rationale for various choices in this treatment protocol is detailed with reference to the pertinent literature. Thus, the clinical success of the technique depends on the correct identification of a case for which this treatment is appropriate and the successful execution of the clinical steps involved.

INTRODUCTION

The esthetic restoration of anterior teeth constitutes one of the greatest challenges in restorative dentistry, and, in this context, porcelain veneers are an increasingly popular treatment option for reestablishing unesthetic teeth.^{1,2} Currently, the use of adhesive procedures makes this treatment possible with the preservation of as much tooth structure as is feasible while satisfying the patient's restorative needs and esthetic desires.³ Porcelain veneers should be used as a solution to esthetic problems, involving morphologic modifications as in relation to tooth color, shape, contour, size, volume, and positioning.⁴⁻⁶ Moreover, veneers may be indicated to have a place in the restoration of loss of tooth structure due to disease or trauma.⁴

Since its introduction, porcelain veneer restoration has proven to be a durable and esthetic modality of treatment.⁷⁻⁹ With the excellent progress made through the introduction of adhesive systems in bonding capability to both enamel and dentin, more conservative restorative adhesive techniques have become possible for addressing unesthetic tooth appearance.³ Composite resin can be used to mask tooth discolorations and/or to correct unesthetic tooth shape and/or position. However, such restorations still suffer from limited longevity, thereby reducing the esthetic result in the long term.⁹ Thus, porcelain veneers are proposed as durable restorations with superior esthetics.

The porcelain materials commonly indicated for use as veneers are sintered feldspathic porcelain or hot-pressed glass ceramic because of their translucency and potential for use in small thicknesses.¹⁰⁻¹² Their variety in tonality from opaque to translucent allows mimicking of the natural tooth structure, resulting in satisfactory esthetic results.¹³ Besides, ceramic restorations present lower failure rates with regard to long-term survival^{14,15} and are considered more durable than direct composite veneers as long as patients are adequately selected and the veneers are prepared following meticulous clinical procedures.^{9,14} Therefore, the aim of this report was to present an esthetic approach to reestablishing the esthetics and balance of the smile with porcelain veneers as the restorative strategy.

CASE REPORT

A 25-year-old man, a modeling agent, sought for treatment complaining of the esthetic of his smile and wishing to improve his appearance (Figure 1). Following the clinical and radiographic evaluations, the presence of discolored restorations in the central incisors and disharmony in the shape of lateral incisors and canines was diagnosed (Figures 2). After treatment modalities were discussed with the patient, the decision was made to prepare the six maxillary anterior teeth for feldspathic porcelain veneers to reestablish the size and the shape of the teeth and, through this approach, to increase the esthetics of his smile.

To begin the treatment, a home dental bleaching of maxillary and mandibular teeth was performed using a 16% carbamide peroxide gel (Whiteness, FGM Products, Santa Catarina, Brazil), four hours per day, for 30 days. Next, it was anticipated that two weeks would be required to complete the next step of the treatment, which was to replace the restorations of the central incisors (Z350, 3M ESPE,



Figure 1. Pretreatment aspect, facial view of the patient.

São Paulo, Brazil; Figure 3). Meanwhile, a dental cast of the patient was obtained for preparation of the wax-up (Figure 4) and for the construction of the mock-up. This procedure allows a tridimensional previsualization of the final result prior to the procedure, which is irreversible.¹⁶ From the dental cast, three silicone (Zetaplus, Zhermack, Labordental, São Paulo, Brazil) impressions were obtained; two of these were used for tooth preparation, one in a horizontal dimension and the other in a vertical dimension (Figure 5). The third was used for the mock-up and the provisional restorations.

Tooth preparation for porcelain veneers must be uniform and, whenever possible, restricted entirely to the enamel. This goal was attained in the present patient by means of calibrated spherical diamond



Figure 2. Intraoral view of the anterior maxillary teeth. The maxillary central incisors present extensive restorations of composite resin, and the lateral incisors and canines present alterations in shape and position. All anterior teeth present color alteration.



Figure 3. Aspect of the teeth after dental bleaching and after the substitution of the resin restorations.

burs at the cervical region and burs with a depth-limiting device on the facial surface of the tooth. The remaining facial enamel was reduced to the level of these grooves using a tapered-cylinder, round-end diamond bur (KG Sorensen, São Paulo, Brazil). For the proximal area, metal sandpaper (KG Sorensen) was used to create a separation between the teeth in order to facilitate the definition of the proximal margin, the impression procedure, and the positioning of the veneers. The incisal third was prepared, reducing only the buccal surface, maintaining enamel tissue in this region for adhesion of ceramic and resin. During this phase, it was important to use the silicone matrix, obtained from the wax-up, to guide the amount of reduction in tooth preparation. Finally, all angles were rounded, and an extrafine, tapered-cylinder, round-end diamond burr (KG Sorensen); silicone rubber (Enhance, 3M ESPE); abrasive disks (Pop-On, 3M ESPE); and felt disks (Feltros Diamond, FGM Products) were used to smooth the prepared surface (Figure 6). The final amount of wear was 0.8 mm at the medium third and 0.4 mm at the cervical third.



Figure 4. Diagnostic wax-up.



Figure 5. Diagnostic mock-up for a guide to tooth preparation.

For the impression technique, two retraction cords (Ultrapack, Ultradent Products, São Paulo, Brazil) of different diameters were placed in the gingival sulcus, and a complete impression with a double-viscosity polyvinyl siloxane material was made after removal of the second cord (Figure 7). The first retraction cord was also removed, and the desired color for the porcelain veneer was selected using a special scale. This is an important step in determining the final results, requiring effective communication between the practitioner and the technician. Finally, provisional restorations were made with a bis-acryl resin (Luxatemp Plus, DMG, Hamburg, Germany; Figure 8). The maxillary and mandibular casts were sent to the dental technician for pouring, creation of dies, and fabrication of feldspathic porcelain veneers (Empress Esthetic, Ivoclar Vivadent, São Paulo, Brazil).

Once the veneers were received from the technician (Figure 9), they were carefully positioned to verify marginal adaptation, alignment, shape, and color, with completely satisfactory results. Prior to the



Figure 6. Teeth aspect after the preparation for ceramic veneers.



Figure 7. Placement of retraction cords for impression.

luting procedures, teeth were submitted to a prophylaxis with pumice and rubber cup. The conditioning of internal surfaces of the restorations was performed through application of 9.5% hydrofluoric acid for one minute (Condac Porcelana, FGM Products; Figure 10-a) and washing under running water and air-drying; afterward, a silane coupling agent (Prosil, FGM Products) was applied (Figure 10b). The luting of the veneers was performed for each tooth individually, following the same sequence for each. After isolation of the gingiva and the prepared tooth, teeth conditioning with 37% phosphoric acid (Condac 37, FGM Products) for 30 seconds (Figure 11a), rinsing, and careful drying were performed. Next, a one-bottle bonding system (Single Bond, 3M ESPE) was applied, and the surface was gently air-dried and polymerized for 40 seconds (Figure 11b).

The luting agent used in this case was flowable resin A1 (Natural Flow, DFL, São Paulo, Brazil). It was applied in the internal surface of the veneer, and then the veneer was positioned (Figure 12). After polymerization for five seconds, excess cement was removed using manual instruments (Figure 13), and the veneer was once more light cured at the facial and lingual sides for 40 seconds. After the placement



Figure 8. Use of a mock-up to fabricate provisional restorations.



Figure 9. Porcelain laminate veneers.

of all veneers (Figure 14), finishing and polishing of the cement line were performed with flexible aluminum oxide disks. A final adjustment of the ceramic was performed with diamond burs FF (KG Sorensen) in the areas marked with graphite. At adjusted surfaces, polishing was performed to avoid additional wear. The cervical margins were verified, and the excess cement was removed with strips of sandpaper (Figure 15). The final result can be seen immediately and in a clinical follow-up at 12 months with the facial (Figure 16) and intraoral (Figure 17) aspects of the patient.

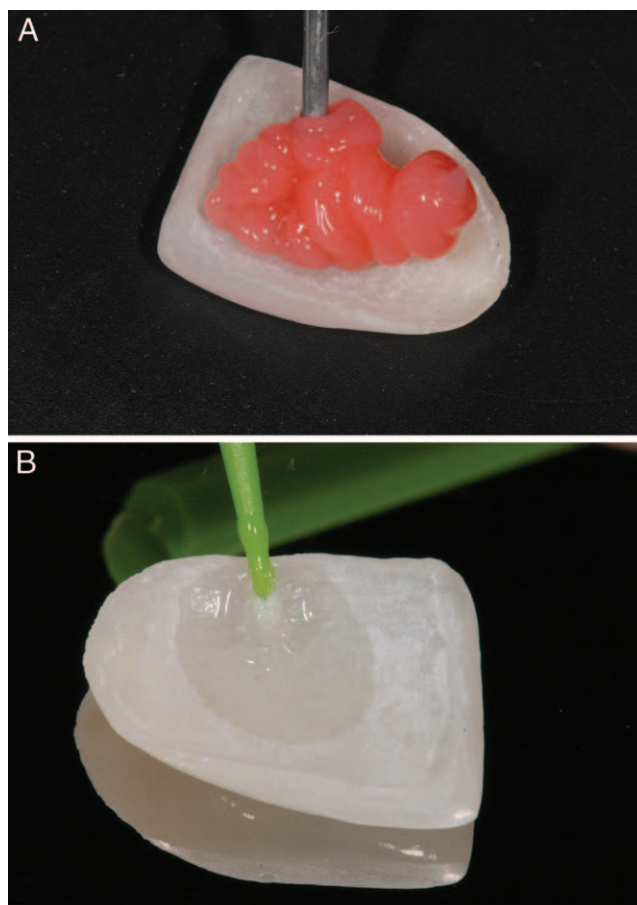


Figure 10. Conditioning of the internal surface of the ceramic veneer with application of hydrofluoric acid (a) and application of silane ceramic primer (b).

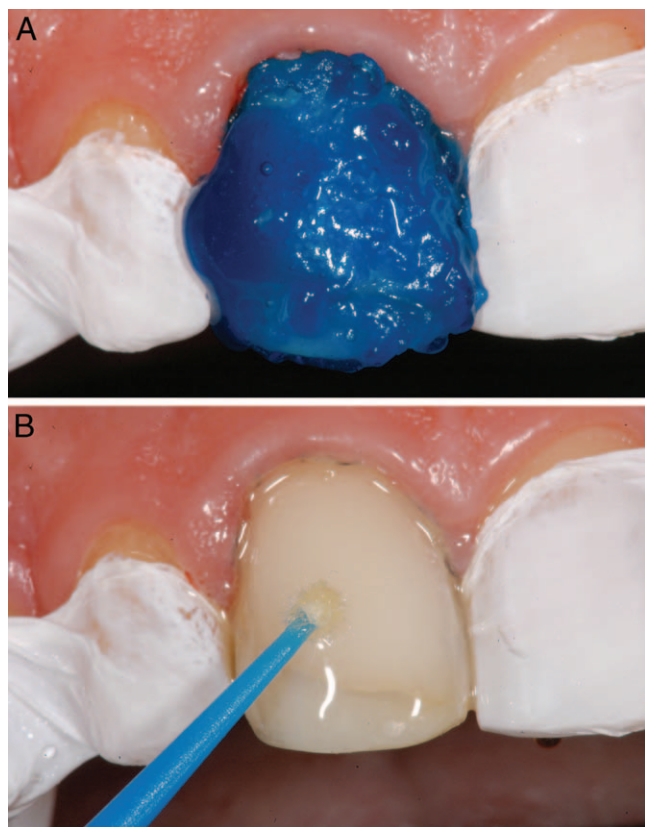


Figure 11. Conditioning of the tooth with application of phosphoric acid (a) and application of the adhesive system (b).

DISCUSSION

At present, ceramic veneers are used routinely to treat unesthetic anterior teeth. Clinical success of this treatment depends on the correct selection of the

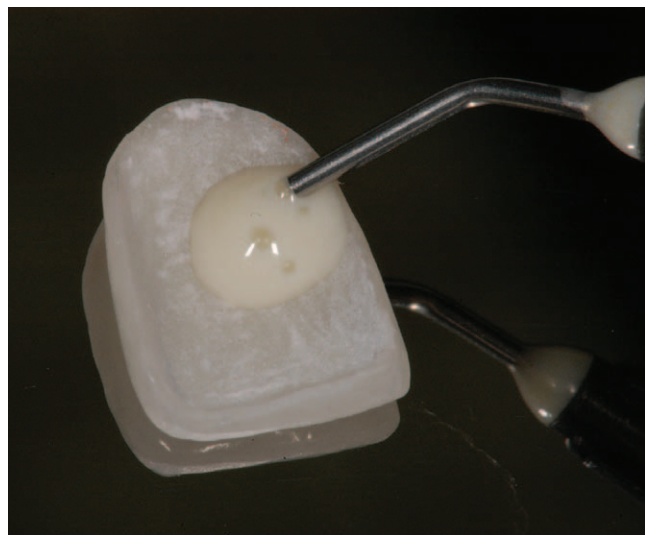


Figure 12. Application of flowable resin in the ceramic veneer.

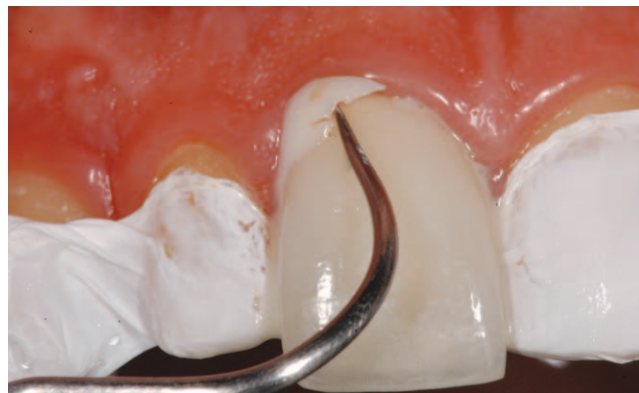


Figure 13. Removal of excess luting agent.

case. Indications of whether laminate veneers should be used as a conservative solution to an esthetic problem may include the following: presence of discolored teeth resistant to vital bleaching procedures, displeasing shapes or contours and/or lack of size and/or volume, the need for morphologic modifications, diastema closure, minor tooth alignment, restoration of localized enamel malformations, fluorosis with enamel mottling, teeth with minor chipping and fractures, and misshapen teeth.⁴⁻⁶ The contraindications must also be recognized. The placement of veneers is contraindicated when there is reduced interocclusal distance, deep vertical overlap anteriorly without horizontal overlap, severe bruxism, or parafunctional activity.⁵

In this report, the patient complained about the esthetic of his smile, which presented extensive restorations in the central incisors, morphologic alterations in shape and contour, and the presence of a black space between the left central and lateral incisors. Treatment possibilities with composite



Figure 14. Final aspect immediately after the cementation of the veneers.



Figure 15. *Postoperative immediate view.*

resin or ceramic veneers, as well as their advantages and limitations, were shared with the patient. Although composite resin may be indicated for a less invasive approach, this type of restoration would suffer from limited longevity because the material remains susceptible to discoloration, wear, and

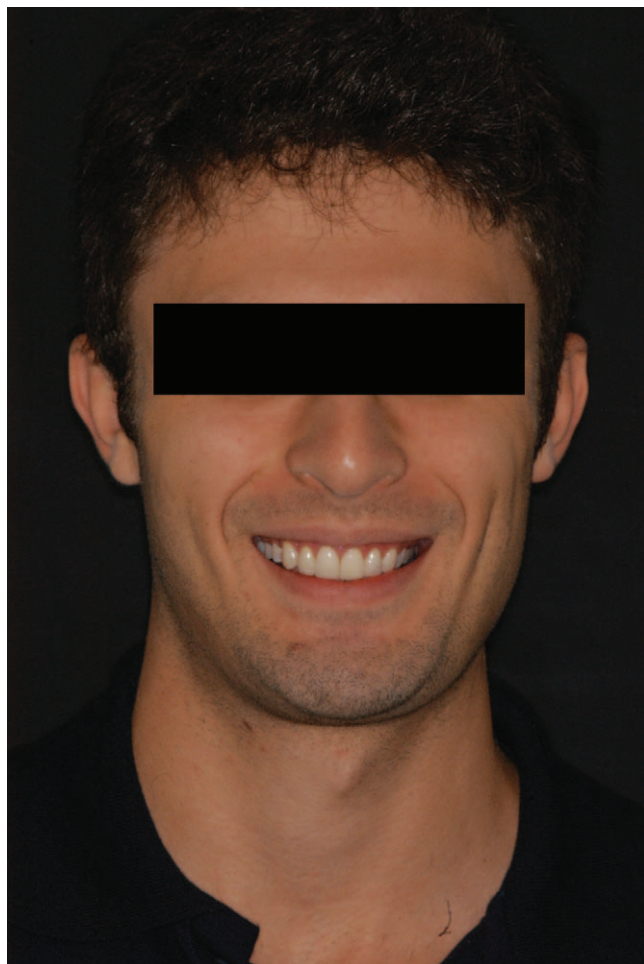


Figure 16. *Facial view of the clinical follow-up after 12 months.*



Figure 17. *Extraoral view of the clinical follow-up after 12 months.*

marginal fractures, thereby reducing the esthetic result in the long term.¹⁴ On the other hand, porcelain veneers were proposed as being durable anterior restorations with superior esthetics and, considering the advances in the ceramic and bonding materials, were currently indicated for this type of treatment.¹⁷

Various clinical studies have supported the indication of ceramic veneers. According to Meijering and others,¹⁸ survival rates for veneer restorations were 94% for porcelain restorations, 90% for indirect composite restorations, and 74% for direct composite restorations. Other previous studies have demonstrated that the survival rate for bonded porcelain laminate veneer restorations is more than 90% over 10 years of clinical service.^{14,19,20} Della Bona and Kelly (2008)²¹ compared the clinical evidence for all-ceramic restorations, reporting that the ceramics are particularly well suited for veneer restorations, which have failure rates (including loss of retention or fracture) of less than 5% at five years. Other authors found that the feldspathic porcelains showed similar long-term survival rates: 96% at five years, 93% at 10 years, and 91% at 12 years.^{14,15} Both feldspathic porcelain and glass-infiltrated ceramics presented long-term survival rates of approximately 96% to 98% at five years.^{20,21}

The success of the treatment after the correct indications depends on the adequate application of the techniques. With the intention of improving the final esthetic result, a bleaching protocol and replacing the discolored restorations were established as first steps of the treatment. This is necessary because the final color exhibited by a porcelain veneer will be the result of the interaction

between porcelain laminate, substrate, and luting cement.²

In the present case, veneers were made with feldspathic porcelain. These ceramics provide excellent esthetic value and demonstrate high translucency, just like natural dentition.¹¹ Although their mechanical properties are low, with flexural strength usually ranging from 60 to 70 MPa,²² currently they are appropriate for less invasive treatments and higher levels of esthetics, as in veneers. With this material, it is possible to have thicknesses of less than 0.5 mm with or without preparation of the enamel. The ideal conditions for the bond between veneer and substrate are the remainder of the tooth being 50% or more of the tooth enamel, 50% or more of the bonded substrate being enamel and 70% or more of the margin being enamel.^{5,11,17,21} These conditions are in accordance with those presented in the case description, where thicknesses of veneers are approximately 4 mm in the cervical third and 8 mm in the middle third. At the incisal third, in order to be conservative and maintain enamel in this region, the enamel reduction was performed only on the buccal surface.¹⁷

The mock-up technique was employed at the time of the tooth preparation. This device is advised for the delicate removal of the minimal required space for thin porcelain veneers.⁸ It allows for the final visualization of the irreversible procedure¹⁶ and can facilitate the communication between the clinician and the patient. The complementary step in this phase is the fabrication of provisional restorations. They are important to accommodate the gingival tissue to the restorative material and to preview the phonetics and occlusal comfort necessary at the end of the treatment.¹³

The ceramic veneer technique includes the bonding of a thin porcelain laminate to tooth surface, enamel, and/or dentin, using adhesive techniques and a luting composite to change the color, shape, and/or position of anterior teeth.³ The success of the treatment depends on adequate conditions of bonding between the veneers and the tooth complex that involve parameters such as the strength and durability of this union.¹⁴ In the present report, the cementation material used was flowable resin composite. This is a photocured material that interferes minimally with the esthetic stability of ceramic restorations.^{23,24} Although resin luting dual-cured cements have superior mechanical properties, such as shear strength and hardness, the flowable resin is more suitable for these cases. The original color of the chemical- or dual-cured cements may change

over time due to oxidation of the tertiary amine content, and this characteristic can jeopardize the esthetic appearance of the restoration, especially in thin ceramic veneers.²³⁻²⁵ Therefore, besides the flowable resin promoting adequate sealing between ceramic and tooth substrate with less nanoinfiltration,²⁴ this material is also more indicated for cementation of esthetic restorations due to its color stability.

CONCLUSION

Porcelain veneers are indicated in cases of teeth needing alterations in color and shape and with extensive restorations. This treatment presents advantages, such as a minimum thickness of tooth reduction, bonding between ceramic and enamel and dentin, and a satisfactory esthetic result due to the inherent properties of the ceramics.

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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Effects of Light Activation, Agent Concentration, and Tooth Thickness on Dental Sensitivity After Bleaching

G Moncada • D Sepúlveda • K Elphick
M Contente • J Estay • V Bahamondes
E Fernandez • OB Oliveira • J Martin

Clinical Relevance

Increases in the concentration of bleaching agents directly affect tooth sensitivity, and LED/laser activation and tooth thickness are not correlated with tooth sensitivity after dental bleaching.

SUMMARY

Examining three bleaching systems, this *in vivo* clinical trial evaluated the relationship among tooth sensitivity, light activation, and

agent concentration, and it correlated dental sensitivity with tooth thickness.

Materials and Methods: Eighty-seven volunteer patients were included. Inclusion criteria were the presence of anterior teeth without restorations as well as the absence of a previous bleaching experience and absence of non-carious cervical lesions or dental pain. Exclusion criteria included pregnancy or breastfeeding, a maximum of TF3 hypoplasia, tetracycline-fluorosis stains, malpositioned teeth, orthodontic treatment, periodontal disease, and/or analgesic/anti-inflammatory intake. Patients were randomly assigned to

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three bleaching groups: Group A (n=25) was treated with 15% H₂O₂ and nitrogenous-titanium-dioxide and was light activated (Lase Peroxide Lite, DMC, SaoCarlos, Sao Paulo, Brazil); Group B (n=27) was treated with 35% H₂O₂ and was light activated (Lase Peroxide Sensy, DMC); and Group C (n=35) was treated with 35% H₂O₂ (White Gold Office, Dentsply, 38West Clark Ave., Milford, USA) without light activation. Tooth sensitivity (TS) was self-reported by the patients using the visual analog scale (VAS) at baseline (TS0), immediately after treatment (TSI), and at seven days after treatment (TS7). In 46 patients, tooth thickness was determined by computed tomography. TS0, TSI, and TS7 were compared between the A and B groups to determine the effect of concentration and between the B and C groups to determine the effect of light using analysis of covariance. The correlation between tooth thickness and TSI was determined by Spearman Rho test (SPSS 15).

Results: Eighty-seven patients were evaluated at baseline, and 61 were evaluated at seven days. Separated by groups, tooth sensitivity, expressed as VAS value at the time points TS0, TSI, and TS7, respectively, were as follows: Group A: 13.76 ± 13.53, 24.40 ± 25.24, and 5.94 ± 5.5; Group B: 15.07 ± 18.14, 42.4 ± 31.78, and 8.68 ± 17.99; and Group C: 10.80 ± 14.83, 31.51 ± 29.34, and 7.24 ± 9.2. Group A showed significantly lower tooth sensitivity than group B at TSI ($p=0.032$). No differences were observed in the tooth sensitivities between groups B and C. No correlation was encountered between tooth thickness and tooth sensitivity immediately after treatment ($\text{Rho}=-0.088, p=0.563$). The median tooth thickness was 2.78 ± 0.21 mm.

Conclusions: Increases in the concentration of bleaching agents directly affect tooth sensitivity, and LED/laser activation and tooth thickness are not correlated with tooth sensitivity after dental bleaching.

INTRODUCTION

Tooth appearance is an important factor in beauty and attractiveness, and patients often demand esthetic dental treatments. Tooth bleaching is one of the most conservative dental treatments that can improve or enhance the smile and has thus gained popularity in regular oral care.¹⁻³ Currently, tooth

bleaching has been recognized as an efficacious and safe method with which to treat discolored teeth.⁴

Power bleaching reduces the total in-office time by energizing the bleaching agent using light sources, such as lasers or plasma arc light. The theoretical benefit lies in the light's ability to heat the hydrogen peroxide, increasing the rate of decomposition of oxygen to form oxygen-free radicals and enhancing the release of stain-containing compounds.⁵ However, it has been observed that while light energy increases bleaching efficacy, it also increases the intrapulpal temperature.^{6,7} Expert clinicians know the potential risk associated with tooth heating, and they need to consider the issue of pulp health before rendering this treatment on vital teeth.⁸

Tooth sensitivity is one of the most common side effects of bleaching treatment; this phenomenon directly depends on the bleaching agent concentration and the application time. Therefore, high-concentration agents used in in-office procedures usually generate discomfort.⁹⁻¹³ Tooth sensitivity normally persists for up to four days after the conclusion of bleaching treatment,^{14,15} but longer periods of sensitivity have been reported.^{16,17}

In in-office dental bleaching, tooth sensitivity is directly associated with the bleaching agent's ability to reach the pulp chamber by penetrating through dental tissues and establishing contact directly with the pulp.^{18,19} The amount of peroxide that can penetrate the pulp chamber may be affected by the thickness of the teeth.²⁰ A greater thickness would offer the pulp better protection from the bleaching agent.²¹ Additionally, pulp penetration would be affected by the concentration of the bleaching agent, as low concentrations of peroxide would extend less deeply into the pulp chamber.^{9,13}

The objective of this randomized controlled trial was to determine the relationship among tooth sensitivity, light activation, and agent concentration and to correlate dental sensitivity with tooth thickness in the application of three different bleaching systems.

MATERIALS AND METHODS

This study was approved by the Ethics Committee and Research Office of the Dental School, Chile University (protocol PRI-ODO-012-1).

Experimental Protocol

This prospective clinical study included 87 volunteer patients (64 female and 23 male), aged 18 through 37 years, attending the Operative Dentistry Clinic at

the Dental School, Chile University. The inclusion criteria were the following: 1) anterior healthy vital teeth without restorations; 2) patients without bleaching experience; 3) lack of noncarious cervical lesions; and 4) lack of dental pain. The exclusion criteria were the following: 1) pregnancy or breastfeeding, 2) greater than TF3 hypoplasia (Thylstrup-Fejerskov), 3) tetracycline/fluorosis stains, 4) malpositioned teeth, 5) orthodontic treatment, 6) periodontal disease, and 7) analgesic/anti-inflammatory intake. After informed consent was obtained, patients were coded and randomly assigned to one of the three bleaching groups (EF-OO), performed by power analysis and a sample size system with PASS software, version 2004 (Keyville, UT, USA) (clinicians K.E., D.S., and M.C.).

Group A ($n=25$) contained patients that were treated with 15% H_2O_2 and nitrogenous-titanium-dioxide (prepared according to the manufacturer's instructions) and were light activated (light activation involved six LEDs composed of 470 nm and 1800 mW as well as three infrared laser diodes of 830 nm and 450 mW/cm²; Whitening Lase II equipment, DMC, Rua Sebastiao Moraes 831, Sao Carlos, Sao Paulo, Brazil). Three 15-minute applications of the bleaching agent were performed via alternating cycles of one minute and 30 seconds, completing five cycles of light activation per arch, reaching a total treatment time of 45 minutes.

Group B ($n=27$) contained patients treated with 35% H_2O_2 and then light activated (Lase Peroxide Sensy, DMC), according to the manufacturer's instructions. They were treated with three 10-minute applications of bleaching agent. Each application included 60% irradiation time, with a total treatment time of 30 minutes.

Group C ($n=35$) contained patients treated with 35% H_2O_2 (White Gold Office, Dentsply, 38West Clarke Ave., Milford, USA) for 45 minutes without light activation. The bleaching agent was prepared according to the manufacturer's instructions.

All teeth were cleansed with soft brushes at low speed using fine pumice powder and water. Teeth and gum tissues were dried with air (triple syringe, 25 psi). The gingiva was protected with a gum barrier (Lase Protect, DMC) and was photo-polymerized for 30 seconds with Whitening Lase II equipment (DMC).

Tooth Sensitivity (TS) Determination

TS or discomfort caused by the bleaching treatment was self-assessed with the use of the Visual Analog Scale (VAS), in which the patient quantified his

painful response by making a mark in a 100-mm-long line that was anchored by word descriptors at each end: "no pain" at the left end and "very severe pain" at the right end. The patient marked the point on the line that he felt represented his perception of the pain. Patients were questioned: "How severe is your pain today? Place a vertical mark on the line below to indicate how bad you feel your pain is today." The VAS score was determined by measuring in millimeters from the left-hand end of the line to the point that the patient marked.^{22,23}

TS was measured only for the central upper incisors and was acquired by one clinician (J.M.) at three time points: at baseline (TS0), immediately after treatment (TS1), and seven days after treatment (TS7).

Tooth Thickness Determination

In 46 patients, tooth thickness was determined by cone beam computed tomography (CBCT) (MyRay Dental Imaging, Via Bicocca 14/c 40026, Imola, Italy), with the following specifications: FOV 4 inches, 15.7 seconds, 90 kVp, 10 mA (max), 50.8 uSv per exam, high resolution, in volume slices of 0.5-mm thickness. The scanner was requested for other clinical reasons (orthodontics, implants, third molar surgery, or temporomandibular joint). The tooth thickness was determined directly on the screen with the use of a bidimensional tool measurement in the Skyview software (MyRay Viewer 3D). One radiologist (J.E.) acquired three measurements made at the center of the labial dental surface in the buccal-palatal axis using a reformatted image of each tooth (Figures 1–3). To reduce bias, the clinician who evaluated tooth thickness was not aware of which group the patients belonged to in the study.

Data Analysis

After verifying the normality of the data distribution and the homogeneity of variances (Levine test), the tooth sensitivity was compared in each group three times using a one-way analysis of variance and *post hoc* Tukey tests. To determine the effect of the bleaching agents' concentration on tooth sensitivity, groups A and B were compared; to determine the effect of light on tooth sensitivity, groups B and C were compared, both using the analysis of covariance (ANCOVA) test. Tooth thickness was correlated with tooth sensitivity, immediately and after seven days of treatment, with the Spearman Rho test. In all tests, the level of significance was set at $\alpha = 0.05$, and calculations were performed using the SPSS 15.0 software package (SPSS Inc, Chicago, IL, USA). (VB-GM Statistics)

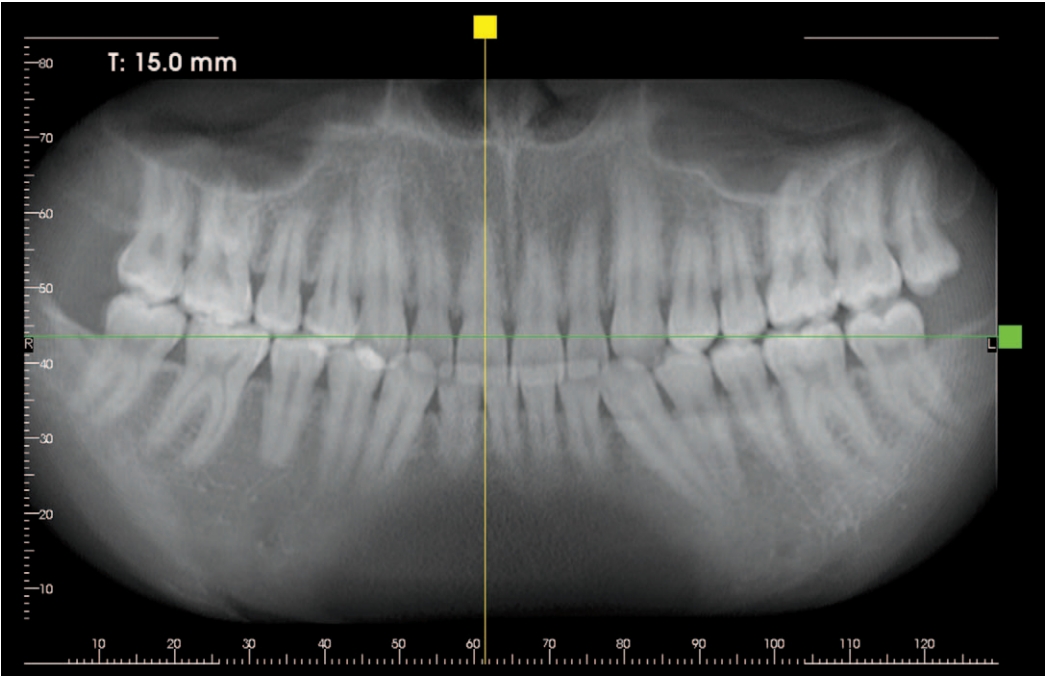


Figure 1. Reformatted panoramic image of 15-mm depth. The vertical line is the reference used for sagittal slices related to the major axis of the dental crown. This line was located in the center of the crown and determined the location of the measurement made in the sagittal plane.

RESULTS

Eighty-seven patients (median age, 23.15 ± 3.68 years) were evaluated at baseline and immediately after bleaching, and 61 patients (median age, 23.25

± 3.54 years) were evaluated seven days after treatment. Most of the patients were female and fell in the range of 18-27 years of age (Tables 1 and 2). Gender did not affect tooth sensitivity initially

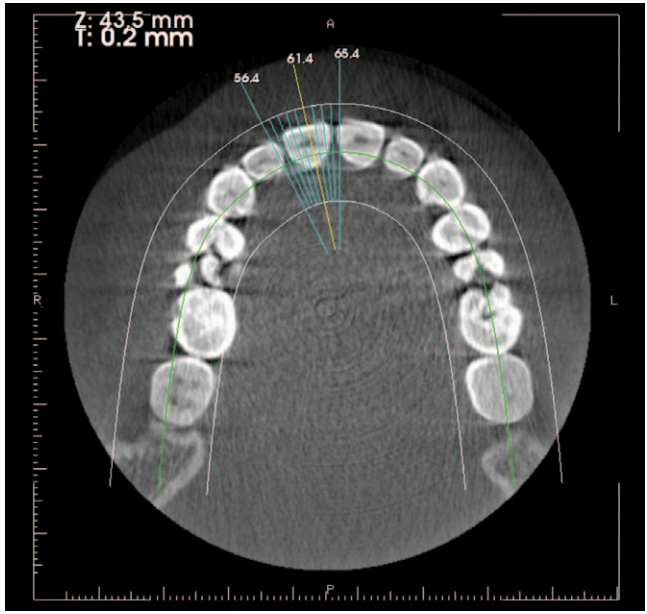


Figure 2. Axial reformatted image. The yellow line crosses the center in the sagittal plane, perpendicular to the major axis of the tooth crown. This was used to build a sagittal reformatted image, and the curve of the dental arch (green line) was used as a reference.



Figure 3. Sagittal reformatted slice of 0.5-mm depth, made in the center of the crown (right central incisor). Lines A, B, and C show the measures of the tooth thickness on the labial face of each tooth.

Table 1: Distribution by Age and Gender at Baseline and Immediately After Treatment

	N	Male		Female		18-27 Years		28-37 Years	
		N	%	N	%	N	%	N	%
Group A	25	6	24.00	19	76.00	23	92.00	2	8.00
Group B	27	7	25.93	20	74.07	24	88.89	3	11.11
Group C	35	10	28.57	25	71.43	31	88.57	4	11.43
Total	87	23	26.43	64	73.56	78	89.65	9	10.34

($p=0.67$), either immediately after treatment ($p=0.126$) or seven days after treatment ($p=0.313$). At baseline the tooth sensitivities of the groups were compared and did not show statistical differences ($p=0.449$ between groups A and B; $p=0.726$ between groups B and C, by ANCOVA test).

All tested bleaching systems generated tooth sensitivity immediately after treatment and returned to baseline levels seven days after treatment. This increase was statistically significant for groups B and C ($p<0.05$) but not for group A ($p=0.247$) (Tables 3 and 4).

Bleaching with 15% hydrogen peroxide and TiO_2 with LED/laser activation resulted in significantly lower tooth sensitivity relative to bleaching with 35% hydrogen peroxide and LED/laser activation immediately after treatment ($p=0.032$). Differences in the bleaching concentration did not result in tooth sensitivity differences after seven days ($p=0.644$) (Table 3).

In groups B and C, a significant increase in tooth sensitivity was observed immediately after treat-

ment ($p=0.001$ and $p=0.002$, respectively). After seven days, both groups returned to baseline tooth sensitivity. No differences were observed to be associated with the use of light activation, as both groups failed to exhibit a statistically significant discrepancy in tooth sensitivity immediately after treatment ($p=0.191$) or seven days after treatment ($p=0.921$) (Table 4).

The CT analyses were performed on 46 patients (92 teeth), and they revealed a median labial tooth thickness of 2.78 ± 0.21 mm (Figures 1 through 3). No correlation was observed between tooth thickness and tooth sensitivity immediately after treatment ($\text{Rho}=-0.138$, $p=0.36$) or after seven days ($\text{Rho}=-0.202$, $p=0.25$).

The 46 patients examined by cone beam CT were distributed by groups as follows: group A: $n = 10$; group B: $n = 10$; and group C: $n = 26$. Correlation between tooth sensitivity and tooth thickness, separated by groups, was not statistically significant in Group A or B, and showed low correlation in Group C (Spearman test) (Table 5).

Table 2: Distribution of Age and Gender at Seven Days After Treatment

	N	Male		Female		18-27 Years		28-37 Years	
		N	%	N	%	N	%	N	%
Group A	18	4	22.22	14	77.78	17	94.44	1	5.56
Group B	22	6	27.27	16	72.73	20	90.91	2	9.09
Group C	21	6	28.57	15	71.43	18	85.71	3	14.29
Total	61	16	26.22	45	73.77	55	90.16	6	9.83

Table 3: Mean tooth Sensitivity of Groups A and B at Baseline, Immediately After Treatment, and Seven Days After Treatment, Compared at Different Stages of Evaluation and Between Groups

	Initial VAS Value $\pm$ SD	Immediate VAS Value $\pm$ SD	7-d VAS Value $\pm$ SD	p-Value Initial/ Immediate	p-Value Initial/7 d	p-Value Immediate/7 d
Group A	13.76 $\pm$ 13.53	24.40 $\pm$ 25.23	5.94 $\pm$ 5.50	0.247	0.062	0.029
Group B	15.07 $\pm$ 18.14	42.40 $\pm$ 31.78	8.68 $\pm$ 17.99	0.001	0.056	0.000
p-Value between groups	0.449	0.032	0.644	—	—	—
Abbreviations: VAS, visual analog scale; SD, standard deviation.						

DISCUSSION

In the present study, all in-office bleaching systems showed an increase in tooth sensitivity immediately after treatment. However, the sensitivity returned to baseline levels seven days after treatment, sometimes reaching a level even lower than baseline. Sensitivity often occurs during the early stages of tooth bleaching, and for most patients, it is tolerable to complete the treatment.²⁴ Salem and Osman¹⁵ reported that tooth sensitivity was a temporary side effect that disappears after four days of treatment in most patients. The fact that sensitivity reached levels lower than baseline seven days after treatment was also observed by Trowbridge and Silver,²⁵ who stated that this phenomenon can be explained by a positive emotional predisposition that may activate the central nervous system's pain inhibitor, causing the release of endorphins and decreasing painful sensations.

In our study, a high standard deviation of tooth sensitivity values was observed. Tooth sensitivity is caused by the passage of hydrogen peroxide molecules through the enamel and dentin into the pulp chamber.²⁶ This results in pulp inflammation, which affects the pulp sensory nerves that can trigger

increased response to stimuli, such as cold drinks, until the inflammation subsides.²⁷ Therefore, tooth sensitivity may vary with the different factors that affect this passage into the pulp, such as presence of dental cracks, dentin exposure, or pulp chamber dimensions. Additionally, the high standard deviation of sensitivity could be due to the subjective nature of the sensitivity threshold and/or because sensitivity is not dependable and is not associated with the use of a particular bleaching system.²⁸ Based on the high standard deviation of postoperative tooth sensitivity that was observed in this and other studies,²⁷⁻³¹ it is difficult to obtain an accurate measurement of problems in the population,³² and clinicians have a limited ability to predict the tooth sensitivity that may affect each patient. Additionally, because of this complex etiology, a definitive strategy for sensitivity prevention has not yet been developed.²⁸

Clinically, tooth sensitivity is the most common side effect of bleaching; thus, this treatment is not adequate for every patient.²⁴ A complete clinical history is necessary to recognize any previous abnormal responses to temperature changes or other stimuli.²⁹ In the current study, no patients present-

Table 4: Mean tooth Sensitivity of Groups B and C at Baseline, Immediately After Treatment, and Seven Days After Treatment, Compared at Different Stages of Evaluation and Between Groups

	Initial VAS Value $\pm$ SD	Immediate VAS Value $\pm$ SD	7-d VAS Value $\pm$ SD	p-Value Initial/ Immediate	p-Value Initial/7 d	p-Value Immediate/7 d
Group B	15.07 $\pm$ 18.14	42.40 $\pm$ 31.78	8.68 $\pm$ 17.99	0.001	0.560	0.000
Group C	10.80 $\pm$ 14.83	31.51 $\pm$ 29.34	7.23 $\pm$ 9.20	0.002	0.433	0.001
p-Value between groups	0.726	0.191	0.921	—	—	—
Abbreviations: VAS, visual analog scale; SD, standard deviation.						

Table 5: Correlation Between Tooth Sensitivity and Tooth Thickness, Separated by Groups, (Spearman Test)

	<i>p</i>	Rho
Group A	0.906	-0.43
Group B	0.067	0.60
Group C	0.040*	-0.405
* Statistically significant ($\alpha=0.05$).		

ed with irreversible tooth sensitivity, and tooth bleaching is a safe treatment when the dental history of the patient is considered. Thus far, there are no reported cases of pulp necrosis caused by tooth bleaching²⁴ or of long-term adverse pulp sequelae when the proper techniques are employed.³ However, teeth with caries or exposed dentin, teeth with surfaces in close proximity to pulp horns, or those that are suspected to have cracks are potentially at risk for developing severe sensitivity and thus are not recommended for bleaching.²⁴ In such cases, the use of an ambulatory bleaching system, which depends on the use of carbamide peroxide, may be considered.²⁹

When comparing the tooth sensitivity that was developed in the group treated with 15% hydrogen peroxide with that of the group treated with 35% hydrogen peroxide, when both were light activated, a lesser concentration of bleaching agent resulted in less sensitivity immediately after treatment ($p=0.03$). This finding is in agreement with the findings of Benetti and others¹³ and Gokay and others,⁹ who concluded that increasing peroxide concentrations would affect tooth sensitivity. This result indicates that agents with low concentrations will be more favorably accepted by patients; therefore, these agents may be used in every patient, even in those at risk of developing severe sensitivity.

When comparing groups treated with 35% hydrogen peroxide with and without light activation, no differences in tooth sensitivity were observed. It has been proposed that lasers may decrease tooth sensitivity,^{33,34} but high-intensity LEDs included in the lamp may raise the temperature,^{35,36} neutralizing this beneficial effect. Different light sources have been applied in dental whitening. Utilizing light sources in in-office dental bleaching with 35% hydrogen peroxide, on vital teeth, did not prove to

be more effective. Light is not important in clinical results; it apparently affects only the treatment time and differences in color stability were not found through six months of evaluation.³⁷

Even though there were differences observed in tooth sensitivity between agents with different concentrations, the fact that all patients presented with this side effect cannot be ignored. Evidence indicates that the initial diffusion of peroxide into and through the enamel may reach the dentino-enamel junction and dentin regions. Indeed, *in vitro* experiments by a number of authors³⁸⁻⁴² have demonstrated the penetration of low levels of peroxide into the pulp chamber of extracted teeth after exposure times of 15 to 30 minutes, with intact teeth showing less penetration of peroxide than restored teeth. In our study, the total treatment time per appointment was 45 minutes for groups A and C and 30 minutes for group B. This finding likely indicates that in all patients, the peroxide reached the pulp chamber, explaining the increase in tooth sensitivity observed in all studied groups. The clinically reversible effects of tooth sensitivity have been histologically studied by Fugaro and others⁴³ in other types of treatment, including bleaching with 10% carbamide peroxide. These authors observed that peroxide might initially cause mild, localized pulp reactions. However, the slight histological changes that were observed did not affect the overall health of the pulp tissue and were reversible within two weeks of the conclusion of treatment.

Finally, no correlation between tooth thickness and tooth sensitivity was found, either immediately after treatment or after seven days. In recent years, CBCT has been demonstrated to be one of the most accurate methods for the study of hard tissue in dentistry. CBCT is used for numerous clinical applications, especially because of its low cost, easy accessibility, and low radiation compared with multi-slice computerized tomography.⁴⁴ The measurements obtained by CBCT technology have proven to be accurate and concordant with physical measurements.⁴⁵⁻⁵⁰ The present observations on the relationship between dental bleaching and dental thickness offer the first available conclusions on this topic. The present study found that labial tooth thickness was not related to tooth sensitivity in bleaching treatments. Labial tooth thickness showed high uniformity and low standard deviation, and these results could be associated with the average age of the participants and the characteristics of the sample, as the sample was comprised of young adults without cavities or restorations who

had esthetically aligned anterior teeth, without a loss of molars or premolars.

The patients in group C studied by CBCT were the only patients who showed a moderate degree of statistically significant correlation between tooth sensitivity and tooth thickness; however, caution must be used in interpreting this result, given the low number of samples by group.

For tooth sensitivity and thickness of the 46 patients examined by CBCT, the 12 younger (18-20 years) and the 12 oldest (25-37 years) were compared and differences in sensitivity between groups immediately ($p=0.124$) or seven days after treatment ($p=0.391$) were not found, also differences in tooth thickness ($p=0.311$) were not found. No correlation was found between age groups and sensitivity immediately ($p=0.933$) and seven days after treatment ($p=0.209$).

Although this study did not identify a correlation between tooth thickness and sensitivity, De Souza Costa and others⁵¹ histologically observed the presence of differences in the inflammatory pulpal response to bleaching when comparing upper premolars with lower incisors.

CONCLUSIONS

Increases in the concentration of bleaching agents also increases tooth sensitivity immediately after treatment. After seven days of treatment, tooth sensitivity returned to baseline for both concentrations tested. The light activation of bleaching agents did not affect dental sensitivity. No correlation between tooth thickness and dental sensitivity was found immediately after treatment.

The present study provided additional clinical information related to the risks of tooth pain after bleaching, and the results aid in determining the optimal bleaching agent concentration and light source to enhance these treatments.

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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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Clinical Evaluation of Self-etch and Total-etch Adhesive Systems in Noncarious Cervical Lesions: A Two-year Report

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LC Ramp

Clinical Relevance

This two-year clinical trial evaluated three adhesive systems to restore noncarious cervical lesions with composite resin restorations. No significant differences were observed between restorations bonded with a one-bottle total-etch, a one-bottle self-etch, or a two-bottle self-etch adhesive.

SUMMARY

Objective: The purpose of this study was to compare the clinical performance of two self-etch dental adhesives with Single Bond Plus, a traditional one-bottle total-etch dental adhe-

sive, for the restoration of noncarious cervical lesions.

Materials and Methods: A total of 156 restorations were placed in noncarious cervical lesions with a minimum depth of 1.5 mm. Patients had no chronic periodontal disease and had normal salivary function. Each patient received restorations on three teeth, each bonded with either Adper Single Bond Plus, Adper Easy Bond, or Adper Scotchbond SE dental adhesive. All lesions were restored with Filtek Supreme Plus composite resin. All teeth were isolated with a rubber dam, received a short enamel bevel, and were cleaned with flour of pumice. The adhesives and resin composite were applied following the manufacturers' instructions. Restorations were clinically evaluated at baseline, six months, one

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year, and two years using modified US Public Health Service criteria.

Results: Two-year retention was recorded as 97.3%, 90.5%, and 95.2%, for Single Bond Plus, Scotchbond SE, and Easy Bond, respectively. Statistical analysis did not show a significant difference ($p > 0.05$) in clinical performance between any of the three adhesives after a period of two years.

INTRODUCTION

Noncarious cervical lesions (NCCLs) are slowly progressing clinical conditions with multiple etiologies that offer unique challenges to adequate dental restoration.¹⁻³ The incidence of NCCLs ranges from 5% to 85%, and the number, size, and depth of the lesions increase with patient age.⁴ The main etiologies of NCCLs are abrasion, erosion, or abfraction. Although many authors claim a single etiology for these lesions, their pathogeneses appear to be multifactorial.⁵⁻⁸ Treatment for NCCLs may include restorations, occlusal adjustment, and oral hygiene instructions.⁹ Primary indications for treating NCCL are sensitivity, esthetics, plaque retention, and the need for the affected tooth to abut a removable partial denture.^{9,10} It has been suggested that restoring NCCLs may reduce tooth flexure during occlusal load, thereby strengthening the teeth and perhaps slowing the progression of the NCCLs.¹¹ To preserve tooth structure, NCCLs are generally restored with tooth-colored materials, such as resin composite, glass ionomer, or compomer. Of these materials, resin composites are used most often because of their excellent esthetic and physical properties.

The success of composite resin Class V restorations depends in large part on the properties of the bonding agent used. Residual stress resulting from polymerization shrinkage and long-term durability may be affected by external factors, such as multidirectional loading during mastication, thermal stress by cold and hot stimuli, and wear from tooth brushing.¹²⁻¹⁵ In particular, repetitive compressive and tensile stresses caused by tooth flexure in cervical lesions can contribute to restoration loss.^{16,17} In addition, the surface of NCCLs typically consists of sclerotic dentin, which is resistant to acid etching due to hypermineralized intertubular and peritubular dentin and may prevent maximum adhesion.¹⁸

In the evolution of adhesive technology from one generation to the next, the impetus has been to

improve bond strength while simplifying application procedures. The first clinically successful bonding agents had separate conditioning, priming, and bonding steps. Most modern adhesives combine these functions into one or two bottles. Although many simplified adhesives perform adequately in laboratory studies compared with their traditional multistep counterparts,¹⁹⁻²³ simplified systems generally display poor clinical performances.²⁴ Clinical trials are necessary to verify laboratory results and to evaluate long-term adhesive performance.

The aim of this prospective randomized controlled clinical trial was to evaluate the performance of a one-bottle self-etch adhesive, a two-bottle self-etch adhesive, and a well-established one-bottle total-etch adhesive in Class V resin-based composite restorations on NCCLs over two years. The null hypothesis was that the total-etch adhesive would provide better clinical performance than the self-etch adhesives.

METHODS AND MATERIALS

Fifty-two patients were recruited from subjects attending the BioHorizons Research Clinic at the University of Alabama at Birmingham. The local Institutional Review Board approved the clinical trial protocol, and all subjects gave informed consent by signing a consent form. During the screening examination, inclusion and exclusion criteria were used to evaluate acceptable subjects (Table 1). The procedure was thoroughly explained to each patient and their questions were answered. Each patient had at least three NCCLs with at least a 1.5-mm depth measured by a periodontal probe. Each patient received three Filtek Supreme Plus (3M ESPE, St Paul, MN, USA) restorations bonded with Adper Single Bond Plus, Adper Scotchbond SE, and Adper Easy Bond (3M ESPE). The adhesive materials, compositions, and mode of application are described in Table 2.

Restoration Procedure

All lesions were restored following protocol by two calibrated and experienced investigators. Each patient received three restorations, and each tooth was randomly assigned an adhesive for a total of 156 restorations.

The teeth were cleaned with flour of pumice and a prophylaxis cup (Whip Mix Corporation, Louisville, KY, USA) followed by rinsing and drying. Shade selection was performed using the Vita shade guide to select the appropriate Filtek Supreme Plus resin

Table 1: *Inclusion and Exclusion Criteria*

Inclusion Criteria	Exclusion Criteria
• Is aged 19 years and older	• Is taking part in an evaluation of other restorative materials/systems
• Has a minimum of three noncarious Class V lesions >1.5 mm in depth	• Does not have three noncarious lesions or the lesions are <1.5 mm deep
• Is a regular dental attendee who is able to return for assessments	• Is not able to tolerate the time required to place the restorations
• Is in good medical health and able to tolerate the dental procedure	• Has a history of adverse reaction to any materials used in the study
• Does not have rampant caries	• Is an irregular dental attendee
• Does not have chronic periodontitis or carious lesions	• Maintains an unacceptable standard of oral hygiene
• Is able to tolerate the dental procedure	• Has chronic periodontitis or rampant caries
• Has normal salivary function	• Has severe salivary gland dysfunction
	• Is unable to return for recall appointments

Table 2: *Adhesives and Composite Used in the Study*

Materials	Classification	Composition	Application
Adper Single Bond Plus	Ethanol/water-based, one-bottle, etch-and-rinse adhesive	Scotchbond acid: 37%; Phosphoric acid adhesive: silica nanofiller, Bis-GMA, HEMA, dimethacrylates, ethanol, water, copolymer (polyacrylic-polyitaconic acids), camphorquinone	a) Acid-etch for 15 s; b) Rinse for 15 s; c) Air-dry for 30 s; d) Leave dentin visibly moist; e) Apply two coats of adhesive for 10 s; f) Air-dry for 10 s at 20 cm; g) Light-cure for 10 s
Adper Scotchbond SE	Water-based, two-bottle, self-etch adhesive	Liquid A: water, HEMA, rose bengal dye; Liquid B: UDMA, TEGDMA, TMPTMA, HEMA; phosphate, MHP, zirconia nanofiller, camphorquinone	a) Apply liquid A; b) Apply liquid B on top for 20 s; c) Air-dry 10 s; d) Apply another coat of liquid B; e) Air thin; f) Light-cure for 10 s
Adper Easy Bond	Ethanol/water-based, one-bottle, self-etch adhesive	Silica nanofiller, HEMA, Bis-GMA, methacrylated phosphoric esters, dimethacrylate, polyalkenoic acid, ethanol, water, camphorquinone	a) Apply two coats of adhesive for 20 s; b) Air thin for 5 s; c) Light-cure for 10 s
Filtek Supreme Plus	Nanocomposite	Silica/zirconia filler: non-agglomerated/non-aggregated nanosilica filler and loosely bound agglomerated zirconia/silica nanocluster, consisting of agglomerates of primary zirconia/silica particles; Matrix: Bis-GMA, Bis-EMA, UDMA, TEGDMA	a) Use incremental placement (dentin shade <1.5 mm, others <2 mm each layer); b) Light-cure 40 s for dentin shade and 20 s for others

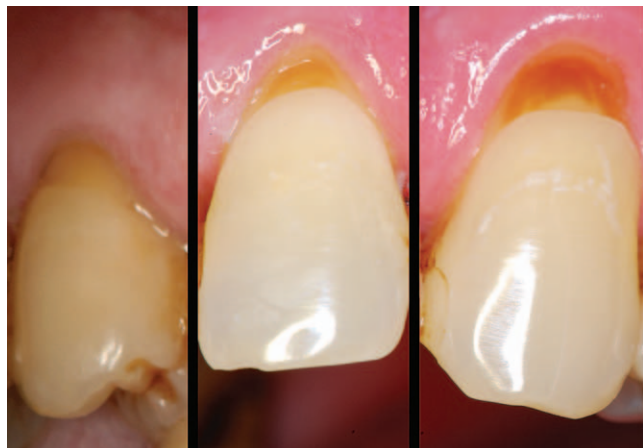


Figure 1. Preoperative NCCLs on teeth #4, #5, and #12 from left to right.

shade. After providing local anesthesia, the teeth were isolated using a rubber dam and appropriate retainers. A 0.5-mm bevel was prepared on the occlusal margin of the lesion on the enamel using an OS 2 bur (Brasseler USA, Savannah, GA, USA). The order of the adhesives was determined by drawing slips from a box containing the names of the three adhesives. Starting with the lowest numbered tooth, the adhesives were applied in the order drawn. The assigned adhesive was applied to the lesion following the manufacturer's instructions (Table 1). Filtek Supreme Plus Restoratives were placed according to manufacturer's instructions and cured using a G Light (GC America, Chicago, IL, USA). The output of the curing light was assessed daily using a LASER power meter (FieldMate, Coherent Inc, Santa Clara, CA, USA) to ensure proper output ($>700 \text{ mW/cm}^2$). The restorations were finished and polished using an

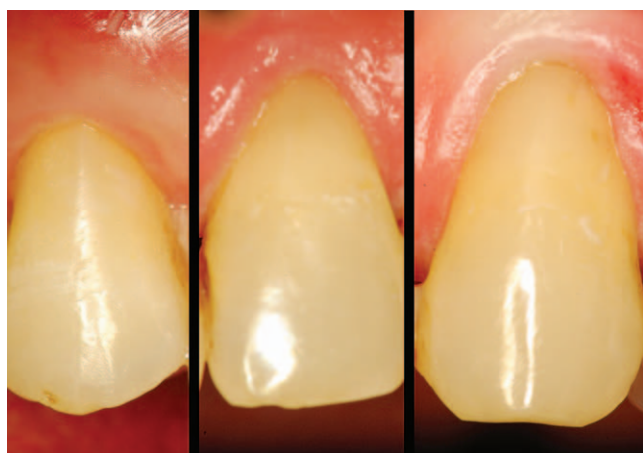


Figure 2. Class V restorations at baseline on teeth #4 (Scotchbond SE), #5 (Easy Bond), and #12 (Single Bond Plus) from left to right.

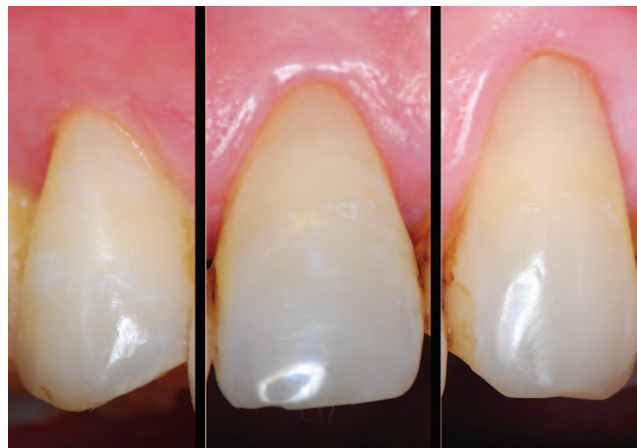


Figure 3. Class V restoration at the six-month follow-up on teeth #4 (Scotchbond SE), #5 (Easy Bond), and #12 (Single Bond Plus) from left to right.

established protocol with 7901 and OS 2 finishing burs (Brasseler USA), Enhance Finishing, and PoGo Polishing Systems (Dentsply/Caulk, Milford, MA, USA). Digital images of the lesions were taken before and after preparation at baseline and at the six-month, one-year, and two-year recall visits. Figures 1 through 5 show NCCLs and the Class V restorations in a subject at before the procedure, at baseline, and at the six-month, one-year, and two-year recall visits.

Clinical Evaluation

Two calibrated examiners evaluated the restorations at one week (baseline), six months, one year, and two years. The examiners and the subjects were blind to which adhesive was used for each of the restorations. The restorations were evaluated using a modified US



Figure 4. Class V restoration at the 12-month follow-up on teeth #4 (Scotchbond SE), #5 (Easy Bond), and #12 (Single Bond Plus) from left to right.

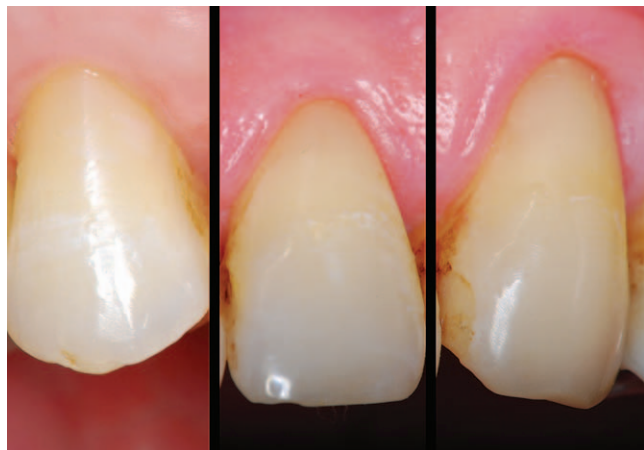


Figure 5. Class V restoration at the 24-month follow-up on teeth #4 (Scotchbond SE), #5 (Easy Bond), and #12 (Single Bond Plus) from left to right.

Public Health Service²⁵ criteria adapted by Loguerio and others²⁶ and Barnes and others.²⁷ In the event that the examiners differed in their evaluation outcome, a consensus was reached before the subject was dismissed.

Clinical evaluation of each restoration was performed with magnification, a mouth mirror, an explorer, and a periodontal probe. Retention, anatomic form, marginal discoloration, marginal integrity, surface roughness, color match, and staining were all measured on a three-tiered scale: alpha, bravo, and charlie. Secondary caries was measured using a two-tiered scale: alpha and charlie. Endo ice (Coltene/Whaledent, Cuyahoga Falls, OH, USA) was used to assess postoperative thermal sensitivity. Endo ice was applied to a cotton pellet that was placed on the restoration for three seconds; the patient was then asked to indicate their pain level from on a scale from 1 to 10, with 1 representing no pain and 10 representing the worst pain they could imagine (eg, childbirth, kidney stones, major surgery). Then the gingival index around the restorations was recorded using the criteria of Loe and Silness and ranked 0-3.²⁸

Statistical Analysis

Descriptive statistics were used to describe the frequency distribution of the evaluated criteria. The difference in performance of the three adhesives was assessed at the baseline and after each recall visit (six months, one year, and two years) by the McNemar's test ($\alpha=0.05$). Postoperative pain level was evaluated by a paired *t*-test ($\alpha=0.05$). The Friedman test was used to compare the gingival

Table 3: Restorations Distribution With Different Adhesives

Materials	Anterior	Premolar	Molar	Total
Adper Single Bond Plus	18	28	7	52
Adper Scotchbond SE	17	29	5	52
Adper Easy Bond	16	30	6	52
Total number of restorations	51	87	18	156

index around each restoration followed by the paired sign post-hoc test ($\alpha=0.05$).

RESULTS

Table 3 shows the distribution of restorations in anterior, premolar, and molar teeth. The table shows that the restorations were placed mostly on premolars and distributed evenly. Of the 156 restorations at baseline, 96%, 83%, and 75% were available for assessment at six months, one year, and two years, respectively. Recall percentage was computed based on the number of observations recorded at each time interval as a percentage of total observations evaluated at baseline. Retention of the restorations was 97%, 90%, and 95% for Single Bond Plus, Scotchbond SE, and Easy Bond, respectively at two years (Table 3).

Nominal variables (retention, anatomic form, marginal discoloration, marginal integrity, surface roughness, color match and staining, secondary caries) were analyzed with McNemar's test for correlated proportions (Table 4). Because of the relatively small numbers of Bravo and Charlie ratings, the scale was modified to "A" and "not A" (NA). Counts of two case/control discordant combinations—A/NA and NA/A—were determined for each nominal variable using the outcome matched by the patient. Three separate analyses were used to compare the outcomes between each material investigated. Because of the small numbers of discordant cells, the normal approximation of the binomial distribution could not be used, and the *p* values were determined using the exact binomial probability. The alpha level was set at a Bonferroni-adjusted level of 0.0166. The null hypothesis for testing these parameters was that the same number of discordant combinations was equally likely ($p=0.5$) for each pair of materials tested. Analysis of each nominal

Table 4: Nominal Variables (% Alpha) for Each Adhesive

	% Alpha			Exact Binomial P-value		
	Easy Bond	Scotchbond SE	Single Bond Plus	Easy Bond vs Scotchbond SE	Easy Bond vs Single Bond SE	Single Bond vs Scotchbond SE
Retention						
Baseline	100.00%	100.00%	100%	NA	NA	NA
6 mo	100.00%	98.08%	98.04%	NA	NA	1.0000
1 y	97.78%	93.33%	86.67%	0.0625	0.5000	0.3281
2 y	95.24%	90.48%	97.30%	NA	0.5000	0.7500
Anatomic form						
Baseline	92.59%	94.23%	94.44%	0.7500	0.7500	1.0000
6 mo	94.23%	96.15%	92.31%	0.6250	0.7500	0.5000
1 y	95.56%	95.45%	84.78%	0.1094	0.7500	0.2188
2 y	90.48%	87.50%	91.89%	0.7500	0.5000	0.5000
Color match						
Baseline	92.59%	94.34%	96.30%	0.5000	0.6250	0.7500
6 mo	94.23%	94.23%	90.38%	0.5000	0.7500	0.5000
1 y	91.30%	88.89%	86.67%	0.3125	0.4688	0.5469
2 y	90.70%	85.37%	92.11%	0.7500	0.1875	0.4375
Marginal integrity						
Baseline	98.15%	98.11%	98.15%	1.0000	1.0000	1.0000
6 mo	100.00%	94.23%	94.23%	0.2500	0.2500	0.7500
1 y	76.09%	68.89%	75.56%	0.3867	0.2417	0.3867
2 y	55.81%	63.41%	73.68%	0.1074	0.4375	0.2344
Marginal discoloration						
Baseline	100.00%	100.00%	100.00%	NA	NA	NA
6 mo	98.08%	96.15%	96.15%	0.7500	NA	0.7500

Table 4: Nominal Variables (% Alpha) for Each Adhesive (cont.)

	% Alpha			Exact Binomial <i>P</i> -value		
	Easy Bond	Scotchbond SE	Single Bond Plus	Easy Bond vs Scotchbond SE	Easy Bond vs Single Bond SE	Single Bond vs Scotchbond SE
1 y	91.11%	84.44%	84.09%	0.2188	0.3281	0.4102
2 y	76.74%	78.05%	78.95%	0.4512	0.5469	0.4922
Surface roughness						
Baseline	98.15%	100.00%	100.00%	NA	NA	NA
6 mo	96.15%	94.23%	98.08%	0.7500	0.7500	0.5000
1 y	82.61%	77.78%	84.44%	0.4922	0.3281	0.4102
2 y	30.23%	35.59%	39.47%	0.2500	0.5000	NA
Secondary caries						
Baseline	100.00%	100.00%	100.00%	NA	NA	NA
6 mo	100.00%	98.08%	98.08%	NA	NA	1.0000
1 y	95.56%	93.33%	93.33%	0.6250	0.5000	0.6250
2 y	95.35%	95.12%	97.37%	NA	0.7500	0.7500
Staining						
Baseline	100.00%	100.00%	98.15%	NA	NA	NA
6 mo	100.00%	98.08%	98.04%	NA	NA	1.0000
1 y	95.65%	93.33%	93.33%	0.6250	0.5000	0.6250
2 y	95.35%	95.12%	97.37%	NA	0.7500	0.7500
Abbreviation: NA, not A.						

variable revealed no statistical difference at any time period between any two material combinations.

Pain in response to thermal stimulation was recorded using a visual analog scale for each tooth at each time interval, with 1 being no pain and 10 being severe pain. The null hypothesis was that there is no difference in pain between the materials tested. These data were analyzed for normality and equality of variance. Logarithmic transformation

$\ln(x + 1)$ was applied to stabilize the variance. A paired *t*-test was used to test each possible pair of mean values. The results are given in Figure 6. Statistically different mean pain values were noted at baseline and at one year between Easy Bond and Single Bond Plus, with Single Bond Plus showing the greater pain level ($p=0.0166$), but no statistical difference was observed at the six-month and two-year recall visits ($p>0.05$).

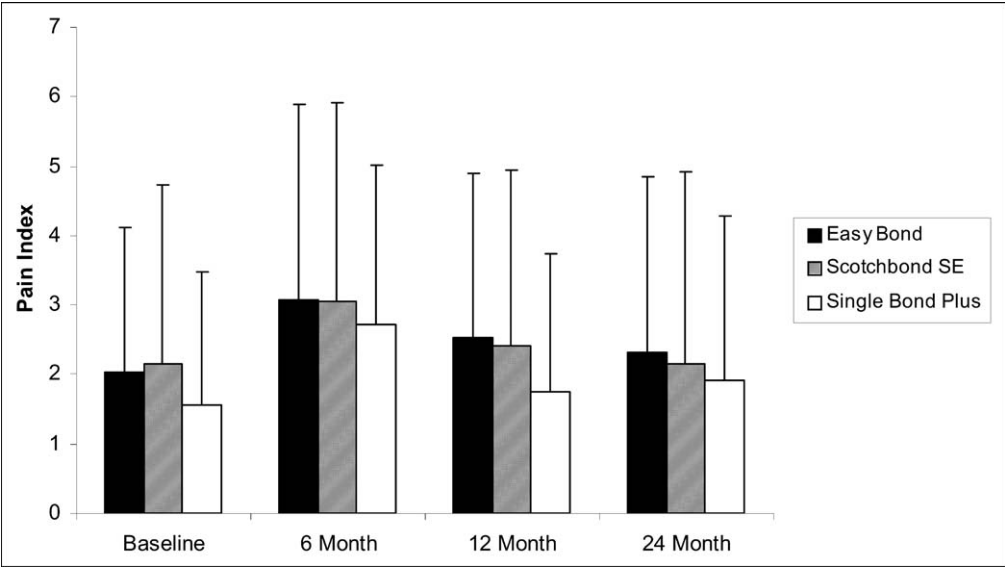


Figure 6. Mean pain index for three adhesives at baseline and recall visits.

Table 5: Gingival Index (Median and Range) for Each Adhesive at Each Recall			
Time	Material	Gingival Index	
		Median	Range
Baseline	Easy Bond	0	0-1
	Scotchbond SE	0	0-1
	Single Bond Plus	0	0-1
6 mo	Easy Bond	0	0-2
	Scotchbond SE	0.5	0-2
	Single Bond Plus	0	0-1
1 y	Easy Bond	0	0-1
	Scotchbond SE	0	0-1
	Single Bond Plus	0	0-1
2 y	Easy Bond	1	0-1
	Scotchbond SE	1	0-2
	Single Bond Plus	1	0-1

The gingival index (Table 5) data were analyzed using Friedman’s analysis of variance (ANOVA) at each time interval. At the two-year time point, Friedman’s ANOVA was <0.05 ; therefore, each material combination was examined with a paired sign post-hoc test. No significant difference in gingival indices for any material combination was noted ($p=0.0166$).

DISCUSSION

This study used three adhesives (Single Bond Plus, Scotchbond SE, and Easy Bond) to bond composite resin (Filtek Supreme Plus) to three NCCLs in each patient. This prospective double-blind, randomized, controlled clinical trial was conducted to measure the clinical effectiveness of adhesive bonding resin on composite restorations in NCCLs. Regarding the clinical effectiveness of the adhesives at two years, no significant difference between the three adhesives was seen. Previous studies have reported, however, that three-step etch-and-rinse adhesives have superior clinical performance compared with simplified adhesives, especially if longer evaluation times are taken into consideration.^{22,29-31}

In the current study, the restoration retention for Single Bond Plus, Scotchbond SE, and Easy Bond adhesives were 97%, 90%, and 95%, respectively, at two years, suggesting long-term durability. The guidelines for dentin and enamel adhesive materials put forth by the American Dental Association (ADA) suggest that the retention rate at six months must

be at least 95% for provisional acceptance, whereas the retention rate at 18 months must be at least 90% for full acceptance.³² Although an 18-month recall was not performed in this study, the two-year data show that each of these adhesives fulfills the permanent adhesive acceptance criterion.

In a systematic review of adhesive clinical trials, Peumans and others²⁴ reported that although 79% of the two-step etch-and-rinse adhesives fulfilled the provisional acceptance of the ADA guidelines (95% retention at six months), only 51% fulfilled the full acceptance criterion (90% retention at 18 months). The suggested reasons for the inconsistent retention rate of two-step etch-and-rinse adhesives are their propensity to form an optimal hybrid layer and their tendency to leave more residual solvent in the adhesive layer, which can result in increased hydrolytic degradation over time.^{33,34} In this study, each of the adhesives fulfilled the ADA guideline with 97% (Single Bond Plus), 90% (Scotchbond SE), and 95% (Easy Bond) retention at two years.

The ADA guideline for adhesives asks for less than 10% charlie for marginal integrity at 18 months.^{35,36} In this study, the two-year data showed 3%, 5%, and 5% charlie scores in Single Bond Plus, Scotchbond SE, and Easy Bond, respectively. The adhesives used in this clinical trial also appear to meet the guidelines for marginal quality of composite resin restorations.

The current study compared three adhesives: a one-bottle self-etch adhesive, a two-bottle self-etch adhesive, and a two-bottle etch-and-rinse adhesive. Similar comparisons have previously been made in the laboratory, with the self-etch adhesives producing significantly lower bond strengths to enamel, but the results for dentin are not consistent.³⁷⁻⁴⁴ In this clinical study the overall clinical performance did not differ between the three adhesives after two years. This suggests that the two-bottle self-etch adhesives used in this study may have potential for decalcifying NCCLs, thereby creating a clinically acceptable bond that withstands occlusal forces for two years as well as the one-bottle total-etch adhesive does, but a longer clinical study is needed to confirm this hypothesis.

In this study, the self-etch adhesives showed clinically acceptable retention rates (90% and 95% for Scotchbond SE and Easy Bond, respectively) at two years. Other studies have reported various retention rates for Class V restorations using self-etch adhesives. Friedl and others⁴⁵ and Van Dijken⁴⁶ reported retention rates of 84% and 79.8% for self-etch adhesives, after two years. On the other hand,

Kim and others⁴⁷ reported a 100% retention rate for self-etch adhesives after 2 years. In a study similar to this clinical trial, Perdigão and others⁴⁸ reported retention rates similar to ours but their last follow-up was 18-months. They reported retention rates of 100%, 90.9% and 92.3% for restored NCCLs using Single Bond Plus, Scotchbond SE, and Easy Bond, respectively. In their clinical trial, the adhesives were applied in two coats and attention was paid to solvent removal before curing. The high retention rates in our study might be related to this careful two-coat application. Such a protocol would prevent the formation of a dry spot, which could produce an area without optimal hybridization and a lack of sufficient resin saturation in the upper hybrid layer.^{31,49,50} Another reason for the high retention rate of self-etch may be attributed to the enamel bevel. The bevel may facilitate the self-etching effect of the adhesive on unground enamel which is somewhat resistant to etching.⁵¹

The retention for Single Bond Plus, Scotchbond SE, and Easy Bond at 24 months was 97%, 90%, and 95%, respectively. The lower retention value for Scotchbond SE might be due to being a water based adhesive, while the other two are ethanol based. This is supported by Carvalho and others who reported that a mixture of 35% 2-hydroxyethyl methacrylate (HEMA) in 65% ethanol produced greater resin infiltration than 35% HEMA in 65% water.⁵² They determined that when the ethanol evaporated, there was less matrix collapse, allowing more HEMA to remain in the matrix, where it protected the collagen fibrils and strengthened the hybrid layer.⁵²

CONCLUSION

Within the limitation of this study, the three adhesives tested presented acceptable clinical performance with no statistical differences between them in a two-year period. The null hypotheses that the total-etch adhesive would have better clinical performance was rejected. This study continues as longer-term evaluations will be performed to compare the long-term performance of these self-etch adhesives.

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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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The Normalized Failure Index: A Method for Summarizing the Results of Studies on Restoration Longevity?

FJT Burke • V Singh • NHF Wilson

Clinical Relevance

A reliable means of combining the results from a number of clinical studies on longevity of restorations could be helpful to clinicians when they are planning treatment.

SUMMARY

Satisfactory restoration longevity is central to operative dentistry and is the subject of a wide variety of publications. However, combining the results of a number of studies to provide an overview, for example, for a meta-analysis may be problematic because of the heterogeneity of the data, and a high proportion of studies may therefore not be included. It is the purpose of

this study to present a means whereby the data from cohort studies may be combined to present a representation of restoration longevity, termed the “Normalized Failure Index.”

INTRODUCTION

Clinicians are beholden to provide safe and effective restorations with optimal longevity, even more today than in the past, given that patients are living longer and retaining more of their natural teeth. Dental restorations, however, have a limited clinical durability,¹ with the replacement of failed restorations accounting for >60% of all operative dental procedures.² When restorations need replacement, tooth structure is lost, with the patient entering into an accelerating repetitive restorative cycle involving larger restorations, weakening of remaining tooth tissues and structures, and more complex treatments. The ability to predict longevity of restorations of different materials and types is therefore central to longitudinal patient care, let alone patient understanding of treatment provision. To date, however, there is no generally accepted simple but meaningful means of aggregating data on restora-

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tion longevity. It is the aim of this paper to propose a means whereby this goal may be achieved.

Materials for Direct Load-Bearing Restorations

The clinical decision as to which restorative material to select for specific applications is complex, involving many factors, including the type and status of the tooth, the patient, the clinician, and the properties of the materials. Different restorative materials perform best in different clinical circumstances, and it is not generally possible to simply substitute one material for another and expect optimum long-term success.

Materials available for use in the provision of direct restorations include dental amalgam, resin composites, compomers, and glass-ionomers. Of these, amalgam and resin composites are most commonly selected for restorations in load-bearing situations in posterior teeth in the UK³ and elsewhere in the world, but the use of amalgam is diminishing internationally.⁴ Nevertheless, amalgam continues to be considered by some to offer a number of advantages over other restorative materials in the restoration of posterior teeth. These advantages are considered to include low cost (albeit that the cost of restorative material is a very small proportion of the cost of the provision of a restoration), ease of use for those familiar with handling dental amalgam, apparent success when used in less-than-ideal circumstances (eg, in the presence of poor moisture control), and its apparent relative insensitivity to the consequences of variation in operative technique. The disadvantages of using amalgam as a restorative material include the requirement for preparation of the tooth being restored, including the sacrifice of sound tooth tissue, in order to create a retentive cavity form unless an amalgam bonding technique is utilized; its poor esthetics (this being of relevance in the current climate of increasing patient demand for good esthetics of both posterior and anterior teeth); and concerns of some patients, let alone environmental issues, regarding the use of a mercury-containing material.

In contrast, the use of resin composites in the restoration of posterior teeth facilitates the application of minimally invasive techniques, provides the opportunity to use adhesive technologies to protect and preserve remaining tooth tissues, and results in tooth-colored restorations, with the capacity to meet the ever-increasing esthetic expectations of patients. However, for those who tend to achieve less-than-

satisfactory outcomes in the application of resin composites or who work under circumstances that encourage the placement of low-budget invasive restorations (eg, some third-party fee-per-item remuneration arrangements), the use of composite resins can be considered to be technique sensitive and thereby challenging, especially given that satisfactory clinical outcomes take longer to achieve with esthetically pleasing composite resins.⁵

Methods of Clinical Evaluation

Studies on restoration longevity may be prospective or retrospective. Regarding prospective studies, randomized controlled trials (RCTs) are considered to be the gold standard but tend to investigate the potential and patterns of deterioration of restorative materials in clinical service in selected patients rather than efficacy. Meta-analysis is a statistical technique whereby the data from two or more RCTs are combined, most frequently to provide an overview of clinical attributes of specific interventions. Systematic review methodology is central to meta-analyses so that all relevant studies are included. Meta-analysis has been defined as a technique that combines results from several independent clinical trials that are considered by the analyst to be "combinable."⁶ It has been considered, however, that pitfalls abound in the execution of meta-analyses, the value of which are determined by the number and quality of the underlying studies.⁷ Notwithstanding the variability of RCT methodologies in assessments of restorative materials, the results of such studies tend to be at variance with the findings of restoration outcomes studies in primary care settings, notably in respect of failure rates⁸—the highly controlled arrangements necessary for a robust RCT being different to the more pragmatic arrangements necessary to successfully complete studies in the demanding primary care setting. As a result, very few clinically relevant RCTs are reported on the longevity of restorations in clinical practice, and, as a result, meta-analyses on the clinical longevity of restorative materials are sparse and of dubious relevance to the general provision of care by practitioners.

An alternative means of investigating the performance of restorative materials in clinical service is the longitudinal cohort study. Such studies investigate the performance of dental restorations in a cohort of patients over a period of time. These studies lack the randomization and, more often than not, the restrictive control element of RCTs. These studies, however, provide useful data, but, as with

RCTs, there tends to be lack of standardization of investigative methodology between studies, resulting in lack of direct comparability. In contrast to RCTs of restorative materials, longitudinal cohort studies in operative dentistry, which tend to have greater clinical relevance, let alone being less costly to run than RCTs, offer the means to develop a much-needed evidence-based approach to the restoration of teeth using, in particular, novel restorative materials that tend to have a commercial life expectancy of three to five years.

Retrospective cross-sectional studies are also carried out in restorative dentistry.⁹ Such studies are much simpler to perform than RCTs and longitudinal cohort studies, examining the performance of restorations that are failing or failed and the reasons for failure. These studies, however, have been considered to suffer important weaknesses,¹⁰ in particular, if the results are expressed in terms of mean age of failed restorations rather than Kaplan-Meier statistics, the later being a method for analyzing incomplete survival data with individual dates of “life” and “death,” developed by Kaplan and Meier in 1958 (described in Collett¹¹ and also in Opdam and others¹⁰). In this method, the lifetime of restorations that have failed, as well as those that remain in service, is taken into account. Furthermore, defining what constitutes restoration failure is a critical issue in studies of restoration longevity, in particular, when possible interventions include repair or replacement.

It is considered that reliance on data from any one type of study is incapable of giving an overall picture of the performance of a restorative material in clinical service; however, data and findings from different types of study are difficult to compare and contrast. Those looking for an overall picture of the performance of different restorative materials in clinical service are therefore left with a dilemma. Setting aside considerations of the nature of the deterioration of restorations in clinical service, it is suggested that the critical parameters are the rate and nature of failure. Regarding rate of failure, relevant data may be derived from RCTs and longitudinal cohort studies. To bring such data together to give a measure of the success of restorations of different types and materials, a novel index is proposed: the Normalized Failure Index.

The aims of the project were the following:

- To review all prospective clinical trials over the last 30 years to obtain data on the failure rate of

amalgam and composite restorations in posterior teeth

- To calculate the value of the proposed Normalized Failure Index as a measure of the performance of restorations of different materials in clinical service

MATERIALS AND METHODS

Data Collection

Using Medline and Embase, a literature search was conducted to identify publications reporting controlled clinical trials of amalgam and resin composite restorations in posterior teeth. The reference lists of the retrieved publications were also searched for studies not included in the databases. Where a study was reported in a series of papers, data were taken from the paper reporting the longest-term data available only, thereby including data for all studies identified on no more than one occasion.

Inclusion Criteria

To determine which papers should be included in the review, the following criteria were used:

- Studies of at least three years duration.
- Studies containing >30 restorations at baseline.
- Studies published in English or with an English translation.
- Studies from the past 30 years.
- Studies reporting on occlusal and occlusoproximal restorations in adult (>18 years of age) patients.
- Studies including “open sandwich” technique restorations, preventive resin (sealant) restorations, and tunnel restorations were excluded.

From the selected studies, the following information was extracted: name of the first author and the year of publication of the study, the length of the study in years, the number of restorations examined at the end of the study, the number of failed restorations, and the mean annual failure rate, determined by dividing the number of failures at the end of the study by the number of restorations remaining in the study divided by the number of years of observation and expressing as a percentage.

To calculate the Normalized Failure Index, the number of restorations examined in each study was multiplied by the annual failure rate to give the failure index (Figure 1). The failure indices from all the included studies were then added together, and this figure was divided by the total number of failed restorations to give the Normalized Failure Index (Figure 2). To demonstrate the use of the Normalized

$$\frac{\text{Restorations failed}}{\text{Restorations evaluated} \times \text{No of years' duration}}$$

Figure 1. Calculation of the failure index

Failure Index, publications for composite and amalgam restorations that fulfilled the inclusion criteria were used.

RESULTS

The data collected in respect of amalgam and composite restorations are presented in Tables 1¹²⁻²² and 2^{12,17,18,20,23-42}, respectively, together with the values obtained for the failure index. When the data for all the included studies were combined (indicated by the figures in the bottom line of Tables 1 and 2), the Normalized Failure Index for amalgam was calculated ($2616 \div 2542$) to be 1.0, with the corresponding value for composite ($5988 \div 1979$) being 3.0.

DISCUSSION

This study introduced the concept of the Normalized Failure Index and used it to examine the survival rates of amalgam and resin composite restorations placed in load-bearing situations in posterior teeth—with the data having been obtained from a review of controlled clinical studies dating back 30 years to the time that composites began to be used in load-bearing situations in posterior teeth. The papers included in the investigation were those that a group of dentists deemed “best available” studies, namely, studies of at least three years’ duration and involving >30 restorations placed at the commencement of the study. Of the studies available, there were more addressing resin composites than amalgam. The composite studies, however, tended to include smaller numbers of restorations, and, overall, fewer composite restorations were included, although this was still substantial ($n=1979$). The reason for this difference may be considered to be multifactorial, ranging from arrangements to undertake clinical assessments of the many composite restorative systems introduced in the last 30 years to the cost differential between clinical studies of amalgams and composite systems. Furthermore, the amalgam studies tended to be older and longer given that amalgams, unlike composite systems, were not subject to such change and, as a consequence, the subject of extended investigations.

The large numbers of restorations included in the present investigation, together with the calculation

of the Normalized Failure Index, may be considered to provide an overview of the performance of amalgams and composite systems in controlled clinical studies. In considering the overall Normalized Failure Index values, these indicated that composite systems, when assessed by this approach, performed less well than amalgams when used in similar, controlled situations. The results, however, do not concur with those published in 2004 in a review of the literature by Manhart and others⁴³ in which the mean values for failure of restorations of differing types were calculated, with the mean annual failure rate for amalgam restorations being 3.0% and 2.2% for direct composite restorations, both placed in stress-bearing situations. Such calculations, which did not take into account the numbers of restorations in each study (as the Normalized Failure Index does), indicated that resin composite restorations in posterior teeth performed better than amalgam restorations, contrary to the findings of the present work. In this respect, it is to be remembered that failure rates for occlusal and occlusoproximal restorations in controlled clinical studies tend to be much lower than in practice-based studies in which materials are applied under circumstances that prevail in the general practice setting.⁸

The results of the study by Manhart and others⁴³ indicated that composite systems had a higher mean annual failure rate than amalgams when overall mean values were calculated. It could be argued, however, that this simple calculation does not provide a valid perspective, as the different size of the studies (ie, the number of restorations included in each evaluation) is not taken into account. A novel approach was therefore adopted. The product of multiplying the annual failure rate by the number of restorations included for examination at the end of the study was termed the failure index. The failure index for all the papers was totaled and divided by the total number of restorations, to provide an index: the Normalized Failure Index. In this way, studies including larger numbers of restorations have a greater impact on the proposed comparative measure of success in clinical service. This approach of applying the Normalized Failure Index may be considered also to produce a more valid measure of performance than a simple mean age of failure, as used in many

$$\frac{\text{Failure Index total}}{\text{Number of failed restorations}}$$

Figure 2. Calculation of the Normalized Failure Index

Table 1: *Amalgam Studies*

Study: First Author's Name	Study Duration (y)	Number of Restorations Evaluated in the Study	Number of Restorations Reported as Having Failed	Mean Annual % Failure Rate	Failure Index (B) (No. of Restorations × Mean Annual Failure Rate)
Collins (1998) ¹²	8	52	3	0.7	36
Doglia (1986) ¹³	5	96	7	1.5	144
Johnson (1992) ¹⁴	5	175	0	0	0
Kreulen (1998) ¹⁵	15	1171	199	1.1	1288
Osborne (1991) ¹⁶	14	367	47	0.9	330
Mair (1998) ¹⁷	10	35	2	0.6	21
Mjör (1993) ¹⁸	5	88	4	1	88
Plasmans (1998) ¹⁹	8	291	23	1	291
Roberts (1992) ²⁰	3	55	2	1.2	66
Summit (2001) ²¹	5	40	9	4.5	180
Wilson (1996) ²²	5	172	9	1	172
Total		2542			2616

studies, given that the impact of different sizes of clinical investigations may be minimized through the normalization process. It could be argued that Kaplan-Meier statistics offer similar advantages. It

is, however, suggested that the findings of such statistics and the Normalized Failure Index, may be viewed as complementary to give an informed overview of performance.

Table 2: *Composite Studies*

Study: First Author's Name	Study Duration (y)	Number of Restorations Evaluated in the Study	Number of Restorations Reported as Having Failed	Mean Annual % Failure Rate	Number of Restorations × Mean Annual Failure Rate (B)
Busato (2001) ²³	6	90	13	2.4	216
Collins (1998) ¹²	8	161	22	1.7	274
de Rosa Rodolpho (2006) ²⁴	17	282	98	2	564
Ernst (2001) ²⁵	3	165	35	7.1	1164
Freilich (1992) ²⁶	3	105	1	0.3	315
Gaengler (2001) ²⁷	10	62	16	2.5	161
Gordan (2005) ²⁸	4	39	1	0.6	23
Kohler (2000) ²⁹	5	51	16	6.3	321
Lundin (1999) ³⁰	10	117	25	2.1	246
Mair (1998) ¹⁷	10	56	4	0.7	39
Mjör (1993) ¹⁸	5	91	9	3.3	300
Nordbo (1998) ³¹	7	51	16	4.5	230
Raskin (1998) ³²	10	37	32	8.6	318
Roberts (1992) ²⁰	3	53	5	3.1	164
Sturdevant (1998) ³³	5	97	14	2.9	281
Turkun (2003) ³⁴	7	70	4	0.8	56
Turkun (2005) ³⁵	3	47	3	2.1	99
van Dijken (2000) ³⁶	11	33	9	2.5	83
van Dijken (2002) ³⁷	3	65	17	8.7	566
van Dijken (2003) ³⁸	6	82	3	0.6	49
Wassell (2000) ³⁹	5	65	5	1.5	98
Wendt (1994) ⁴⁰	3	35	3	29.	102
Wilder (1999) ⁴¹	17	85	20	1.4	119
Wucher (2002) ⁴²	3	40	6	5	200
Total		1979			5988

In the present work, if the average of the data presented as the failure index is calculated, the result is 1.22% for amalgam, while the Normalized Failure Index is 1.03. For composite, the average of the calculated failure index is 3.07%, while the Normalized Failure Index is 3.03. There are therefore marked similarities in the outcome of the two approaches. In this respect, it is important to recognize that normalizing data is a form of averaging, but with a provision to limit the effect of "outlying" data. In the absence of outlying data in a data set, normalized values will inevitably be very similar to average values. When outlying data are present, the average value will be somewhat misleading relative to typical values, while normalized values should be more representative. This is what we are attempting to achieve with the Normalized Failure Index: an approach that may often give values very similar to average values but a more representative value than the average when there may be outlying data in the data set or the data set is heterogeneous.

One difficulty in the calculation of the Normalized Failure Index arises if one paper is included that has a much greater number of restorations than other studies. In the first draft of the present work, the paper by Martin and Bader⁴⁴ was included, as it presented the results of 3764 large amalgam restorations. These restorations were placed by a large number of dentists (n=74) who were operating under routine clinical conditions as part of an insurance scheme (Kaiser Permanente, Portland, OR), so it may be considered to represent a wealth of data from a large database with a broad spectrum of patients, and this should not be ignored. However, it differs from the other papers insofar that it used Kaplan-Meier statistical methodology, with success of the individual restorations included being defined as an absence of replacement of the restoration, whereas in the majority of the other studies included in the present work, US Public Health Service (USPHS)-type criteria were utilized. It may therefore be considered that the Normalized Failure Index should be applied only to studies in which the understanding of failure is the same. In this regard, the Normalized Failure Index brings together data from studies that are of similar type/methodology but that may incorporate internal heterogeneity (ie, heterogeneity within the specific designs of the included papers). In the Martin and Bader paper, criteria for success are fundamentally different from USPHS criteria. In this respect, an interesting development from the present study

would be to carry a calculation of the Normalised Failure Index on studies using data from large third-party databases, such as the work by Martin and Bader⁴⁴ and Lucarotti et al.¹

The authors of the present work acknowledge that long-term randomized clinical trials (RCTs) and subsequent meta-analyses are required to fully assess the value of restorative materials for posterior teeth. Such studies are, however, very resource intensive and often begin to yield meaningful results only when test materials, such as resin composite and adhesive systems, have been superseded by new generations of materials. As a consequence, there is an increasing tendency to view such studies as having limited value as an assessment of efficacy, in particular, when conducted in environments other than general practice. Furthermore, it is the opinion of the authors that it is unlikely that there will be RCTs in sufficient numbers to appropriately investigate the many varied new materials and restorative systems anticipated in future years, in particular, RCTs in the real-world setting of general dental practice, the environment in which materials find their principal application. As a consequence, the Normalized Failure Index may be considered to be a useful means to bring together data on restoration longevity from cohort studies, which are more common and in many ways more realistic and manageable in the settings in which the test materials will eventually be used. As with any index, let alone the normalizing of data, it is accepted that there are certain limitations and loss of detailed data, as included in reports of individual studies. In this regard, the Normalized Failure Index is proposed as a readily calculable new tool for summarizing the results of a number of studies that use similar methodologies. A limitation may be that values for mean failure rates, as used in the calculation of the Normalized Failure Index, do not reveal different patterns of failure, such as a number of early failures followed by a limited tendency to failure, as compared to good early performance with subsequent increasing tendency to fail (N. Opdam, personal communication). In addition, potentially substantial studies should now be commissioned to investigate its statistical validity since there is no precedent for its calculation.

An alternative method of assimilating data from a number of studies is the meta-analysis. It would be helpful to be able to compare the Normalized Failure Index with a meta-analysis for purposes of validation. The authors are not, however, aware of

such an analysis having been carried out on the longevity of amalgam compared to composite systems. In addition, meta-analyses can suffer from a shortage of homogeneous comparable data from a variety of studies, with many candidate studies having to be excluded through the application of various inclusion and exclusion criteria. As such, meta-analyses are therefore generally restricted, by the nature of the analysis and the need for homogeneity of the data, to only a small number of studies. This approach has the benefit of strict criteria but invariably leads to the exclusion of large amounts of valuable data of clinical relevance. The concept of the Normalized Failure Index is to allow inclusion of a much larger number of studies that may be more heterogeneous.

Finally, the finding, according to the Normalized Failure Index, that composite resins performed less well than dental amalgam in occlusal and occluso-proximal preparations is considered to be of particular note. With the increasing application of resin composites in minimally invasive preparations, it will be of considerable interest and importance to monitor the ways in which resin composite materials may begin to be found to realize their potential in the restoration of posterior teeth and to further modify the teaching and practice of operative dentistry accordingly.

CONCLUSION

A novel method of assimilating results from a number of studies on restoration longevity, the Normalized Failure Index, has been described. According to the Normalized Failure Index, when applied to a selection of studies conducted over the last 30 years, resin composites were found to perform less well than dental amalgam in the restoration of posterior teeth.

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.

Addendum

Subsequent to this paper having been accepted for publication, new evidence has emerged on the clinical performance of posterior composites. Amongst the new information now available in the literature, the data presented in papers by Opdam et al.⁴⁵ and Pallesen et al.⁴⁶ are considered to be of particular importance, with both papers reporting favourable durability of large numbers of posterior composites over extended periods -twelve and eight years respectively, with the restorations. These studies provide new evidence from

the "real world" of primary dental care of the ways in which resin composite materials are being found to realise their potential in the restoration of posterior teeth. The Normalized Failure Index, if adopted, will require frequent updating to provide a contemporaneous measure of the performance of materials such as resin composites in clinical service.

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The Management of Defective Resin Composite Restorations: Current Trends in Dental School Teaching in Japan

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Clinical Relevance

Repair rather than replacement of defective restorations increases the longevity of existing restorations while avoiding the needless removal of the restoration in total.

SUMMARY

Aim: The aim of this article is to investigate the contemporary teaching of the management of defective direct resin composite restorations in dental schools in Japan.

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Methods: A questionnaire relating to the teaching of the management of defective resin composite restorations was developed and e-mailed to 29 dental schools in Japan in 2010.

Results: Completed responses were received from 19 of the 29 invited schools (response rate = 66%). Eighteen schools (95%) report that they included the teaching of repair of direct defective resin composite restorations in their dental school programs. Thirteen schools reported that they included both clinical and didactic instruction on the repair of direct resin composite restorations. Fourteen schools did not teach any mechanical roughening of the exposed resin composite restoration surface before undertaking a repair. The most commonly reported treatment was acid etching with phosphoric acid (12 schools). The most commonly taught material for completing repairs was a flowable resin composite (16 schools).

Conclusion: The teaching of repair of defective resin composite restorations is well established within many Japanese dental schools, to a greater extent than in some other regions of the world. The impact of this teaching on subsequent clinical practices in Japan should

be investigated. Furthermore, it is concluded that there is a need for much stronger leadership in operative and conservative dentistry, ideally at the global level, to resolve differences in key aspects of operative procedures such as repairs.

INTRODUCTION

Notwithstanding developments in dental materials, one of the most significant advances in dental practice in recent times has been the shift from a “mechanically focused” to a more “biologically focused” approach across the spectrum of dentistry, with an emphasis on minimally invasive treatments.¹ In the fields of prosthodontics and operative dentistry, such developments are evident in, for example, the development of predictable adhesive resin retained bridges in preference to conventional bridges and the increasing use of resin composite for the management of lesions of caries in posterior teeth rather than the “traditional” use of amalgam.¹⁻⁴

The main advantages of such techniques include the avoidance of excessive loss of healthy tooth tissue to create mechanical retention and the facilitation of the placement of certain restorations as well as reduction in the need for subsequent advanced restorative maintenance, often involving restoration replacement and financial outlay for the patient and third-party providers of oral health care.

In many countries, there has been a significant increase in the placement of resin composite restorations in posterior teeth in dental schools in recent years. In the late 1990s, dental students in Western Europe and North America graduated with limited, mainly didactic instruction in the placement of resin composites in posterior teeth.^{5,6} A similar pattern was noted at that time in dental schools in Japan.⁷ However, 10 years later, dental students in the United Kingdom and Ireland gained more experience in the placement of posterior resin composites than amalgam (55%: 45% composite: amalgam), while those in North American schools gained similar amounts of experience at posterior resin composite placement (49%: 51% composite: amalgam).^{8,9} This development will drive many changes in the clinical practice of dentistry over the coming years, as a new generation of dentists, skilled in the placement of posterior resin composite restorations, will drive the delivery of more minimally invasive forms of dentistry, let alone pressures from patients and third-party funders to minimize iatrogenic

damage and the resultant costs incurred in lifelong oral health maintenance programs.

In Japan, the treatment of lesions of caries in posterior teeth has taken a different direction, effectively following a reduction in the use of amalgam since the 1970s. Treatment choices include the placement of resin composite or indirect metal restorations in the restoration of posterior teeth.¹⁰ A recent survey of Japanese dental school teaching has indicated that resin composite accounts for 45% of posterior restorations placed by Japanese dental schools.¹⁰ This finding, while lower than initially anticipated, was much greater than the proportions (ca. 30%) within UK/Irish, US, Canadian, and Iranian dental schools at this time.¹¹⁻¹⁶

Placement of resin composites in posterior teeth, using modern approaches and techniques, offers many advantages, such as the implementation of the principles of minimally invasive dentistry, reinforcement of weakened tooth structure, marginal seal created by adhesion and bonding, and improved esthetics.¹⁷⁻²¹ Practice-based research has indicated that resin composite restorations placed in posterior teeth may be found to exhibit greater longevity than less conservative amalgam restorations when well placed in appropriate situations.²² However, all restorations will, over time, feature signs of degradation. The challenge for clinicians becomes that of deciding when intervention is required and what form this intervention should take.²³

The traditional approach to the management of restorations exhibiting signs of marginal deterioration (defective margins) or secondary caries as diagnosed clinically has been total restoration removal and replacement. This approach is based on the long-held premise that restorations with defective margins suffer damaging leakage and that lesions of caries formed at the margins of restorations adversely affect the tooth restoration interface down to and including the base of the cavity. This premise is increasingly viewed as false and, if accepted as false, leads to the regrettable conclusion that countless patients have been exposed to overtreatment.²⁴ It has been estimated that as many as 56% of restorations placed by dental practitioners are replacement restorations rather than restorations placed in the management of new lesions of caries.²⁵ Apart from the needless use of manpower, consumables, and financial resources, procedures cause iatrogenic damage, increasing the risk of the need for endodontic therapy and, in turn, crown work. The realization that caries occurring at the

margins of a restoration are in reality “new” lesions of caries rather than “recurrent” caries means that localized repair of defective restorations rather than total restoration replacement is possible.²⁴ Such an approach prolongs the longevity of a restoration while avoiding the damaging effects of excessive cavity preparation, leading to avoidable weakening of the remaining tooth tissue and pulpal complications.

Some areas of the world have witnessed advances in the teaching of resin composite restoration repairs,²⁶⁻²⁹ particularly in countries where the teaching of posterior resin composites has seen similar advancement in recent years. The aim of this article is to investigate the contemporary teaching of repairs in the management of defective resin composite restorations in dental schools in Japan, where teaching of posterior resin composites is already well advanced in comparison to many other regions of the world.

MATERIALS AND METHODS

A questionnaire based on previous investigations²⁶⁻²⁹ regarding the teaching of the management of defective composite restorations was prepared (in English). This questionnaire was e-mailed to the person identified as being responsible for the delivery of operative dentistry teaching programs within the 29 dental schools with undergraduate programs in Japan.

Information sought included the following:

- The teaching of resin composite repair techniques in their dental school program
- The nature of this teaching
- The reasons for including this teaching
- Clinical indications for repair
- Views on the longevity of resin composite repairs
- Techniques taught for resin composite restoration repair

Both “open” (free-text) and “closed” (tick box) styles of questions were included. Nonrespondents were followed up by e-mail on two occasions. Information collected was entered onto an electronic database. Descriptive results are reported.

RESULTS

Completed responses were received from 19 of the 29 invited schools (response rate = 66%). Responses were collected over a nine-month period. No incomplete responses were received.

Extent and Nature of Teaching

Eighteen schools (95%) report that they included the teaching of repair of direct resin composite restorations in their dental school programs. The one respondent school that reported not presently teaching repair of direct resin composite restorations did not indicate its reasons for not doing so. Neither did it indicate if it intended including this teaching in coming years.

When asked, those schools that indicated that they were presently teaching repair of direct resin composite restorations gave the following reasons:

- Clinical experience: 13 schools
- Existing evidence: six schools
- Information from case reports: six schools

Thirteen schools reported that they included both clinical and didactic instruction on repair of direct resin composite restorations. Four schools reported that they provided “ad hoc” clinical experience to their students. Four schools reported that they provided “didactic-only” teaching with no clinical experience.

Indications for Repair

General Indications—A summary of the general indications taught for the repair rather than replacement of direct resin composite restorations is reported in Table 1. The most common indication was “tooth substance preservation” (18 schools).

Restoration-Related Defects—When asked to consider which restoration defects of direct resin composite restorations were appropriate for repair rather than replacement, the most common reasons were marginal defects (18 schools), marginal dis-

Table 1: *Summary of the General Indications Taught for Repair Rather Than Replacement of Direct Resin Composite Restorations (Maximum Possible Number of Responses = 18)*

Indication	Number of Schools
Tooth substance preservation	18
Reduced risk of harmful effects on the pulp	12
Reduction in treatment time	8
Reduced costs to the patient	4

Table 2: *Teaching of Restoration-Related Failures Considered Appropriate for Repair Rather Than Replacement of Direct Resin Composite Restorations (Maximum Possible Number of Responses = 18)*

Restoration Related Failure	Number of Schools
Secondary caries	14
Marginal defects	18
Marginal discoloration	16
Superficial/surface color correction	12
Restoration discoloration labial/ buccal	13
Restoration discoloration occlusal	11
Restoration discoloration cervical	11
Restoration discoloration proximal	8
Discoloration involving more than one surface	8
Partial loss of restoration	15
Abrasion/attrition/erosion	12
Bulk fracture of an anterior restoration (incisal)	11
Bulk fracture of an anterior restoration (proximal)	8
Bulk fracture of an anterior restoration (proximal-incisal)	6
Bulk fracture of a posterior restoration (occlusal)	6
Bulk fracture of a posterior restoration (isthmus fracture)	3
Bulk fracture of a posterior restoration (box fracture)	4
Bulk fracture of a posterior restoration (marginal ridge fracture)	10

Table 3: *Clinical Situations Involving Tooth Fracture Adjacent to Existing Direct Resin Composite Restorations Considered Appropriate for Teaching Repair Rather Than Replacement of Direct Resin Composite Restorations (Maximum Possible Number of Responses = 18)*

Restoration Related Failure	Number of Schools
Anterior tooth (tooth fracture from incisal region)	11
Anterior tooth (tooth fracture from proximal region)	8
Posterior tooth (cusp fracture)	7
Posterior tooth (cracked tooth)	7
Anterior tooth (tooth fracture from proximal-incisal region)	6

colouration (16 schools), and partial loss of a restoration (15 schools). The other responses are summarized in Table 2. Defects of posterior direct resin composites considered least appropriate for repair included an isthmus fracture (three schools) and proximal box fracture (four schools).

Fracture of Adjacent Tooth Tissue—Fracture of tooth tissue adjacent to a restoration can be considered appropriate for restoration repair. When asked which situations they felt were appropriate for this, most respondents reported anterior tooth fracture in the incisal region (11 schools; Table 3).

Clinical Techniques for Performing a Repair

Techniques taught for surface treatments of existing resin composite restorations and the materials selected for use in repair and finishing techniques are summarized in Table 4. Fourteen schools did not teach any mechanical roughening of the exposed resin composite restoration before undertaking the repair. The most commonly agreed treatment was acid etching with phosphoric acid (12 schools). Seventeen schools taught the application of a dentine/enamel bonding agent to the prepared surface. The most commonly taught material for completing repairs was a flowable resin composite (16 schools). Popular finishing devices included diamond finishing instruments (16 schools) and finishing points (12 schools).

Table 4: *Techniques Taught for the Repair of Direct Resin Composite Restorations (Maximum Possible Number of Responses = 18)*

Surface Treatments of Existing Composite Restoration	Number of Schools
Acid etching with phosphoric acid	12
Cleaning with slurry of pumice	4
Aluminum oxide air abrasion	4
Acid etching with hydrofluoric acid	2
No mechanical surface treatment	14
Materials Utilized in the Repair Technique	
Dentine/enamel bonding agent	17
Flowable resin composite	16
Silane coupling agent	15
Hybrid resin composite	13
Nanohybrid resin composite	11
Glazing resin	1
Finishing Techniques for the Placed Repair	
Diamond finishing instruments	16
Polishing points	12
Finishing discs	9
Tungsten carbide finishing instruments	7
Polishing paste	4

Patient Acceptance and Treatment Outcome

All 18 schools teaching repair of direct resin composite restorations reported that they found their patients willing to accept a repair as an alternative to restoration replacement. Respondents were asked to indicate what they considered to be the acceptable longevity of a repair to an existing resin composite restoration. Responses were received from all 18 schools. Their responses were as follows:

- Less than three years: two schools
- Three to five years: 13 schools
- More than five years: three schools

Sixteen schools monitored repaired resin composite restorations as part of a recall system. Of these, three schools estimated that repairs increased the longevity of the direct resin composite restoration by the following:

- 10%: one school
- 30%: three schools
- 50%: eight schools
- 100%: four schools

DISCUSSION

At the time of this survey, there were 29 dental schools with undergraduate teaching programs in Japan. Dental school programs generally last for six years in Japan. While the basic curriculum is prescribed by the government, the content and delivery of programs are the responsibility of individual schools. Graduating students are required to complete the national final qualifying examination before receiving their licences (akin to the US state board examinations).¹⁰

As with all questionnaire-based surveys, risks exist in relation to the reliability of responses and the potential of nonresponse bias. Within this survey, a 66% response rate was achieved. This would be regarded as an “above-average” response rate for questionnaire-based surveys: previous work by Tan and Burke has reported an average response rate of 62% for questionnaire-based surveys in the dental literature.³⁰ Notwithstanding this, caution must be exercised in interpreting these results: the potential exists for those who do not practice repair to have not responded (nonresponder bias). However, two follow-up reminders were sent (in keeping with “Dillman’s method”),³¹ and there were no other possibilities of encouraging nonresponders to complete the survey.

Within the responses received, it is seen that 95% of respondent schools teach their students to repair rather than replace defective resin composite restorations. This is in keeping with (if not exceeding) the proportions seen in other regions surveyed around the world, such as Scandinavia (92%), the United Kingdom and Ireland (88%), The United States and Canada (88%), and Germany (88%).²⁶⁻²⁹ However, despite this, the distribution of teaching within Japanese schools was quite close to that of those in the United States and Canada, with “organized”

didactic and clinical teaching occurring in 68% of Japanese respondents and 69% of US and Canadian schools.²⁶ This indicates that the teaching of minimally invasive management of defective restorations is well advanced in Japanese dental schools and bodes well for the future use of minimally invasive dental techniques by graduating Japanese dental students.

With little evidence in the form of appropriately controlled randomized clinical trials to demonstrate the effectiveness of repair when compared to replacement techniques,^{32,33} most of the evidence for repair of defective restorations comes from a small number of clinical trials³⁴⁻³⁷ as well as some laboratory-based research.³⁸⁻⁴⁵ Such studies indicate that some form of mechanical roughening of the exposed restoration surface should be undertaken prior to completing the repair.³⁸⁻⁴⁰ Surprisingly, 78% of Japanese schools (n=14) reported not teaching mechanical surface roughening, with schools, in the main, relying on chemical treatment of the exposed restoration surface with phosphoric acid (12 schools), pumice (four schools), or hydrofluoric acid (two schools). In contrast, 100% of US/Canadian, German, and Scandinavian schools, as well as 93% of UK and Irish schools, reported teaching some form of mechanical roughening of the available restoration surface before completing the repair.²⁶⁻²⁹ In the absence of suitable clinical trials, it is unclear if the inclusion of mechanical roughening of the restoration surface affects the clinical performance of the repair. However, based on the available evidence (albeit laboratory based), Japanese dental schools may wish to consider including this technique within their teaching program.

Based on the available clinical studies as well as laboratory-based studies, the application of a bonding agent is considered important for increasing the bond strength between the "fresh" repair and existing restoration.^{38,41-43} Within these responses, 94% of schools report teaching such a technique. The use of flowable resin composites for effecting the repair is more popular in Japan (89% of schools) compared to other regions (33% of UK and Irish schools, 55% of Scandinavian schools, 60% of US/Canadian schools, and 77% of German schools).²⁶⁻²⁹ Some caution is advised with this practice: while flowable resin composites have a reduced filler load and may offer potential advantages in terms of ease of application and elasticity, their increased porosity and polymerisation shrinkage can cause problems if placed on the external surface of a tooth restoration.⁴⁶

Despite the teaching of repair rather than replacement of defective resin composite restorations being embedded in Japanese dental school programs, it is unclear as to what extent this technique is applied in dental practice in Japan. There is some evidence from the United Kingdom that despite teaching of repair techniques at dental school, these are usually discarded on emergence into independent practice.⁴⁷ This is a regrettable development given evidence that as much as 50% of restorations are replaced within 10 years of initial placement.⁴⁸ This, in turn, results in many patients being exposed to overtreatment and subjected to the associated economic and financial burdens. Investigation of the application of repair techniques in the management of defective restorations within dental practice in Japan is warranted to assess the influence of the positive developments in dental school teaching.

In the meantime, the results of the present study, when taken together with the findings of the related studies,²⁶⁻²⁹ indicate that a strong consensus exists among clinical academics in departments of operative and conservative dentistry around the world that there are merits in repairing rather than replacing defective direct resin composite restorations. With concerted actions through national associations and international and multinational organizations, such as the Academy of Operative Dentistry and the European Federation of Conservative Dentistry, it should be possible to resolve differences in technique, such as the treatment of exposed restoration surfaces, and to disseminate and encourage among general dental practitioners the adoption of the knowledge and skills necessary to effectively apply repair techniques in clinical practice. At the same time, commissioners and funders of third-party oral health care provision should be persuaded of the value of repair techniques as an approach that benefits patients, that offers efficiency savings, and that allows especially younger practitioners to practice the minimal interventive techniques they were taught in their dental school programs. The repair of defective direct composite restorations in this way is a good example of the need for much stronger leadership in operative and conservative dentistry, ideally at the global level.

CONCLUSION

Based on the results of this survey, it appears that the teaching of repair of defective resin composite restorations is established within many Japanese dental schools to a greater extent than other regions of the world. This is to be welcomed, as repair

techniques for defective restorations offer many more advantages to patients than replacement, not the least of which are reduced iatrogenic damage and the associated financial and treatment burdens. The impact of this teaching on subsequent clinical practices in Japan should be investigated. Furthermore, the findings of related studies indicate the need for much stronger leadership in operative and conservative dentistry to at least resolve the differences in key aspects of repair procedures if for no other reason than the benefit of patients.

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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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Bond Strength of Self-etch Adhesives After Saliva Contamination at Different Application Steps

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Clinical Relevance

The effects of oral fluids on the bond strength of bonding systems to enamel/dentin must be considered during clinical application of these materials.

SUMMARY

This study evaluated and compared the effect of saliva contamination and possible decontamination methods on bond strengths of two self-etching adhesive systems (Clearfil SE Bond [CSE], Optibond Solo Plus SE [OSE]). Flat occlusal dentin surfaces were created on 180 extracted human molar teeth. The two bonding systems and corresponding composite resins (Clearfil AP-X, Kerr Point 4) were bond-

ed to the dentin under six surface conditions (n=15/group): group 1 (control): primer/bonding/composite; group 2: saliva/drying/primer/bonding/composite; group 3: primer/saliva/rinsing/drying/primer/bonding/composite; group 4: primer/saliva/rinsing/drying/bonding/composite; group 5: primer/bonding (cured)/saliva/rinsing/drying/primer/bonding/composite; group 6: primer/bonding (cured)/saliva/removing contaminated layer with a bur/rinsing/drying/primer/bonding/composite. Shear bond strength was tested after specimens were stored in distilled water at 37°C for 24 hours. One-way analysis of variance and Tukey post hoc tests were used for statistical analyses. For CSE, groups 2, 3, and 4 and for OSE, groups 6, 2, and 4 showed significantly lower bond strengths than the control group ($p<0.05$). CSE groups 5 and 6 and OSE groups 3 and 5 revealed bond strengths similar to the control. When saliva contamination occurred after light polymerization of the bonding agent, repeating the bonding procedure recovered the bonding capacity of both self-etch adhesives. However, saliva contamination before or

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after primer application negatively affected their bond strength.

INTRODUCTION

The adhesive bond between dental adhesives and tooth structure is negatively influenced by fluid contamination.^{1,2} In the oral cavity, such contaminants occur in the form of saliva, blood, or plasma. They present a common problem during clinical restorative procedures, especially when rubber dam isolation is not feasible, for example, with uncooperative patients, subgingival margins, malpositioned teeth, and partially erupted crowns.³ In addition, most carious cavities are found in sites at or near the gingival margins where saliva contamination is most likely to occur.^{1,4} Therefore, the effects of oral fluids on bond strength of bonding systems to enamel/dentin must be considered during the clinical application of these materials.

Several studies have evaluated the bond strength of bonding systems for normal enamel and enamel contaminated with oral fluids, such as plasma and saliva, and found that the oral fluids reduced the enamel bond strength.^{3,5,6} Dentin bonding is particularly complex when compared with enamel bonding, and studies related to the bonding efficacy of saliva-contaminated adhesive systems to dentin are controversial. Some studies demonstrated that saliva contamination reduces the bond strength of dental adhesives to dentin,^{1,2,4,7} while others reported contradictory results.^{8,9} These differences are due to various influencing parameters, such as the composition of adhesive systems and the type of decontamination treatment used. Townsend and Dunn⁹ suggested that recent self-etch adhesive systems, which used hydrophilic primers, were less sensitive to salivary contamination of prepared tooth surfaces than previous generations of adhesives.

Self-etching adhesives do not require acid etching and removal of the smear layer, which leads to a reduction of postoperative and technique sensitivity. These systems have become increasingly popular in daily practice.¹⁰ However, few studies have been published on the influence of saliva contamination during the different application steps of self-etch systems to dentin.^{1,2,4,9,11}

The purpose of this study was to evaluate the effects of saliva contamination at different bond application steps on the shear bond strength of two different two-step self-etch adhesive systems and to

identify a decontamination method that reestablishes bond strengths comparable with the noncontaminated control group.

MATERIALS AND METHODS

One hundred eighty noncarious human molar teeth were stored at 4°C in 0.2% chloramine-T-containing distilled water after extraction. Soft-tissue remnants and calculus were removed, and the teeth were cleaned with fluoride-free pumice and a rubber cup. The occlusal tooth surfaces were cut slightly below the dentino-enamel junction with a low-speed diamond saw (Isomet, Buehler Ltd, Lake Bluff, IL, USA) under water cooling to expose a flat area of dentin.

The teeth were then embedded in cylindrical molds with fast-set acrylic resin in a manner that exposed the flat dentin surface parallel to the base of the molds. The dentin surfaces were hand polished with 600-grit silicon-carbide abrasive paper for 60 seconds under running water to create a uniform surface and smear layer. The surfaces were then rinsed with distilled water for 15 seconds and gently air dried before application of the adhesives. The teeth were randomly divided into two groups of self-etch adhesive systems: Clearfil SE Bond (CSE) and Optibond Solo Plus SE (OSE). The self-etch adhesives were applied to the dentin surfaces according to the manufacturers' instructions (Table 1) under six surface conditions, as described in Table 2 (n=15/group).

Before each application, fresh saliva was collected from the same individual at the same time of day. The detailed bonding protocols used in the five treatment groups and the control group were as follows:

- Group 1 (control): Adhesive systems were applied to the surface without saliva contamination.
- Group 2: Saliva (0.1 mL) was applied to the dentin surface with a micro brush for 20 seconds, and the surface was then dried with air for five seconds. The primer and bonding agent of the adhesive systems were then applied.
- Group 3: Following primer application, 0.1 mL of saliva was applied to the dentin surface with a micro brush for 20 seconds, the surface was rinsed with water for five seconds, and it was then dried with air for five seconds. The surface was reprimed, and bonding was applied.
- Group 4: After primer application, 0.1 mL of saliva was applied to the dentin surface with a micro brush for 20 seconds, the surface was rinsed with

Table 1: Manufacturers, Primer Acidity, Components, and Application Procedures of the Bonding Agents Used in the Study.

Bonding Agents	Composition	Primer Acidity	Batch No.	Manufacturers' Instructions
Optibond Solo Plus self-etch (OSE); Kerr, USA	Primer: HFGA-GMA, GPDM, ethanol, water, MEHQ, ODMAB Adhesive: Bis-GMA, HEMA, GDMA, GPDM, ethanol, CQ, ODMAB, BHT, filler (fumed SiO₂, barium aluminoborosilicat, Na₂SiF₆), coupling factor A174	pH 1.5	205187, 21168	Primer was applied for 15 s, dried with air for 3 s; adhesive agent was applied for 15 s and dried with air for 3 s; adhesive was reapplied for 15 s and dried with air for 3 s and light cured for 20 s
Clearfil SE Bond (CSE); Kuraray, Japan	Primer: MDP, HEMA, hydrophilic dimethacrylate, photo-initiator, water Adhesive: MDP, Bis-GMA, HEMA, hydrophobic dimethacrylate, photo-initiators, silanated colloidal silica	pH 2	00195A 00193A	CSE primer was applied for 20 s; subsequently, the dentin was dried with a stream of air; then CSE Bond was applied and light cured for 10 s

water for five seconds, and it was then dried with air for five seconds. The bonding agent was applied afterward.

- Group 5: Following application of the primer and bonding agent, the dentin surface was contaminated with 0.1 mL of saliva using a micro brush for 20 seconds, rinsed with water for five seconds, and dried with air for five seconds. The primer and bonding applications were repeated.
- Group 6: Following adhesive system application and saliva contamination, as explained in group 5, the saliva-contaminated dentin surface was slightly removed for 10 seconds with a cylindrical diamond bur (No. 330, MANI, Dia-Burs, Japan), rinsed with water for five seconds, and dried with air for five seconds. The primer and bonding agent were reapplied.

All adhesives were applied strictly according to the manufacturers' recommendations. Corresponding composite resins (Clearfil AP-X, Kuraray, and Kerr Point 4, Kerr) were placed on the pretreated dentin surfaces by packing the material into cylinder-shaped plastic matrices with an internal diameter of 2.3 mm and a height of 3 mm (Ultradent, South Jordan, UT, USA). Excess composite was carefully removed from the periphery of the matrix with an explorer. The composite resin was cured with a curing light (Hilux 250, Benlioglu Dental, Ankara, Turkey) for 40 seconds. The intensity of the light was

at least 400 mW/cm². The specimens were then stored in distilled water at 37°C for 48 hours before bond strength testing. The specimens were mounted in a universal testing machine (model 500, Testometric, Rochdale, Lancashire, UK). A stubby-shaped force transducer apparatus (Ultradent) attached to a compression load cell and traveling at a cross-head speed of 0.5 mm/min was applied to each specimen at the interface between the tooth and composite until

Table 2: Saliva Contamination Conditions and Decontamination Procedures

Group	Dentin Surface Treatments
1 (control)	Primer/bonding/composite
2	Saliva/drying/primer/bonding/composite
3	Primer/saliva/rinsing/drying/primer/bonding/composite
4	Primer/saliva/rinsing/drying/bonding/composite
5	Primer/bonding (cured)/saliva/rinsing/drying/primer/bonding/composite
6	Primer/bonding (cured)/saliva/removing contaminated layer with a diamond bur/rinsing/drying/primer/bonding/composite

failure occurred. The maximum load (N) was divided by the cross-sectional area of the bonded composite posts to determine the shear bond strength in MPa.

Failure modes were evaluated with a stereomicroscope and classified as adhesive if debonding occurred at the resin-dentin bond interface and cohesive if the failure occurred in either substrate (resin or dentin).

Statistical calculations were performed with SPSS 13.0 for Windows. In addition to standard descriptive statistical calculations (mean and standard deviation), the parametric one-way analysis of variance test was carried out to compare the adhesive groups. For the evaluation of subgroups, a Tukey post hoc test was performed. The results were evaluated with a 95% confidence interval. The statistical significance level was established at $p < 0.05$.

RESULTS

Table 3 shows the mean shear bond strength and standard deviation values of the tested groups and failure modes (Figure 1). The bond strength values of CSE were found to be higher than OSE in all groups except for group 3. The two adhesive systems showed different sensitivities to contamination by saliva during the bonding application steps. The water rinsing of primer after saliva contamination and application of the bonding agent resulted in the lowest bond strength for both bonding agents.

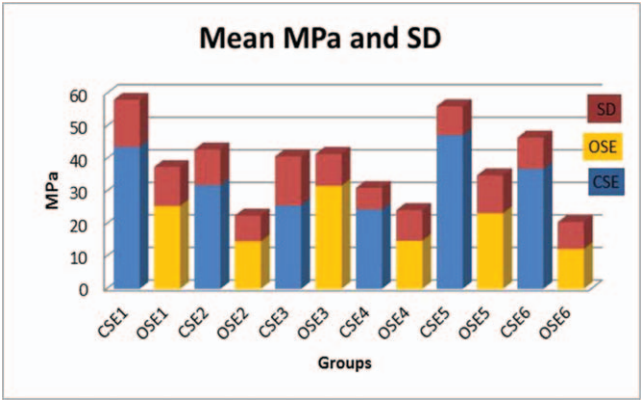


Figure 1. Mean bond strength values and standard deviations (MPa).

For CSE, group 2 (31.9 ± 11 MPa), group 3 (25.7 ± 15.1 MPa), and group 4 (24.4 ± 6.6 MPa) showed significantly lower bond strengths than the control group (43.6 ± 14.5 MPa; $p < 0.05$). However, group 5 (47.2 ± 9 MPa) and group 6 (36.9 ± 9.6 MPa) had no adverse effect on the shear bond strengths ($p > 0.05$).

For OSE, group 2 (14.6 ± 7.9 MPa), group 4 (14.8 ± 9.4 MPa), and group 6 (12.2 ± 8.2 MPa) showed significantly lower bond strengths than the control (25.5 ± 12 MPa; $p < 0.05$). However, this self-etch adhesive system showed more resistance to salivary contamination in group 3 (31.7 ± 9.8 MPa) and group 5 (23.2 ± 11.6 MPa). There was no statistically significant difference among the bond strengths of groups 3 and 5 and the control group ($p > 0.05$).

Table 3: Mean Shear Bond Strength Values (MPa) and Failure Modes of the Tested Groups (n=15) ^a						
Test Group	CSE			OSE		
	Bond Strength Values (Mean ± SD)	Failure Modes		Bond Strength Values (Mean ± SD)	Failure Modes	
1 (control)	43.6 ± 14.5 ^{cd}	80% A	20% CD	25.5 ± 12.0 ^{bc}	93.3% A	6.7% CD
2	31.9 ± 11.0 ^{ab}	86.6% A	13.4% CD	14.6 ± 7.9 ^a	100% A	
3	25.7 ± 15.1 ^a	93.3% A	6.7% CD	31.7 ± 9.8 ^c	86.6% A	13.4% CD
4	24.4 ± 6.6 ^a	93.3% A	6.7% CD	14.8 ± 9.4 ^a	100% A	
5	47.2 ± 9.0 ^d	80% A	20% CD	23.2 ± 11.6 ^b	100% A	
6	36.9 ± 9.6 ^{bc}	86.6% A	13.4% CD	12.2 ± 8.2 ^a	100% A	
Abbreviations: A, adhesive; CD, cohesive dentin. ^a Same superscript letters indicate statistically similar values (p>0.05).						

Saliva contamination of the cured adhesive layer and reapplication of the adhesive system after rinsing (group 5) had no adverse effect on the dentin shear bond strengths for either bonding agent. When the contaminated surface was removed after saliva contamination of the cured adhesive layer (group 6), the bond strength of OSE significantly decreased ($p < 0.05$).

The failure modes of all groups were found to be mainly adhesive in nature.

DISCUSSION

This study evaluated the effect of saliva contamination and possible decontamination procedures on the bond strength of two self-etch adhesive systems to dentin during different application steps. Saliva contamination is frequently encountered in clinical practice. Saliva consists mostly of water (99.4%) with 0.6% solids. The solids are composed of macromolecules such as proteins, glycoprotein sugars, and amylase; inorganic particles such as calcium, sodium, and chloride; and organic particles such as urea, amino acids, fatty acids, and free glucose.¹²

Self-etch adhesive systems are widely used in clinical practice because they eliminate the rinsing phase, which not only lessens the clinical application time but also significantly reduces the technique sensitivity and risk of contamination during the application.¹³ Furthermore, self-etch adhesive systems contain acidic monomers that promote adhesion to smear-covered dentin. The acidic monomers infiltrate and incorporate the smear layer within the hybrid layer.^{14,15} Once saliva contacts the dentin surface, salivary pellicle deposits on the surface and the thickness of the smear layer increase because of the evaporation of water, leaving a film of glycoprotein sugars on the surface. This thick smear layer may affect the bond strengths of self-etch adhesives by inhibiting penetration of the self-etching primer into dentin.

Some studies have reported that proteins in saliva are the main factors responsible for the improper formation of the dentin-adhesive interface when high-molecular-weight macromolecules in saliva may diffuse into dentin tubules^{7,12,16} and compete with hydrophilic monomers during the hybridization process, reducing the bond strength.¹⁷ Moreover, the salivary pellicle protects dental hard tissues against demineralization caused by acid attacks.^{18,19} Similar to previous studies,^{1,3,4} drying the contaminated dentin surface alone significantly decreased the bond strength values to dentin of both self-etch

adhesives when contamination occurred before application of the primer (group 2).

Studies evaluating the effect of saliva contamination on the bond strength of self-etch adhesives demonstrated that contamination after primer application significantly decreased the bond strength, even when the surface was carefully dried.¹⁻⁴ Hiraishi and others¹ suggested that a hydrophilic monomer such as HEMA in the self-etching primer would be easily rinsed away with water from the demineralized dentin, which might result in collapse of the collagen when the dentin surface was air dried after rinsing. The monomers in the bonding agents were not able to effectively penetrate into the dentin because of collapsed collagen and therefore caused decreased bond strength values. Similarly, bond strength values to dentin declined in our study at the same rate (44%) for both bonding systems when the contaminated dentin surfaces were rinsed and air dried after primer application (group 4). The decreased bond strength values significantly increased after reapplication of OSE primer before bonding, but the reapplication of CSE primer did not increase the bond strength values (group 3).

There are two possible explanations for the increase in bond strength values with OSE. When bonding to air-dried dentin, the H-bonding capacity of solvents has been shown to reexpand the shrunken demineralized collagen network after dehydration.^{20,21} Solvents that have a higher affinity to form H-bonds will be able to break the stabilizing H-bonds and other forces that keep the collagen in a shrunken state. Water and ethanol consist of a hydroxyl group that can form strong hydrogen bonds. The hydroxyl group of HEMA also provides hydrogen bonds.²¹ However, the H-bonding capacity of HEMA is limited.²² Therefore, after repriming, OSE primer, which contains water and ethanol, might have been able to reexpand the shrunken demineralized collagen more effectively than CSE primer, which contains water and HEMA. Moreover, water is a poor solvent for organic compounds, but the ethanol in the OSE primer may also have denatured the glycoprotein in the salivary pellicle and cleaned the surface.

The bond strength values of both adhesive systems in group 5 were not altered after saliva contamination of the bonding agent that was applied to and cured on the dentin surfaces. It seems that the salivary proteins could not penetrate into the dentin through the polymerized resin/dentin layer and were removed from the surface by the rinsing and

reapplication of the self-etching primer. A suitable surface for bonding was formed again. These findings are consistent with the study by Arı and others.²³ Conversely, Fritz and others²⁴ have shown that salivary contamination of the polymerized adhesive layer caused a reduction of the bond strength of a total-etch one-bottle adhesive system in both reapplied and non-reapplied adhesive resin groups. However, acid etching was not repeated, while in our study, acid etching was repeated through the application of the primer. Yoo and others⁴ also evaluated the influence of salivary contamination on three “all-in-one” self-etching adhesive systems. They indicated that when saliva contamination occurs after light curing of the adhesive bonding agent, reapplication of the adhesive decreases the bond strength.¹³ The all-in-one adhesives prime and bond the surfaces at the same time. It can be assumed that even though the contaminated surface was treated again, the saliva proteins were not completely removed as they are during the separate priming procedure with two-step self-etch adhesives.

Several studies recommend that a saliva-contaminated cured adhesive layer must be removed with a bur.^{17,23} We could not support these findings in our study as the bond strength values decreased with both adhesive systems when the saliva-contaminated surface was removed with a diamond bur (group 6). However, while the decrease in the bond strength values of CSE was not statistically significant, the bond strengths with OSE decreased significantly. This difference can be attributed to the thickness of the hybrid layer created during the first application of the bonding agent. It can be expected that the OSE primer with a lower pH of 1.5 may have formed a thicker hybrid layer than that formed by CSE (pH 2). Therefore, the hybrid layer created with OSE may not have been sufficiently removed by the slight cutting of the dentinal surface with the bur.

The influence of saliva contamination during different application steps and the differing results with two self-etch adhesives indicate the importance of this investigation and the need for further studies, which should include additional parameters and bonding agents.

CONCLUSIONS

Within the limitations of this *in vitro* study, the following conclusions were drawn:

1. The bond strength values of two-step self-etch adhesive systems are affected by saliva contamination at different adhesive application stages.
2. Saliva contamination before or after primer application significantly decreased the bond strength values of self-etch adhesive systems.
3. Saliva contamination after curing the bonding agent and repeating the bonding procedures did not affect the bonding performance of either self-etch system. However, the removal of the contaminated surface with a diamond bur decreased the bond strength values.

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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Dual-Cured Etch-and-Rinse Adhesive Systems Increase the Bond Durability of Direct Coronal Dentin Restorations

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Clinical Relevance

Bonding composite resin with dual-cured adhesive systems can promote increased bond durability to direct coronal dentin restorations.

SUMMARY

This study aimed to evaluate the bond durability of dentin restorations bonded with light- or dual-cured etch-and-rinse adhesive systems.

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A three-step adhesive system (Scotchbond Multipurpose Plus), an acetone-based two-step adhesive system (Prime & Bond 2.1), and an ethanol-based two-step adhesive system (Excite) were tested. Both the light- and the dual-cured versions were evaluated. High C-factor dentin cavities were prepared on 120 bovine incisors, which were then restored with resin composite (n=10). The samples were stored in water for 24 hours, and half of them were subjected to additional degradation with 10% NaOCl for five hours. The push-out bond

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strength test was performed in a universal testing machine until failure. Failure modes were evaluated by scanning electron microscopy. Data were analyzed by three-way analysis of variance and Tukey tests ($p < 0.05$). The dual-cured adhesive system presented a higher immediate bond strength and durability than those that were light cured. The three-step adhesive system produced the highest values, whereas the acetone-based adhesive system produced the lowest result. Therefore, the use of dual-cured etch-and-rinse adhesive systems can induce increased bond durability to direct coronal dentin restorations.

INTRODUCTION

Successful adhesion to hard tissues is a fundamental requirement for dental materials. This is known to be directly dependent on the quality of the hybrid layer. Hence, any measure to increase the lifetime of adhesives might focus on improving the stability of the bonding interface between these biomaterials and tooth tissues.¹ The simplified two-step adhesives were developed from the traditional three-step etch-and-rinse adhesives. They contain the primer and the adhesive resin in one single solution. Despite being less technique sensitive, these simplified adhesives tend to perform more poorly when compared with their three-step counterparts, especially on dentin.²

Optimal monomer infiltration into the demineralized substrates and the achievement of a high degree of conversion (DC) are crucial factors in establishing long-lasting bonds.³ Under clinical conditions, it seems likely that light may not be able to reach the entire coronal cavity with similar irradiance values during adhesive photoactivation. The curing-light tip is not placed directly toward the cavity wall in deeper areas. It has been shown that a long distance between the curing light tip and the material surface tends to generate loss of irradiance, which can negatively affect dentin bond strength.⁴ These findings suggest that protocols that increase the DC of adhesive systems on deeper dentin surfaces of coronal cavities would contribute positively to the long-term bond durability of restorations. Although the DC of dual-cured etch-and-rinse adhesive systems has been investigated in the presence of light,⁵ there is lack of evidence in the literature to confirm the increased bond durability of coronal dentin restorations bonded with dual-cured adhesive systems. This study aimed to evaluate the bond durability of direct coronal dentin restorations

using light- or dual-cured three-step and two-step etch-and-rinse adhesive systems. The hypotheses tested were that 1) the use of dual-cured adhesive systems would increase the bond durability of dentin restorations and 2) the three-step adhesive system would perform better than the two-step adhesive system.

METHODS AND MATERIALS

The present study evaluated a three-step etch-and-rinse adhesive system (Scotchbond Multipurpose Plus, 3M ESPE, St Paul, MN, USA), an acetone-based two-step adhesive system (Prime & Bond 2.1, Dentsply/Caulk, Milford, DE, USA), and an ethanol-based two-step adhesive system (Excite, Ivoclar-Vivadent, Schaan, Liechtenstein). Both the light- and the dual-cured versions were tested. The Scotchbond Activator/Catalyst (3M ESPE) and the self-cure activator (Dentsply/Caulk) were used in the dual-cured versions of Scotchbond Multipurpose Plus and Prime & Bond 2.1, respectively. Excite DSC (Ivoclar-Vivadent) was used as the dual-cured version of Excite. Table 1 shows further details regarding the chemical components of the materials used in this study.

Bond Durability Analysis

Samples were prepared according to a previously described method for the push-out bond strength test.⁶ A total of 120 bovine incisors, free from cracks and structural defects, were selected. The teeth were disinfected in a 0.1% aqueous solution of thymol at 40°C for no longer than one week. The roots were removed with a water-cooled diamond saw (South Bay Technology, San Clemente, CA, USA) coupled to a precision cutting machine (Isomet 1000, Buehler, Lake Forest, IL, USA). The buccal aspect of the crown was wet ground with 400- and 600-grit SiC abrasive papers in a polishing machine (Labopol-21, Struers, Copenhagen, Denmark) to obtain flat dentin surfaces.

Standardized conical cavities (2 mm top diameter $\times$ 1.5 mm bottom diameter $\times$ 2 mm height) were prepared with conical diamond burs (Komet Inc, Lemgo, Germany) at high speed under air-water cooling. A custom-made preparation device allowed the cavity dimensions to be standardized. The burs were replaced after every five preparations. To expose the bottom surface of the cavities, the lingual surfaces were ground in accordance to the procedure described for flattening the buccal aspects. In this manner, a cavity with a C-factor magnitude of 2.2 was obtained.

Table 1: *Materials Used in This Study*

Commercial Brand/Manufacturer	Composition	Batch No.
Scotchbond Etchant, 3M ESPE, St Paul, MN, USA	35% phosphoric acid	9NL
Adper Scotchbond Multipurpose Plus, 3M ESPE, St Paul, MN, USA	Primer: water, HEMA, copolymer of acrylic and itaconic acids	N124653
	Bonding agent: Bis-GMA, HEMA	N195685
	Activator: ethyl alcohol, sodium benzenesulfinate	N200988
	Catalyst: Bis-GMA, HEMA, benzoyl peroxide, triphenylphosphine	N253750
Excite, Ivoclar-Vivadent, Schaan, Liechtenstein	Dimethacrylates, alcohol, phosphonic acid acrylate, HEMA, SiO ₂ , initiators, stabilizers	N11163
Excite DSC, Ivoclar-Vivadent, Schaan, Liechtenstein	Dimethacrylates, alcohol, phosphonic acid acrylate, HEMA, SiO ₂ , initiators, stabilizers	N01061
Prime & Bond 2.1, Dentsply/Caulk, Milford, DE, USA	UDMA, PENTA, Bis-GMA, butylated hydroxytoluene, 4-ethyl dimethyl aminobenzoate, cetylamine hydrofluoride, initiator, acetone	L491546D
Self-Cure Activator, Dentsply/Caulk, Milford, DE, USA	Sodium p-toluenesulfinate, ethanol, acetone	L469025D
Brilliant NL (A2 shade), Coltène/Whaledent, Altstätten, Switzerland	Methacrylates, dental glass, amorphous silica, photoinitiator	0174947
Abbreviations: Bis-GMA, bisphenol A diglycidyl methacrylate; HEMA, 2-hydroxyethyl methacrylate; PENTA, dipentaerythritol pentacrylate monophosphate; UDMA, urethane dimethacrylate.		

The prepared specimens were assigned to 12 groups (n=10) according to the factors under study (adhesive systems – 3 × curing modes – 2 × aging methods – 2). The adhesive systems were used according to the respective manufacturers' instructions, as follows:

- **Adper Scotchbond Multipurpose Plus:** Dentin was etched with 35% phosphoric acid (Scotchbond Etchant, 3M ESPE) for 15 seconds and washed thoroughly with water for 30 seconds. Excess water was blot dried with absorbent paper, leaving the dentin surface visibly moist (wet bonding). One coat of the primer was applied to dentin and air dried for 10 seconds at 20-cm with an air stream –2.6 bar (this distance was standardized using a millimeter ruler). One coat of the catalyst was applied to dentin and air dried for 10 seconds at 20 cm. One coat of the bonding agent was applied and
- light cured for 10 seconds with a Coltolux LED (Coltène/Whaledent, Altstätten, Switzerland) at 1264 mW/cm² (a radiometer was used to measure the light intensity; model 100, Demetron/Kerr, Danbury, CT, USA). Both the activator and the catalyst were applied only for the dual-cured version.
- **Excite:** Dentin was etched with 35% phosphoric acid for 15 seconds and washed thoroughly with water for 30 seconds. Excess water was blot dried with absorbent paper, leaving the dentin surface visibly moist (wet bonding). Two coats of the adhesive system were applied and agitated against the prepared surfaces for 10 seconds. The adhesive system was dispersed to a thin layer with a weak stream of air for 10 seconds at 20 cm and light cured for 10 seconds with a Coltolux LED. Before applying Excite DSC, the single-dose unit was placed on a firm surface, and the applicator

pressed down. The brush and the initiators came in contact with the adhesive solution.

- Prime & Bond 2.1: Dentin was etched with 35% phosphoric acid for 15 seconds and washed thoroughly with water for 30 seconds. Excess water was blot dried with absorbent paper, leaving the dentin surface visibly moist (wet bonding). Two coats of the adhesive system were applied. The solvent was allowed to evaporate for 10 seconds at 20 cm and light cured for 10 seconds with a Colt lux LED. For the dual-cured version, Prime & Bond 2.1 was mixed to the self-cure activator in a 1:1 ratio.

After applying the adhesive systems, the specimens were placed onto a glass slab. The restorative procedures were performed with a resin composite (Brilliant NL, Coltène/Whaledent) that was bulk inserted into the cavity from its wider side. Photoactivation was performed with the Colt lux LED for 20 seconds. The light tip was positioned directly over the restoration, which had been previously covered with a Mylar strip. The top and bottom surfaces of all restorations were finished with #1200 abrasive papers (Buehler, Lake Bluff, IL, USA) coupled with a polishing machine (Labopol-21, Struers, Copenhagen, Denmark). The samples were stored in distilled water at 37°C for 24 hours, and half of them were subjected to further chemical degradation with 10% sodium hypochlorite (NaOCl) for five hours.⁷

The push-out test was performed in a universal testing machine (Instron model 4411, Canton, MA, USA). An acrylic device with a central orifice was adapted to the base of the machine. Each specimen was placed in the device with the top of its cavity against the acrylic surface. The bottom surface of the restoration was loaded with a 1-mm-diameter cylindrical plunger at a cross-head speed of 0.5 mm/min until failure of the tooth-composite bond at the lateral walls of the cavity. The plunger tip was positioned in a way to touch only the filling material, thereby creating no stress at the surrounding walls. The load required for failure was recorded by the testing machine and later converted into MPa values. The data were analyzed by three-way analysis of variance and the post hoc Tukey test. Statistical significance was established at $\alpha=0.05$.

The fractured specimens were cut in half with a water-cooled low-speed diamond saw (Isomet 1000, Buehler) in order to obtain two specimens. Both specimens were fixed to aluminum stubs with the fractured interfaces upward. Specimens were sputter coated with gold (SDC 050 Sputter Coater,

Baltec, Balzers, Liechtenstein) and evaluated by scanning electronic microscopy (JSM 5600LV, JEOL, Tokyo, Japan) to determine the failure mode. The failure modes were defined as adhesive failure, cohesive failure in composite, cohesive failure in dentin, and mixed failure (adhesive and cohesive).

RESULTS

Bond Durability

Intergroup comparisons are shown in Table 2. Regardless of curing mode, the tested adhesive systems yielded a lower bond strength following the NaOCl aging method. Despite this, the dual-cured materials were found to produce higher immediate bond strength and durability than light-cured materials. The three-step adhesive system (Scotchbond Multipurpose Plus) produced the highest values, whereas the acetone-based simplified system (Prime & Bond 2.1) led to the lowest results.

Failure Modes

The frequency of each failure mode is shown in Table 3. Samples bonded with dual-cured adhesive systems showed a lower number of adhesive failure episodes. Samples subjected to the additional NaOCl aging method showed a higher number of adhesive failures.

DISCUSSION

Because the dual-cured version of all adhesive systems was found to promote an increased bond durability to direct coronal dentin restorations, the first hypothesis tested in this study could be validated. In fact, dual-cured adhesive systems have been traditionally recommended when either bonding fiber posts to the dentin root surface or when performing indirect coronal restorations. The rationale for such a clinical protocol is based on the fact that light tends to become attenuated at the deeper aspect of the root as well as underneath indirect restorations. This also happens because of the incompatibility of light-cured simplified adhesive systems with both self- and dual-cured resin-based luting cements.^{5,8-10} However, our results confirmed the benefits from using dual-cured etch-and-rinse adhesive systems for direct coronal dentin composite restorations.

The dual-cured etch-and-rinse adhesive systems, which were tested in the present study, contain different self-curing promoters. Whereas the three-step etch-and-rinse adhesive system (Adper Scotchbond Multipurpose Plus) requires the use of an

Table 2: Bond Strength Means (Standard Deviations) for Each Adhesive System According to Curing Mode and Aging Method

Adhesive System	Aging Method	Curing Mode	
		Light	Dual ^a
Adper Scotchbond Multipurpose Plus	Water	45.9 (8.8) Ba	64.3 (7.7) Aa
Excite		30.2 (4.9) Bb	37.2 (2.7) Ab
Prime & Bond 2.1		19.4 (4.8) Bc	24.9 (2.6) Ac
Adper Scotchbond Multipurpose Plus	Water and NaOCl	39.1 (8.5) Ba ^b	57.0 (6.3) Aa ^b
Excite		25.3 (3.8) Bb ^b	31.5 (2.8) Ab ^b
Prime & Bond 2.1		15.5 (1.9) Bc ^b	20.9 (1.8) Ac ^b

^a Excite DSC was used as the dual-cured version of Excite. Different uppercase letters in rows and lowercase letters in columns indicate statistically significant differences for each aging method ($p < 0.05$).

^b Statistically significant differences between aging methods for the same adhesive system and curing mode.

activator solution before priming and a catalyst liquid after priming, both the simplified systems (Prime & Bond 2.1 and Excite) contain only one activator component, which is mixed with the adhesive system before usage. All of the activator components are derived from sulfinate salts, which react with acidic resin monomers to produce either

phenyl or benzenesulfonyl free radicals that initiate the self-curing polymerization reaction of the adhesive system.¹¹ This is thought to increase the degree of conversion of the adhesive system, thereby contributing to long-lasting bonds. Moreover, the catalyst liquid that is used after the application of the primer (Adper Scotchbond Multipurpose Plus)

Table 3: Frequency of Failure Mode

Adhesive System	Aging Method	Curing Mode/Failure Mode									
		Light					Dual ^a				
		A	CA	CC	CD	M	A	CA	CC	CD	M
Adper Scotchbond	Water	—	—	6	—	4	—	—	5	5	—
Multipurpose Plus	Water and NaOCl	4	—	2	2	2	2	—	4	2	2
Excite	Water	—	5	1	—	4	—	5	—	1	4
	Water and NaOCl	5	—	1	2	2	3	—	1	3	3
Prime & Bond 2.1	Water	6	—	—	2	2	1	—	2	2	5
	Water and NaOCl	7	—	—	—	3	5	—	—	—	5

Abbreviations: A, adhesive failure; CA, cohesive failure in adhesive; CC, cohesive failure in composite; CD, cohesive failure in dentin; M, mixed (adhesive and cohesive).

^a Excite DSC was used as the dual-cured version of Excite.

contains benzoyl peroxide, which has been reported to initiate a self-curing process of the monomers.¹² The self-cure polymerization is triggered by a reaction between benzoyl peroxide and a tertiary amine, a co-initiator that is often present in resin-based light-cured dental materials. Regardless of exposure to light, the co-initiator releases free radicals to promote monomer conversion.¹³ It is likely that an additional polymerization occurs in the bonding agent of Adper Scotchbond Multipurpose Plus when the benzoyl peroxide-based catalyst is applied and the material is later exposed to light. Although the manufacturer claims that it is unnecessary to use the bonding agent after applying the catalyst, we did not follow its instructions in the face of previous positive results with regard to degree of conversion when mixing the bonding agent with the catalyst liquid.⁵ However, further analysis should be encouraged to investigate whether an increased degree of conversion could be obtained when other adhesive systems, herein tested, are mixed with activator solutions and later exposed to light.

Even though the light source tip was placed very close to the superficial tridimensional cavity margins, it must be assumed that the light gets attenuated in deeper areas. This occurs in most clinical situations and compromises the degree of conversion of the adhesive system. Because of such incomplete monomer conversion, the acidic monomers of simplified systems might become capable of inactivating the tertiary amine co-initiator, which may be present in the composite resin, thereby affecting negatively both the composite conversion and the bond durability.

Our dentin bond durability results are in agreement with previous systematic data as the three-step etch-and-rinse adhesive systems remain the gold standard in terms of bond durability.^{2,14} Consequently, the second hypothesis tested was also validated. In fact, by blending primer and bonding components in a single solution, simplified etch-and-rinse adhesives show a reduced ability to infiltrate the demineralized dentin substrate, thereby producing suboptimal hybridization.¹⁴ In addition, the hydrophilic nature of such adhesives render them more prone to water sorption and consequently more susceptible to the effects of hydrolytic degradation. The solvent present in such adhesives is also more difficult to evaporate, frequently remaining entrapped within the adhesive layer after polymerization.¹⁵

The influence of the adhesive solvent component on dentin bond strength and durability according to dentin moisture conditions has been observed. For

instance, an acetone-based adhesive system was found to perform better than a water/ethanol material only on very wet dentin surfaces.¹⁶ In the present study, because dentin moisture conditions were standardized according to the manufacturers' instructions, it is likely that the lower bond strength values produced by the acetone-based adhesive system, in comparison with the ethanol-based adhesive system, would be attributed not only to the differences between the solvent components. Probably, for both materials, differences between chemical components also justify distinctiveness in bonding performance.

In this study, an accelerated aging test was used to stimulate dentin bond degradation by exposing samples to a 10% NaOCl solution for five hours.⁷ Although this method has been frequently used to accelerate bond degradation in beams, it decreased bond strength in the tridimensional cavities evaluated. In fact, 10% NaOCl can induce oxidation, leading to the fragmentation of resin-unprotected collagen fibrils and affecting bond integrity.¹⁷ Such a solution can also promote resin dissolution at the hybrid layer of adhesive systems,¹⁸ thereby decreasing bond integrity. The high number of adhesive failures in samples subjected to the NaOCl aging method can be justified by the lower integrity of the hybrid layer caused by NaOCl.

Different methods, such as the shear and tensile bond strengths, have been used to measure dentin bond integrity. One disadvantage of these methodologies is that they are generally performed on flat surfaces. In such situations, the C-factor is very low, and the shrinkage stress is not directed at the bonding interface.⁶ For these reasons, the push-out bond strength test was performed in the present study. The advantage of using the push-out test is that the bond strength can be evaluated in a high C-factor cavity (2.2), such as Class I and inlay cavities, with the high-stress generation directed at the bonding area. The method provides a better estimation of the bond strength than does the conventional shear test, because fracture occurs in parallel (not transverse) with the dentin-bonding interface, thereby simulating the clinical condition.¹⁹ Thus, since dual-adhesive systems produced a higher bond durability than light-cured adhesive systems in tridimensional dentin cavities, they might then be able to improve the clinical performance of composite coronal restorations. On the other hand, clinicians should be prepared to increase working time due to a high number of steps. Further clinical trials are still necessary to confirm this assumption.

CONCLUSION

The use of dual-cured etch-and-rinse adhesive systems can provide increased bond durability to direct coronal dentin restorations.

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Surface Properties of Dental Nanocomposites After Finishing With Rigid Rotary Instruments

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V Dhuru • WA Smith

Clinical Relevance

Both nanofilled and nanohybrid dental restoratives appear to have relatively smooth surfaces when finished with tungsten carbide finishing instruments, and such instruments may be used as the final instruments when completing composite restorations.

SUMMARY

This study evaluated the surface characteristics of three nanoparticle resin composites

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(Z350, Heritage 7 Nanohybrid, and Ice) using profilometry and scanning electronic microscopy (SEM) after subjecting them to sequential finishing procedures using rigid rotary instruments. Fifteen 8 mm × 8 mm × 2 mm specimens were fabricated for each tested composite and subjected to one of the following finishing regimens: finishing with green stones followed by white stones, finishing with 45-μm diamond followed by 15-μm diamond, finishing with a 12-fluted carbide followed by a 20-fluted carbide. After finishing, the surfaces were subjected to profilometric testing. Eight parallel tracings were used to scan the finished surface of each specimen. For each recorded profile, the average roughness (R_a) and extreme value descriptor (R_{max}) were recorded. On completion of the profilometric testing, two specimens from each group were randomly selected for qualitative assessment by SEM. Profilometric data was analyzed using a one-way analysis of variance and post hoc Scheffe tests. The results demonstrated that the three control groups of the tested nanocomposites behaved as a coherent group with respect to surface

roughness. With the exception of the nanohybrid Heritage 7 finished with the carbide instruments, all composites showed an increase in surface roughness.

The Z350 and Ice finished with the carbide finishing instruments showed no statistically significant increase in R_a , but both of these composites showed significantly rougher surfaces when finished with diamonds compared with controls. The nanohybrids Ice and Heritage 7 demonstrated significantly higher roughness in terms of R_{max} when finished with stones. The SEM correlated well with roughness measurements. The conclusion may be drawn that diamonds and stones produce unacceptable surfaces in terms of roughness on the tested nanocomposites whereas finishing carbides produce acceptable surfaces.

INTRODUCTION

The introduction of filler particles into dental composites, with some or all of the inorganic particles being in the nanoscale range, has led to an improvement in the physical properties of available restorative materials. Incorporating some proportion of smaller filler particles into a composite formulation generally increases the filler loading of the materials to a limiting point, with benefits to the properties of the material including a reduction in polymerization shrinkage, increases in the strength and modulus of elasticity, and improvement in the polishability.

More specifically, filler particles in the nanoscale range have dimensions below the wavelength of visible light, making them unable to absorb or scatter light. This offers a benefit of improvement in optical properties.¹ Additionally, the small particle sizes lend themselves to improved finishing and polishing procedures, which affect surface roughness, initial gloss after finishing and polishing procedures, and long-term retention of smoothness.¹⁻³ These properties also directly affect the optical properties of the finished restoration.

As with other classes of dental composite materials, for example, microfilled hybrids, finishing and polishing of nanocomposites are essential steps in the completion of a directly placed restoration. Adequate finishing and polishing are required to prevent surface discoloration and plaque accumulation and to optimize esthetics.⁴⁻⁶ Polishing, with decreasing grits of silicon carbide or aluminum oxide coated flexible discs or silicone polishing points, is normally

completed after finishing at high speeds with more aggressive armamentarium, such as finishing diamonds, multi-fluted finishing carbides, and green and white stones. Finishing and polishing procedures are complementary—both are done consecutively; however, because of variations in the extent and position of the restoration and the configuration of most commercially available polishing discs and points, some surfaces of the restoration may be left inadequately polished with the only surface treatment being finishing. Başeren⁷ concluded that the use of polishing devices might not be useful clinically for areas that are not readily accessible.

It has been postulated that nanocomposites, with their smaller filler particles, allow for higher filler loading, which stabilizes such particles within the composite matrix, prevents undue loss of filler particles during finishing procedures, and results in surfaces that experience less surface detriment.⁸ Thus, it is theoretically possible to complete these restorations with finishing alone. Although there is a plethora of evidence in the scientific literature regarding roughness and surface geometry of nanocomposites after finishing and polishing, there is a scarcity of evidence with respect to this class of composite with some or all of the filler particles in the nano-range being subjected to sequential finishing with rigid rotary instruments alone.

The aim of this study was to evaluate the surface characteristics of the selected nanoparticle resin composites after subjecting them to finishing procedures using profilometry and scanning electronic microscopy (SEM).

MATERIALS AND METHODS

A power analysis was performed to determine the optimum number of specimens required to calculate statistical significance. Three nanocomposites were used in this investigation: a true nanofilled restorative, Z350 (3M-ESPE, St Paul, MN, USA), and two nanohybrids, Heritage 7 Nanohybrid (IBT Med, Miami, FL, USA) and Ice (SDI, Bayswater, Victoria, Australia). Sixty specimens (8 mm × 8 mm × 2 mm) were made for each composite, using Teflon-coated stainless steel molds.

In each case, the mold was filled with the test material, the surface of the material was covered with a Mylar strip, and the specimen was cured using an Elipar Free Light 2 (3M-ESPE) with its tip in direct contact with the Mylar strip. Following the respective manufacturers' recommendations, Z350 and Ice specimens were cured for 20 seconds and the

Heritage 7 specimens for 40 seconds. Before and during preparation of the composite samples, the output of the curing light was measured with a radiometer (Demetron LED radiometer, Kerr Corporation, Orange, CA, USA) and gave a consistent reading of 890 mW/cm².

Fifteen specimens from each material were used as controls. The remaining 45 specimens were randomly divided into three groups of 15 each and subjected to one of the following finishing regimens using friction grip, rotary instruments mounted on a four-hole air-driven high-speed handpiece (Midwest Tradition, Dentsply, York, PA, USA):

- 1) Green stones followed by white stones (Dura Stones, Shofu Dental Corporation, San Marcos, CA, USA)
- 2) Diamond burs, fine (45 µm) followed by ultrafine (15 µm) (Swiss Tech, Coltene Whaledent, Cuyahoga Falls, OH, USA).
- 3) Tungsten carbide burs, 12-fluted followed by 20-fluted (Safe Ended Series, S.S. White, Lakewood, NJ, USA)

The finishing procedure was accomplished using a high-speed handpiece running at a maximum speed of 300,000 rpm using water coolant and hand pressure to mimic clinical conditions. One author (QM) was responsible for all finishing of specimens. The finishing instruments were changed after every five specimens. The application time for each instrument was 30 seconds. After finishing, the specimens were washed with a vigorous air/water spray and dried with clean compressed air using the air/water tip on the delivery cart of a dental chair (Adec Proforma, Adec Corporation, Newberg, OR, USA).

After finishing, the composite specimens were quantitatively assessed by profilometry using the Mitutoyo Surftest 401 surface roughness analyzer (Mitutoyo America Corporation, Aurora, IL, USA) with a cutoff of 0.25 mm, a transverse length of 1.6 mm, a sample length of 1.25 mm, and a vertical band width of 50 µm. Eight parallel tracings were used to scan the finished surface of each specimen with a side shift of 0.2 mm between tracings. For each recorded profile, the average roughness (R_a) and extreme value descriptor (R_{max}) were recorded.

Levene's test was used to demonstrate that the roughness values (R_a and R_{max}) were selected from a normal population with equal variances. Statistical analysis was carried out by a one-way analysis of variance and post hoc Scheffe tests (SPSS, version 16.0 IBM Corporation, Armonk, NY, USA).

Table 1: Roughness Values (R_a) of a Nanocomposite and Two Nanohybrids After Various Finishing Regimens (Common Superscript Letters Denote a Significant Difference, $p < 0.05$, From the Control Values)

Finishing Regimen	Z350	Ice	Heritage 7 Nanohybrid
Control	0.1	0.08	0.4
Finishing stones	0.40	1.88 ^b	0.74
Diamonds	0.66 ^a	0.61 ^b	0.63
Multi-fluted carbides	0.41	0.46	0.34

On completion of the profilometric testing, two specimens from each group, were randomly selected for qualitative assessment by SEM (Philips SEM 515, Philips, Eindhoven, Netherlands). A 2 mm × 2 mm section was removed from a corner of each specimen and sputter-coated with gold using a Denton Desktop II sputtering system (Denton Vacuum LLC, Moorestown, NJ, USA) before SEM analysis. Photomicrographs were taken at 300× magnification. Depending on the number, size, and pattern of irregularities noted, the resulting photomicrographs were categorized into one of the following: 1) relatively smooth surface, 2) minor surface alteration, or 3) major surface alteration. Photomicrographs were also taken at 5000× magnification in an attempt to visualize any pattern of resin and filler alterations.

RESULTS

Profilometry

R_a Measurements—There was no significant difference between the roughness measurements for the unfinished surfaces of the nanofilled and nanohybrid materials ($p > 0.05$).

All finishing regimens resulted in a change in the surface roughness compared with the control specimens (Table 1). A nanohybrid (Ice) and the nanofilled (Z350) both showed increases in the average surface roughness when treated with all finishing instruments, whereas the nanohybrid, Heritage 7, showed a decrease in surface roughness compared with the unfinished control when finished with carbide finishing burs.

Table 2: Roughness Values (R_{max}) of a Nanocomposite and Two Nanohybrids After Various Finishing Regimens (Common Superscript Letters Denote a Significant Difference, $p<0.05$, From the Control Values)			
Finishing Regimen	Z350	Composite Type Ice	Heritage 7 Nanohybrid
Control	2.10	2.13	3.20
Finishing stones	3.43	16.0 ^b	18.48 ^c
Diamonds	5.48 ^a	4.47	4.70
Multi-fluted carbides	3.90 ^a	3.73	4.24

Compared with the control specimens prepared under a Mylar strip, there was a significant difference between the R_a for Z350 finished with diamonds and Ice treated with finishing stones and diamonds ($p<0.05$). The surfaces of Ice finished with the stones were statistically rougher than those finished with the diamonds ($p<0.001$). None of the finishing regimens produced statistically significant variations in the roughness values of the Heritage 7 nanohybrid.

R_{max} Measurements—The R_{max} values for Z350 showed significant increases in roughness compared with the control specimens when finished with the diamonds ($p<0.001$) and carbides ($p=0.033$) (Table 2). Additionally, the diamond instruments produced statistically rougher surfaces compared with the stones ($p=0.014$).

Both Heritage 7 and Ice nanohybrids showed highly significant increases in roughness when finished with the stones ($p<0.0001$). The R_{max} values for the surfaces finished with the stones were significantly rougher than those finished with diamonds ($p<0.001$) and carbides ($p<0.001$).

SEM Analysis

Visual assessment with the use of the photomicrographs correlated well with the values obtained for R_a . SEM of the surfaces of the control samples and those of all the three materials finished with carbide burs at 300× magnification showed relatively smooth surfaces (Figures 1a through c and 2a through c).

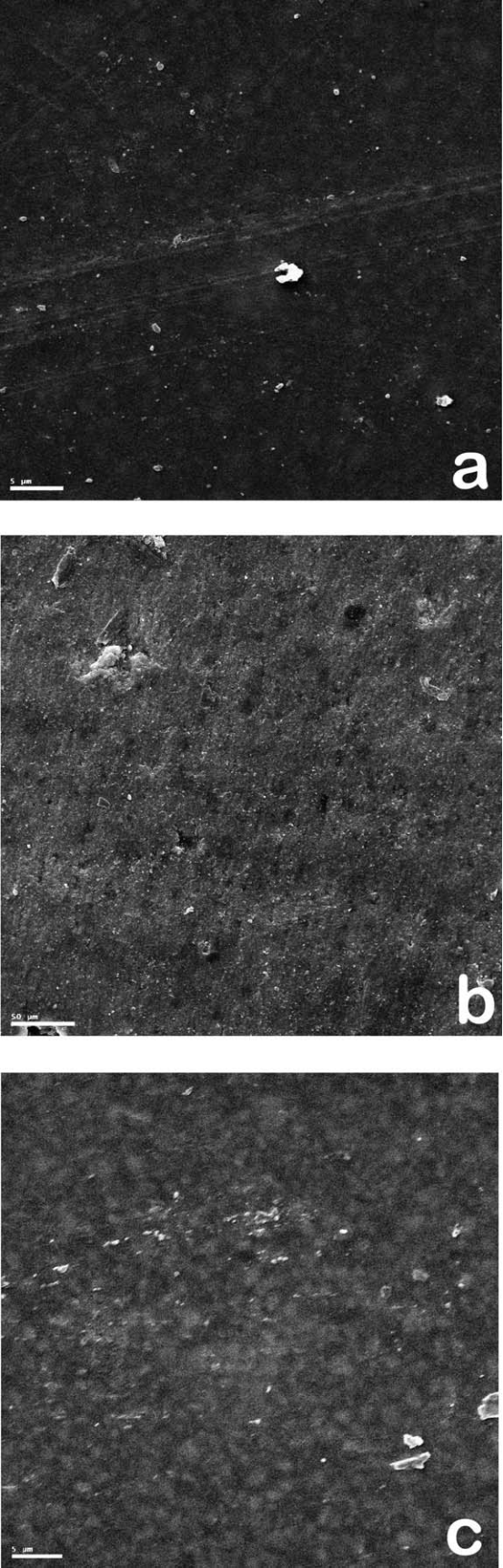


Figure 1. Smooth and homogenous surfaces of the (a): Z350, (b): Heritage 7, and (c): Ice control specimens. (300×).

The nanofilled Z350 finished with the diamonds and observed at 300 $\times$ magnification showed major surface alteration with distinct crests and grooves (Figure 3a). Interestingly, various degrees of surface alterations were noted; larger, more distinct troughs were seen parallel to the direction of finishing, and smaller striations appeared almost perpendicular to the main troughs, which was attributed to the regular spacing of diamonds on the body of the finishing bur. The pattern on the nanohybrids finished with the diamonds produced similar type of troughs, but these appeared to be shallower (Figure 3b,c).

Compared with the effect of the diamond instruments on the composite samples, sequential use of the green and white stones showed only minor surface alterations on both the nanofilled product and the two nanohybrids tested (Figure 4a through c). The widths of the troughs created were approximately one third the widths produced by the diamond instruments on analogous samples, and the distinct troughs were not as deep as those caused by the diamond instruments.

DISCUSSION

A typical profilometer consists of a stylus mounted on a lever arm capable of vertical movement. When the stylus is drawn a specified distance in contact with the test surface, its movement is translated into various parameters of surface roughness. The tracing generated by such movement consists of peaks and valleys, as shown in Figure 5. The parameter, R_a , is the average roughness, which is the mean of the peak-to-valley heights present in the test length. R_{max} is the maximum such value over the test length.

Several authors have used R_a as the main descriptor of surface characteristics of composite materials after finishing and polishing.⁸⁻¹⁰ However, it has been suggested that the use of more than one roughness parameter is important when considering surface characteristics after more than one finishing instrument is used.^{7,11}

As reported in many other studies of surface roughness of composite restoratives after finishing and polishing, the smoothest surfaces were those cured against Mylar strips. All three control groups of the evaluated composites behaved as a coherent

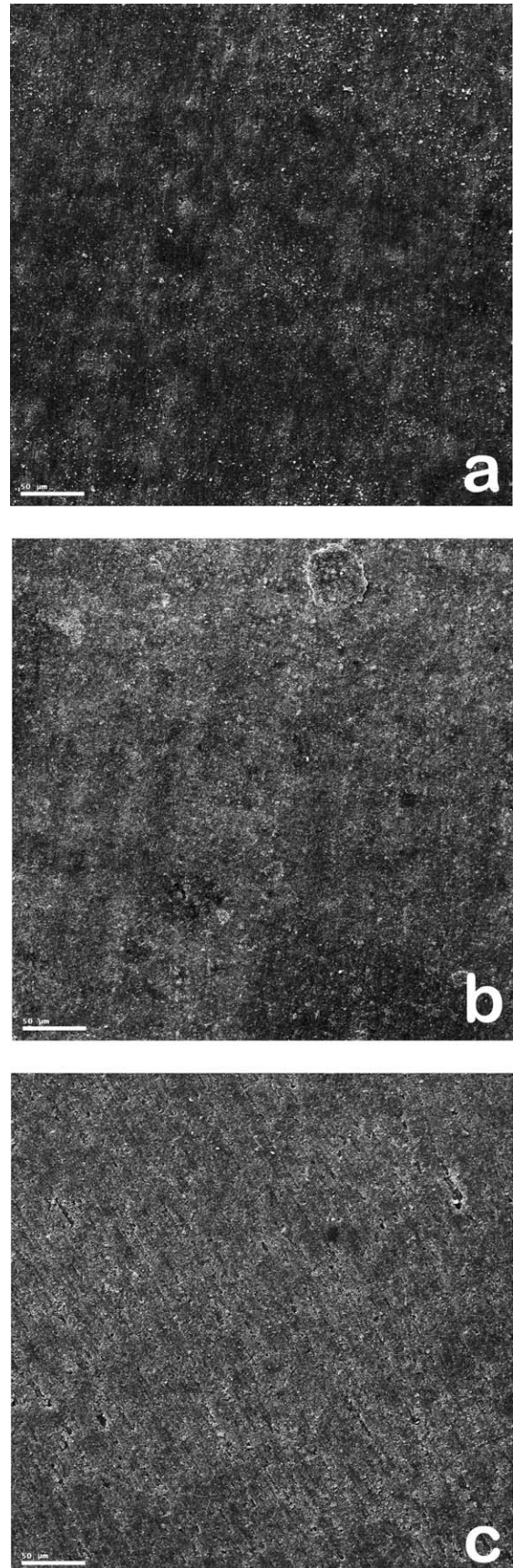
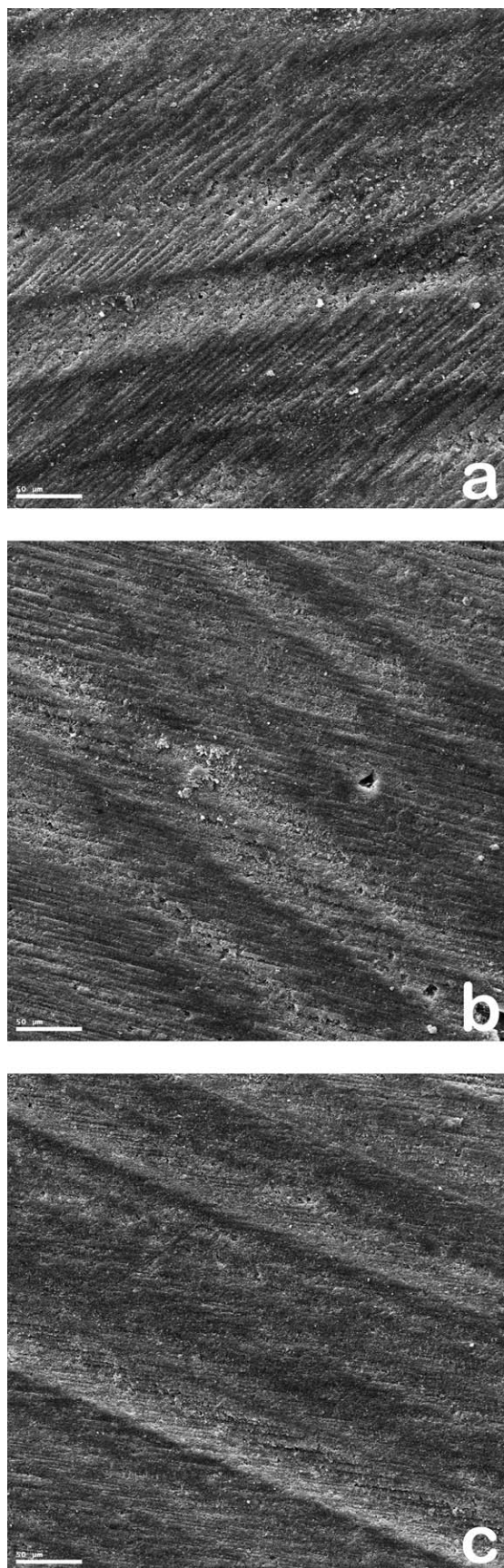


Figure 2. Relatively smooth surfaces of the (a): Z350, (b): Heritage 7, and (c): Ice specimens after finishing with the 12-fluted and 20-fluted carbide burs. (300 $\times$).



group when subjected to statistical tests; there were no statistical differences between them, even though the nanohybrid Heritage 7 demonstrated the largest absolute values for both R_a and R_{max} .

Across all the groups, multi-fluted tungsten carbide burs produced surfaces that were acceptable in terms of quantitative and qualitative assessment. The Heritage 7 specimens finished with the carbide instruments gave an unexpected result of a smoother surface compared with the control of the Heritage 7 group.

This is in contrast to the findings of Berastegui and others,¹² who concluded that both diamonds and finishing carbides should not be used as finishing instruments for composite restorations. However, other researchers have concluded that, because of the low cutting efficiency of finishing carbides, such instruments are best suited for finishing and smoothing hybrid composites.¹³ In an SEM analysis of microfilled and hybrid composites, Ferracane and others¹⁴ concluded that finishing carbides were less efficient at removing material. The results of the current study concur with statements regarding the nature of finishing carbides on composite materials regardless of the filler loading and predominant filler morphology. Indeed, SEM analysis of the nanocomposites finished with the multi-fluted finishing carbides tested demonstrated surfaces that looked almost planed or milled.

Diamonds appear to have a deleterious effect on the surface roughness of both the nanofilled Z350 and the nanohybrid Ice, as evidenced by the R_a values and SEM. Jung¹³ has previously described the characteristic troughs that were observed in this study on other types of composites. He further concluded that finishing diamond instruments should be reserved only for gross removal and contouring because of their high cutting efficiency, a recommendation that could also be adopted for the finishing of nanocomposite materials.

Similarly, based on the R_{max} values and the SEM appearance obtained for the finishing stones, such instruments should not be used for the final polishing. From SEM analysis it appears that finishing stones are much more efficient at removing material from the surface of both nanofilled and

←

Figure 3. (a): Major surface alteration of Z350 nanofilled finished with a 45- μ m finishing diamond followed by a 15- μ m finishing diamond, with distinct troughs and striations noted perpendicular to troughs. Major surface alteration of (b): Heritage 7 and (c): Ice nanohybrid finished with a 45- μ m finishing diamond followed by a 15- μ m finishing diamond, with troughs more widely spaced. (300 $\times$).

nanohybrid composites, and their cutting efficiency can be placed somewhat between that of the finishing carbides and diamonds.

The SEM micrographs of Z350 samples at higher magnification (5000 $\times$) explain the relatively high values of $R_{\max}$ with both the diamonds and carbide finishing burs. The larger particles of Z350 are actually loose agglomerations of nanoparticles, termed “nanoclusters.” They are approximately 0.6–1.4 μm in size, behave as a single unit, and, according to the manufacturer, allow for filler loading of 59.5% by volume. Visualization of the troughs actually shows loss of some of these larger particles (Figure 6). This is in contrast to the manufacturer’s claims that such nanoclusters are often not lost from the surface but, instead, in preference, the individual nanoparticles are lost from the cluster. Roeder and others¹⁰ have discussed the effect of the reduced resin matrix phase on the dislodgement of larger filler particles during the finishing and polishing of the highly filled composites. They concluded that this is due to an inability to stabilize larger particles, with such large particles being plucked off during finishing and with increasing R_a values. Such an argument can be used for the nanocomposites tested in this study. The filler loadings, by volume, as supplied by the manufactures are 59.50% for Z350, 58.89% for the Heritage 7 nanohybrid, and 61.00% for Ice. Such highly filled composites, when subjected to the medium to high cutting efficiency of stones and diamonds, respectively, can lead to surface alterations that may not be compatible with esthetics or surrounding tissue health.

The differences in the SEM results between the nanofilled and the nanohybrid composites finished with the finishing diamonds could be explained by the relative hardness of the filler particle compared with the softer resin matrix. The Z350 has relatively hard zirconia/silica nanoparticles and nanosilica clusters compared with the softer bisphenol A glycidyl methacrylate (Bis-GMA), ethoxylated bisphenol A glycol dimethacrylate (Bis-EMA), and urethane dimethacrylate (UDMA) resin matrix mixture, which facilitates preferential loss of resin compared with filler and gives the appearance of the deep troughs, almost regularly spaced defects. In contrast, the nanohybrid Ice contains strontium glass fillers with hardness values lower than that of zirconia/silica nanoparticles.

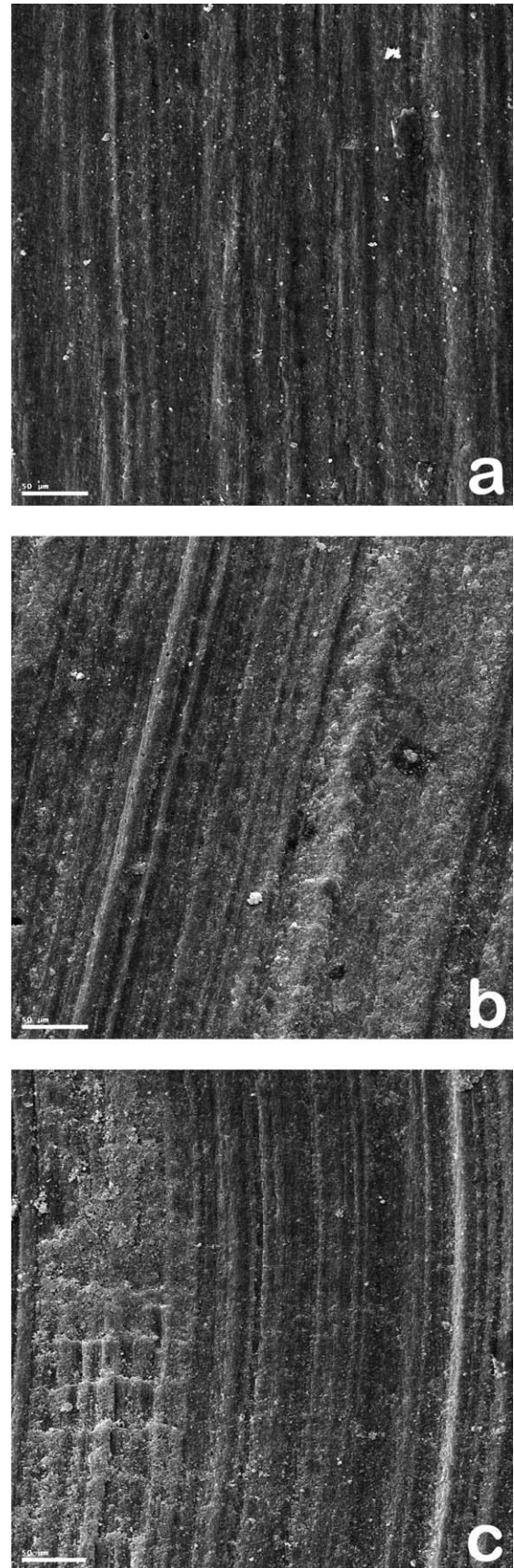


Figure 4. Minor surface alteration of (a): Z350, (b): Heritage 7, and (c): Ice specimens after finishing with green and white stones. (300 $\times$).

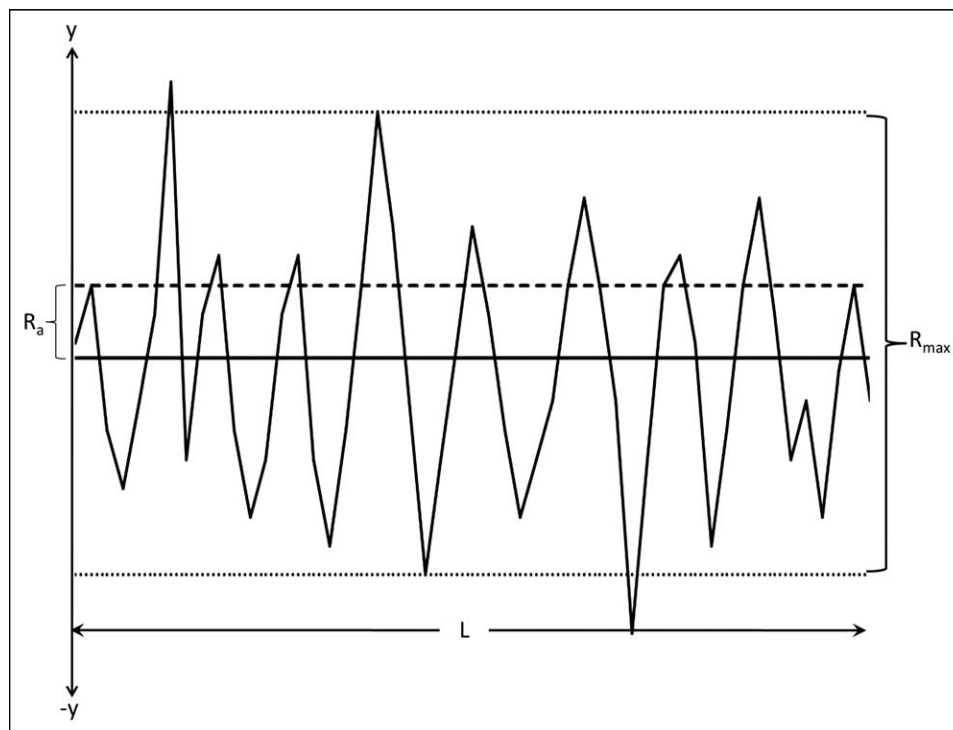


Figure 5. A typical roughness plot.

With the exception of the Ice finished with finishing stones, which produced an R_a value of 1.88, all the nanocomposites finished with the various regimens produced values within or below

the range 0.7-1.0 μm . This is the range reported in the literature to have no appreciable increase in levels of plaque accumulation.^{15,16}

Although finishing with the multi-fluted carbide instruments produced acceptable results in terms of the surface properties, further research is warranted to compare these results with various classes of nanocomposites finished with carbide instruments and then polished with polishing disc, points, or pastes.

CONCLUSIONS

Within the limitations of this study the following conclusions may be drawn:

- 1) The nanofilled Z350 and the nanohybrids Ice and Heritage 7 had the smoothest surfaces when cured against Mylar strips.
- 2) The unfinished surfaces of all the tested composites behaved as a coherent group in terms of roughness measurements.
- 3) Carbide finishing instruments produced surfaces on all the tested composites that were comparable to their unfinished controls.
- 4) Finishing diamonds and stones are unsuitable for completing composites and are associated with significant surface detriment.

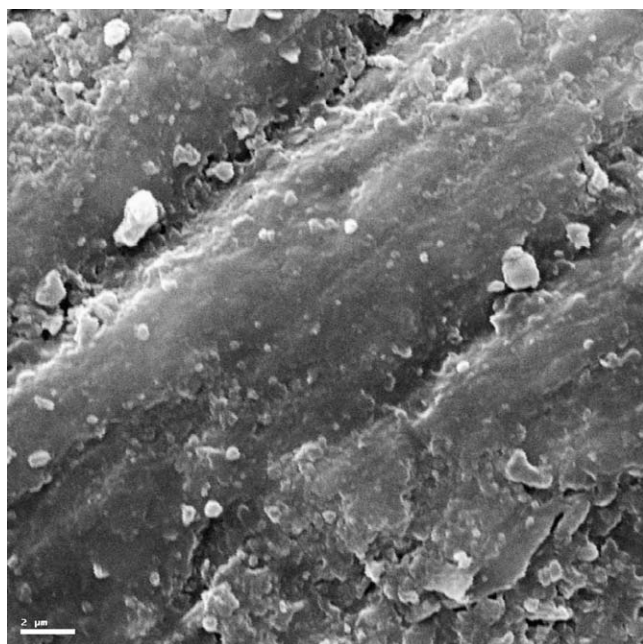


Figure 6. High magnification SEM of the trough of Z350 nanofilled showing particle loss after finishing with a 45- μm finishing diamond followed by a 15- μm finishing diamond. (5000 $\times$).

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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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Experimental Initial Partial Polymerization Method for Fuji II Placement Evaluated for Microleakage With/Without Fuji Coat

JW Chen • B Fletcher • CL Roggenkamp

Clinical Relevance

Sometimes it can be more efficient to impart greater viscosity to resin-modified glass ionomer restorative material for condensability during placement.

SUMMARY

Purpose: This laboratory study evaluated an experimental 1-second initial partial polymerization (IPP) technique using Fuji II LC vs the manufacturer's standard placement (control), both with and without Fuji Coat, relative to microleakage.

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Methods: Class V restorative preparations were placed on the buccal and lingual aspects of 30 permanent, caries-free and restoration-free, third molar teeth. Fuji II LC restorations were placed either following manufacturer-specified guidelines or IPP for 1 second prior to contouring and full light curing. Half of the restorations were placed using the IPP experimental technique and half of the teeth were finished using Fuji Coat LC. Following thermocycling, specimens were sectioned and dye penetration was measured. SPSS 16 was used for statistical analysis ($p < 0.05$).

Results: Mean microleakage results: experimental/varnish (0.08 ± 0.15 mm), control/varnish (0.17 ± 0.35 mm), experimental/nonvarnish (0.33 ± 0.33 mm), and control/nonvarnish (0.58 ± 0.47 mm). Univariate analysis of variance demonstrated significantly less microleakage for the experimental technique ($p < 0.001$), use of finishing varnish ($p < 0.001$), and the combination of experimental/varnish ($p = 0.013$).

Conclusions: The initial partial polymerization technique of Fuji II LC placement significantly reduces microleakage. Fuji Coat LC results in further diminished microleakage.

INTRODUCTION

The increasing trend toward esthetic, minimally invasive restorations has caused a shift in favor of adhesive resin composite and glass ionomer (GI) restorations,^{1,2} commonly involving Class II, III, and V surfaces, especially of pediatric teeth. Adhesive restorations require less tooth preparation than most other types of fillings,² and such minimal removal of tooth structure in cavity preparation remains an important objective of modern dentistry.³

Glass ionomer restoratives have evolved greatly in the last few years.⁴ While these materials allow for more esthetic and conservative restorations, they are also more technique-sensitive.^{5,6} Microleakage is the leading cause of replacing bonded restorations and is responsible for roughly 30% or more of direct restorations being replaced.^{7,8} This can be caused by shrinkage stress, inadequate wetting or adaptation of the material along the cavity wall, and gaps formed between the material and the tooth caused by thermally and mechanically induced stresses.⁷ Microleakage can result in staining of restoration margins, recurrent decay, pulpal sensitivity or damage, and further breakdown of certain restorative materials.⁷

Primary benefits of resin-modified glass ionomer (RMGI) materials over traditional GI materials are their improved translucency, finishability at time of placement, and greater stability regarding imbibition/dehydration.^{9,10} RMGI materials offer reasonable esthetic qualities along with relative ease of handling; low coefficient of thermal expansion; and chemical bonding to cementum, dentin, and enamel as well as to plastics and nonprecious metals.^{6,11,12} Added to these advantages are the release and absorption of fluoride ions over a period of time, a nonetching placement technique, pulpal biocompatibility, soft tissue tolerance, adhesion in a wet field, lower shrinkage values, and reduced microleakage.^{13,14} With potential to act as a fluoride reservoir, GI type restorations are sometimes considered the treatment of choice for patients with high caries activity.¹⁵

GIs are unique in that they form a chemical and micromechanical bond with dentin and, to a lesser extent, with enamel.^{9,16} They exhibit greater affinity

to dentin than do resin-composite materials.¹⁷ Bonding to enamel is largely reliant on ionic and polar forces, whereas bonding to dentin is a more complex interaction.¹⁶ The curing process for glass ionomers is a chemical acid-base reaction that results in an ion-exchange layer between the material and the tooth surface.^{18,19} This layer consists of ionic crosslinks formed as the polyacrylate ions found in the material diffuse with phosphate and calcium ions located on the tooth surface.^{18,19} From this interaction, an adhesive bond is formed with the hydroxyapatite crystals.^{18,19}

The adhesive bond between GI materials and the dentin/enamel surface requires a clean substrate for intimate access of adhesive to its surface, complete wetting of the substrate surface, and liquid-to-solid transformation of the adhesive.¹⁶ Unlike resin-based materials, GIs require only a mildly acidic conditioning agent, and stronger etchants run the risk of substantially reducing the calcium available for binding chemically.²⁰ The conditioner must be rinsed off thoroughly but without leaving the surface overly desiccated. Adequate surface moisture is important to prevent collapsing of the collagen structure of the dentin and to keep dentin tubules exposed for micromechanical bonding in the form of resin tags.²⁰ Resin tags into conditioned enamel also provide some micromechanical bonding to enamel.²⁰ Moist, conditioned surfaces allow more complete wetting of the bonding surfaces by the adhesive.²¹ The existing hydrophilic or polar nature of glass ionomer materials has been further enhanced by addition of the hydroxyethyl methacrylate (HEMA) resin component.¹⁶

HEMA and bis-glycidyl methacrylate (Bis-GMA) were introduced to make glass ionomers photosensitive for visible-light hardening¹⁷ in order to provide dental operators greater control of the working time. Glasspoole and others²⁰ found that the bond strengths of most light-cured RMGIs significantly exceeded those of self-cured materials. Perhaps due to the immediate adherence of the material to tooth structure as opposed to adhesion developing over time, RMGIs are reported to exhibit better adaptation to dentin than traditional glass ionomer materials.²² The relative resin content of tooth-colored restorative products determines whether their characteristics are more closely related to traditional GIs or to resin composites.¹⁷

Water is an important component of the setting reaction of GI materials and affects the structure of the material.^{23,24} Water balance must be controlled to permit sufficient maturation of GI materials

before exposure to the oral environment.^{23,24} Traditional GI cements and, to a lesser extent RMGI materials, are prone to hydration or dehydration following placement.^{23,24} On one hand, excessive hydration immediately following placement can be harmful to the surface of the material,²³ but dehydration on the other hand can lead to shrinkage and crazing.²⁴ GI restorations, including RMGIs, should be covered with a protective varnish to prevent hydration and dehydration for the first hour.¹⁷

RMGI materials have become versatile and widely used. One challenge that remains, however, is the low viscosity at initial placement. The material's fluidity can cause it to slump and sag out of the preparation during placement. Difficulty in manipulating low-viscosity material can lead to voids in the restoration. Greater time for placement or difficulty in handling can lead to increased likelihood of contamination, particularly in some pediatric patients.⁵

Investigators in the present study found that a brief, 1-second partial light-cure during placement of RMGI material mildly stiffened the consistency and improved its handling characteristics. The material became packable and no longer tended to flow out of some of the restorative preparations. This initial partial polymerization (IPP) technique for improved management and control of the material has not been addressed or included in the manufacturer's instructions. The purpose of this investigation was to determine if there would be any adverse microleakage effects on Fuji II RMGI restorations placed using this IPP technique compared with those placed following the manufacturer's standard procedure.

METHODS

Thirty extracted, caries- and restoration-free permanent molars were collected from two oral surgery offices and stored at room temperature in sterile, deionized water for less than 6 months. The teeth were then cleansed of soft tissue with a curette and stored in deionized water with 0.05% sodium azide until ready for use.²⁵

The specimens were randomly divided into two groups of 15 (Figure 1) and placed in two separate containers with individual numbered compartments. Each specimen's number was engraved into the enamel of the mesial tooth surface with a diamond bur. Group 1 specimens had GC Fuji Coat LC placed over the restorations, while group 2 specimens did not. To ensure that each specimen was subjected to

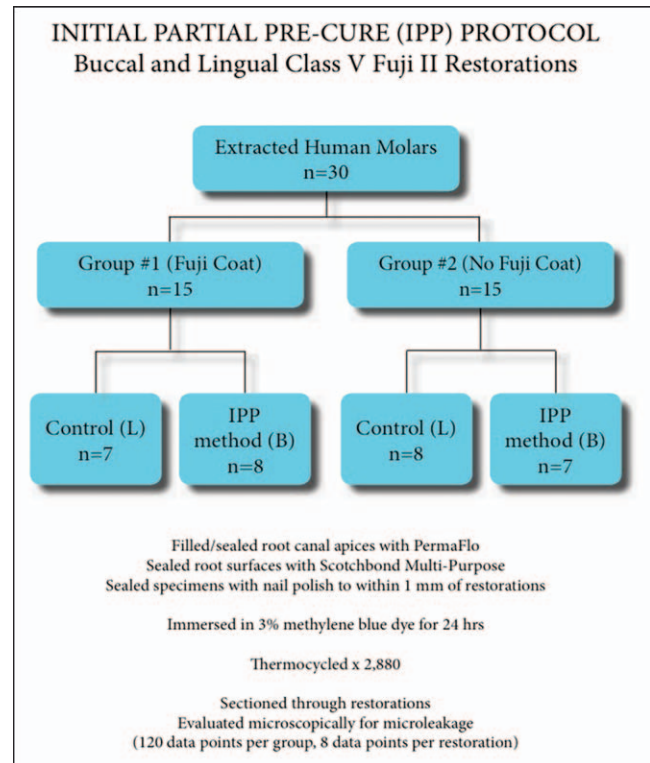


Figure 1. Flow chart showing group subdivisions of this study leading to 120 data points from the original 30 human extracted molars.

the same time between each step in the procedure, one tooth was alternately selected from each group throughout the duration of the test. This would also ensure that any potential for improvement or fatigue effect in the operator's technique would be evenly distributed between both groups and across both restorative techniques.

Class V preparations were excavated on the buccal and lingual surfaces coronal to the cemento-enamel junction of the extracted molars. All preparations were placed by the same operator (the primary investigator) and measured approximately 3 mm wide × 1.6 mm deep × 4 mm long. These dimensions were translated to the specimens by small marker holes punched in a Mylar strip designating the four corners of the preparation. This template was positioned over the buccal and lingual surfaces of the tooth, and marks were placed on the tooth surface through the perforated plastic. A deionized-water-cooled high-speed turbine handpiece (Midwest Tradition Highspeed Handpiece, Dentsply Professional, York, PA, USA) was used with a 330 carbide bur (H330RZ-FG size 008, 1.6 mm length, Axis Sybron Dental Specialties, Coppell, TX, USA) to prepare the preparations. The length of the bur head

served as a depth guide, and each bur was replaced after 10 preparations. Surfaces to be restored using the experimental IPP technique were marked with two horizontal hash marks on the apical third of the root surface. Eight specimens in group 1 and seven specimens in group 2 had the experimental IPP technique used on the buccal surfaces. Preparations were cleansed with air and deionized water, then placed back in deionized water in their individually labeled compartments. Once all the preparations had been completed, specimens were placed in Ziploc bags filled with deionized water and cleansed in a sonic bath (Quantrex L&R Ultrasonics, L&R Manufacturing Company, Kearny, NJ, USA) for 45 minutes to ensure that all debris was removed.

GC Cavity Conditioner (GC America Inc, Alsip, IL, USA), with 20% polyacrylic acid, was then applied to the cavity preparation for 10 seconds. This conditioner was rinsed away thoroughly with deionized water and dried without desiccating the dentin or enamel surfaces using Kimwipes (Delicate Task Wipers, Kimberly-Clark Kimtech Science, Neenah, WI, USA) to wick the moisture away. GC Cavity Conditioner is recommended by the manufacturer to improve the adhesive strength of GC Fuji II LC material to tooth structure.

GC Fuji II LC capsules were first tapped firmly against the workbench surface to loosen the powder, and then activated by pushing the plunger until it was flush with the main body. Each capsule was placed immediately into the metal GC capsule applicator, and the lever clicked once to ensure full activation. After mixing in the amalgamator (Ivoclar Vivadent Silamat, Amherst, NY, USA) for 10 seconds at high speed (4000 rpm), each mixed capsule was immediately loaded into the GC capsule applicator with two clicks applied to prime the capsule. The RMGI was extruded directly into the cavity preparations, minimizing air bubbles. The material was then either contoured and light-cured according to the manufacturer's specifications with a one-time full 20 seconds of polymerization light exposure or submitted to a 1-second IPP step prior to condensing into the preparation and contouring followed by the final 20-seconds light-polymerization step. Being less than 1.8 mm in depth, all restorations were placed in bulk instead of incrementally, then condensed and contoured using a No. 11 IPC (Interproximal Carver, Ultradent Products Inc, South Jordan, UT, USA). GC America Inc recommends that all Fuji II LC restorations greater than 1.8 mm in depth be placed incrementally to avoid excessive curing shrinkage that can result in

cohesive failure of a restoration.²⁶ A 3M Elipar S10 LED visible-light polymerizing device (3M ESPE, St Paul, MN, USA) was selected for its 1-second exposure-time-setting feature to achieve consistency in the partial polymerization step. Clear vinyl plastic tubing (clear vinyl tubing, 10 mm [3/8 inch], ID No. SVIG 20, Watts, North Andover, MA, USA) was cut approximately 50 mm long and adapted as a friction-fit sleeve over the light-guide tip. This could be adjusted up or down on the light guide shaft to serve as a proximity gauge (Figure 2). Illumination from the polymerizing light was transmitted through the lumen of the tube to the restorative material. Any possible light concentrating effect was totally inadvertent. Testing at various distances determined that 43 mm produced optimal consistency of the Fuji II material for appropriate manipulation. Irradiance at this distance was measured to be 180-190 mW/cm². Calibration was determined with a Demetron Light Meter (Kerr Sybron Dental Specialties, Middleton, WI, USA) to assure correct power and light wavelength in the range of 430-480 nm.

Following subsequent full light polymerization, restorations were finished flush to the tooth surface with a 30-bladed finishing bur (Komet H274UF 016, Komet, Rock Hill, SC, USA) under water spray, and polished with medium-fine and fine Ultradent Jiffy Cups (Ultradent). GC Fuji Coat LC was then placed over the restorations in group 1 and light cured for 10 seconds. Capsules were routinely stored at 4°-25°C. Once the restorations had been placed, the specimens were stored in deionized water at 23°C with 100% humidity.

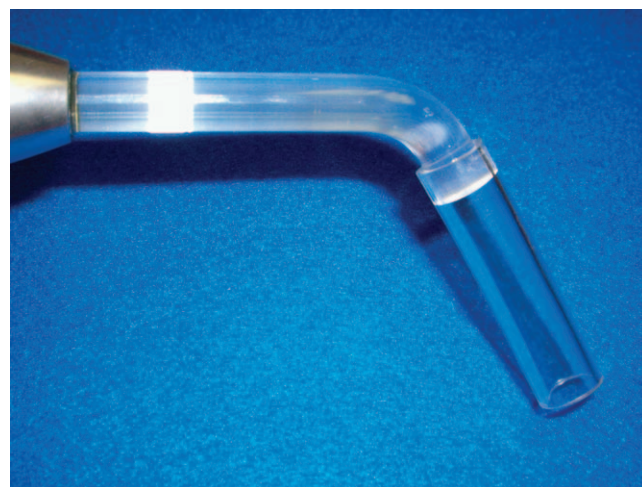


Figure 2. Transparent vinyl tubing placed on the Elipar S-10 light guide tip as an accurate distance-measuring device calibrated for consistent 180-190 mW/cm² illumination of the Fuji II restorative material surface.

The root apices of all specimens were sealed with PermaFlo composite resin (Ultradent) prior to thermocycling. This was accomplished by etching all root surfaces for 15 seconds, then applying Peak LC bonding agent (Ultradent) over the etched surfaces, and light-polymerizing for 10 seconds. Finally, PermaFlo resin was injected into the root canals, extruded over the external apical third of the roots, and light-polymerized for 20 seconds. Following thermocycling, the root surfaces were coated with 3M ESPE Scotchbond Multipurpose Plus (3M ESPE) to ensure that the roots remained sealed. This was accomplished by etching for 15 seconds, rinsing and drying the root surfaces, coating the root surface with Scotchbond Multipurpose Plus, and light-polymerizing for 10 seconds. The oxygen-inhibited layer was wiped off. To further seal all surfaces of the specimens, fingernail polish (Sally Hansen Hard as Nails Extreme Wear, Morris Plains, NJ, USA) was placed to within 1 mm of the restorations. Black fingernail polish was placed on all root surfaces, blue fingernail polish on the coronal half surrounding the experimental restorations, and orange on the coronal half surrounding the control restorations. This step was to limit dye penetration to the tooth-material interface and not be confounded by structural defects in the tooth itself. Specimens from group 1 and group 2 were placed in separate mesh pouches and immersed in a 3% solution of methylene blue dye for 24 hours in a sealed container.²⁷

The teeth were next submitted to thermocycling between 5°C and 55°C in deionized water with a dwell time of 30 seconds in each bath for a period of 2880 cycles (52 hours). Once the specimens were removed from the thermocycler, plastic toothpicks (Qiaoshou Handicrafts Factory, Zhejiang, China) were fixed in position across the occlusal surfaces and centered over the buccal and lingual restorations using Zap-A-Gap cyanoacrylate and accelerator (Super Glue Corporation, Rancho Cucamonga, CA, USA). Pink-colored toothpicks indicated the GC Fuji Coat LC specimens, and green toothpicks the non-coated specimens. No contamination of the restorative surfaces occurred during placement of the toothpicks. Following dye exposure, specimens were removed from their mesh pouches and surfaces cleaned with deionized water and pumice under light finger pressure. Specimens were then encased in acrylic resin (polymethyl methacrylate diethyl phthalate polymer No. 003-07-0358, monomer No. 871-06-0719, Esschem Co, Linwood, PA, USA) with the color-coded plastic toothpicks visibly positioned

at the top of the acrylic cylinders. This helped to ensure the proximity of the restorative material to the tooth structure following the sectioning of the teeth. Restorations were sectioned twice vertically in a buccal-lingual direction using a slow-speed diamond wheel saw (Model 650, South Bay Technologies Inc, San Clemente, CA, USA). The plastic toothpicks served as guides to ensure that each cut passed properly through the buccal and lingual restorations. A horizontal cut with distilled water coolant using the McBain Instruments Leitz 1600 diamond saw (McBain Systems, Simi Valley, CA, USA) subsequently separated the sectioned restorations from the apical half of the roots. All surfaces of each specimen and acrylic cylinder were dried using Kimwipes and placed in a dry storage container to prevent further dye penetration.

The method of sectioning yielded eight data points per restoration with a total of 120 data points per restorative technique (Figure 1). The vertical depth of dye penetration at the tooth-restorative interface was recorded in millimeters using a light microscope (Leco M-400-H1, Akashi Corporation, Hakone, Japan).

Statistical Package for the Social Sciences (SPSS) 16.0 computer software was used for descriptive and inferential statistics. Descriptive statistics for the dye penetration included means, standard deviations, frequencies, and graphs. Inferential statistics included *t*-tests, univariate analysis of variance (ANOVA), and Fisher least significant difference (LSD) post hoc tests, at significance level $p < 0.05$

RESULTS

Of the anticipated 480 data points, 479 were used to conduct the statistical analysis. One data point from the control group was lost from failure to section one restoration in the proper orientation.

Table 1 and Figures 3, 4 and 5 summarize the mean microleakage values and standard deviations for the sample restorations organized by restoration technique and use of finishing varnish.

The mean microleakage for the restorations using the experimental technique + finishing varnish was 0.08 ± 0.15 mm compared to 0.33 ± 0.33 mm without finishing varnish. The mean microleakage for the restorations using the control technique + finishing varnish was 0.17 ± 0.35 mm compared to 0.58 ± 0.47 mm without finishing varnish. The total combined microleakage + finishing varnish was 0.13 ± 0.27 mm compared to 0.45 ± 0.42 mm without finishing varnish. Mean microleakage of 0.20 ± 0.30

Table 1: Mean Microleakage of Experimental and Control Techniques

Technique	Dependent Variable Microleakage		
	Finishing Varnish	Mean, mm	SD, mm
1-Second precure (IPP)	Nonvarnish	0.331	0.330
	Varnish	0.079	0.150
Control	Nonvarnish	0.578	0.472
	Varnish	0.170	0.347
Total combined	Nonvarnish	0.453	0.424
	Varnish	0.125	0.271

Abbreviation: IPP, initial partial polymerization.

mm along the occlusal margin was lower than 0.38 ± 0.42 mm along the cervical margin.

t-Test analyses were performed for the restorative techniques, finishing-varnish usage, and restorative margin locations. Two-tailed *t*-tests showed a significant difference in observed microleakage for the three test variables (restoration technique, finishing varnish, and margin location) with significance of $p < 0.001$ for all *t*-tests.

Univariate analysis of variance, shown in Table 2, depicts the significant difference in microleakage observed in the restorative technique, finishing

varnish, and a combined restorative and finishing varnish variable analysis. The experimental technique, denoted as “1-second precure (IPP)” in Table 2, had significantly less microleakage than the control group ($p < 0.001$). The restorations that had finishing varnish had significantly less microleakage than the nonvarnished restorations ($p < 0.001$). When the experimental IPP technique was combined with the finishing varnish variable, denoted as “precure (IPP) with varnish” in Table 2, the observed microleakage was significantly less than all other restorative techniques and finishing-varnish combinations ($p = 0.013$).

Combinations of restorative technique and finishing-varnish usage were compared using the Fisher LSD post hoc test (Table 3). Comparing the precure (IPP)/varnish with the control/varnish group showed a significant difference in microleakage ($p = 0.044$). And, all of the other combinations demonstrated a significant difference in microleakage ($p < 0.001$) when compared against each other.

Figures 3 and 4 show the statistically significant decrease in microleakage found with the experimental IPP technique group vs the control technique group as well as the varnish-finished and non-varnish-finished groups.

DISCUSSION

RMGI restoratives offer many popular advantages but may have one management drawback, which is fluidity upon placement. It has been found that a controlled appropriate degree of partial polymerization could effectively change the material from

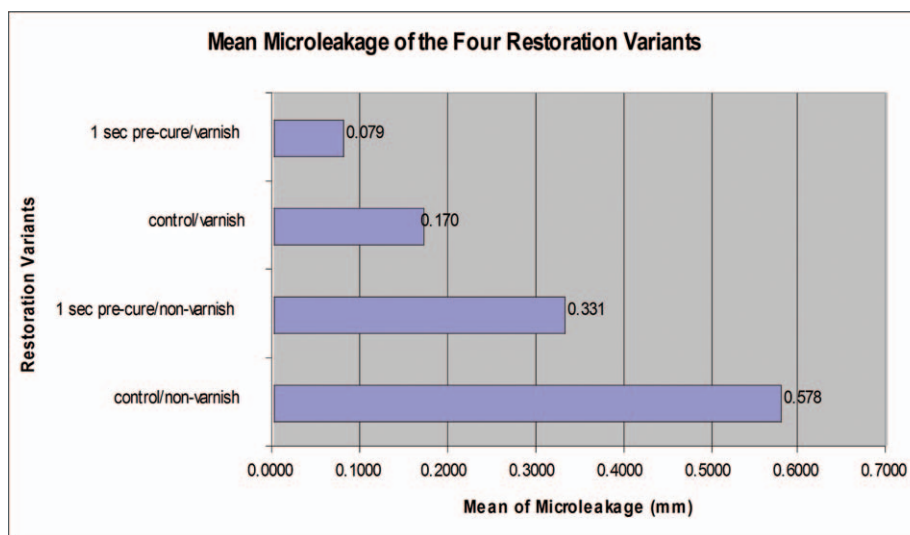


Figure 3. Mean microleakage values of IPP and conventional groups.

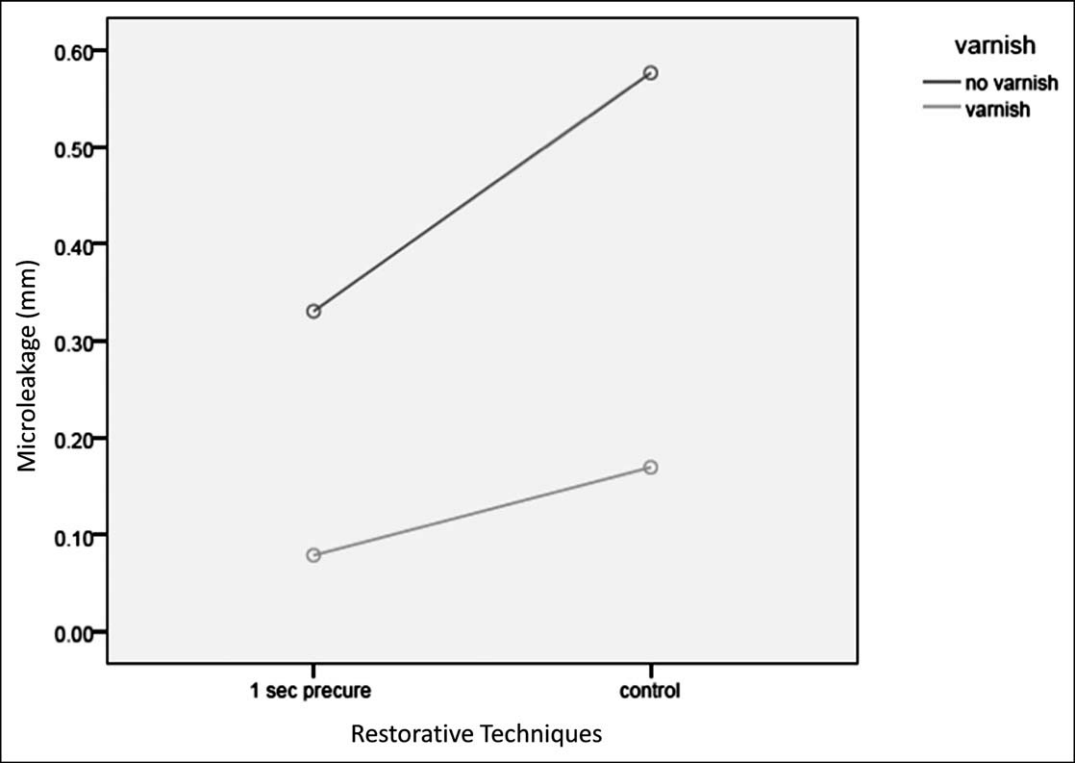


Figure 4. Means of microleakage (mm) of restorative technique and finishing varnish.

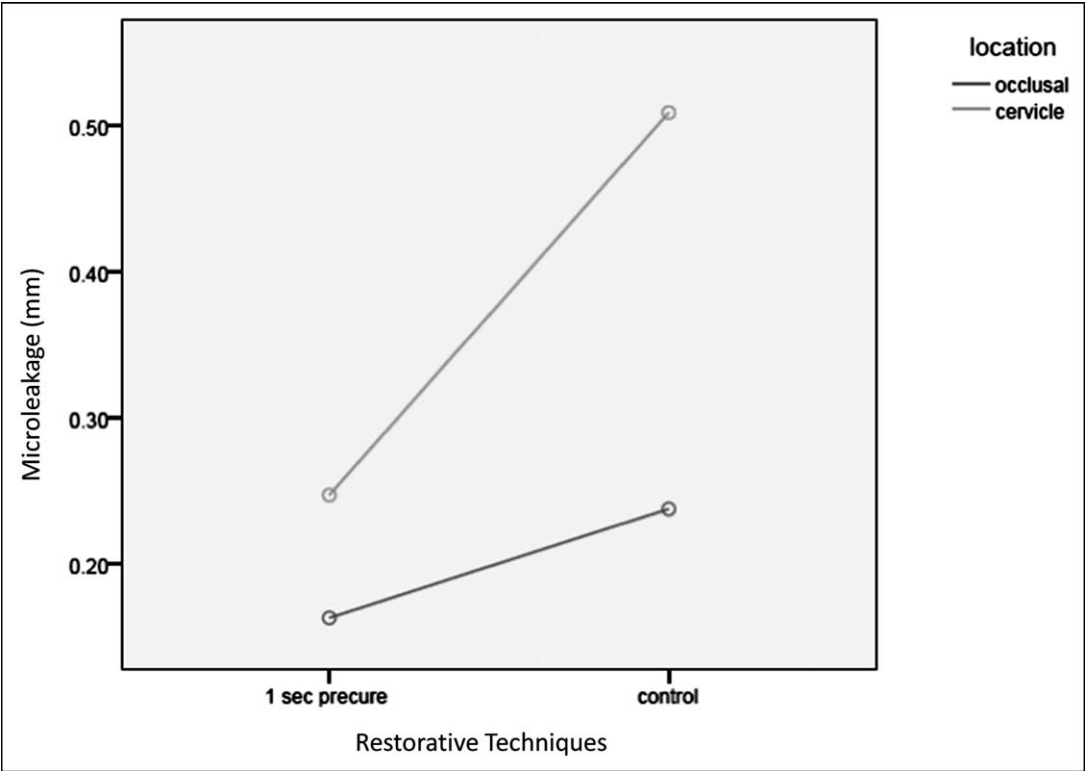


Figure 5. Means of microleakage (mm) of restorative technique and margin location.

Table 2: Univariate Analysis of Variance

Univariate Analysis of Variance		
Source	Mean Square	p-Value
1-Second precure (IPP)	3.406	<0.001
Finishing varnish	13.049	<0.001
Precure (IPP) with varnish	0.735	0.013
Abbreviation: IPP, initial partial polymerization.		

flowable to a more condensable state that holds shape and position during placement. A student pilot study determined that 1-second polymerization light time was optimal, and this technique has been used regularly in the graduate pediatric dental clinic by some operators for at least a couple of years.

Controlling fluidity is especially of concern on walls facing downward or laterally such as on maxillary teeth or Class V restorations where gravity can cause the material to sag or droop from the cavity preparation (Figure 6A,B,C). After the soft-cure (or “tack-cure”) IPP step, RMGI can be initially condensed into place and remain relatively intact through subsequent additions and final manipulation before full light-polymerization (Figure 6D).

Data of the present study showed significantly less microleakage when the IPP step of Fuji II LC was employed prior to contouring and complete polymerization of the material. Apparently, this technique can allow improved handling characteristics of the material with no apparent degradation of the final bonding interface, as indicated by reduced microleakage. Combined with the manufacturer’s recommended Fuji Coat LC varnish, microleakage was further reduced.

There are several potential reasons for differences observed in the amount of microleakage between the two restorative techniques. The RMGI became more packable, possibly allowing greater compaction of the filler particles and increased density of matrix material at the tooth-material interface. This condensability could contribute to a more immediate adherence of the material to tooth structure and earlier initiation of chemical bonding. The greater stability of the material due to increased viscosity may have reduced or prevented voids during placement.

Table 3: Fisher LSD Post Hoc Test

Fisher LSD Post Hoc Test		
Combination 1	Combination 2	p-Value
Precure (IPP)/Varnish	Control/Varnish	0.044
	Precure/Nonvarnish	<0.001
	Control/Nonvarnish	<0.001
Control/Varnish	Precure/Varnish	0.044
	Precure/Nonvarnish	<0.001
	Control/Nonvarnish	<0.001
Precure (IPP)/Nonvarnish	Precure/Varnish	<0.001
	Control/Varnish	<0.001
	Control/Nonvarnish	<0.001
Control/Nonvarnish	Precure/Varnish	<0.001
	Control/Varnish	<0.001
	Precure/Nonvarnish	<0.001
Abbreviations: IPP, initial partial polymerization; LSD, least significant difference.		

Of the 60 restorations representing the two restorative techniques, only four restorations exhibited no microleakage. Of these four restorations, all were from the Fuji Coat LC group, and three were from the experimental group with only one from the control group. The data also demonstrated a significant microleakage difference when comparing the occlusal margin with the cervical lesion. The cervical margin had significantly more microleakage, perhaps due to a variation of enamel, dentin, and possibly cementum along the margin despite efforts to keep the restorations above the cemento-enamel junction and in enamel. This potential factor has been noted in previous *in vitro* studies.^{18,28,29}

Use of a finishing varnish such as Fuji Coat can prevent early hydration or dehydration and is especially important during the first hour following placement of RMGI restorations.^{23,24} Water plays a key role in the acid-base reaction by acting as the

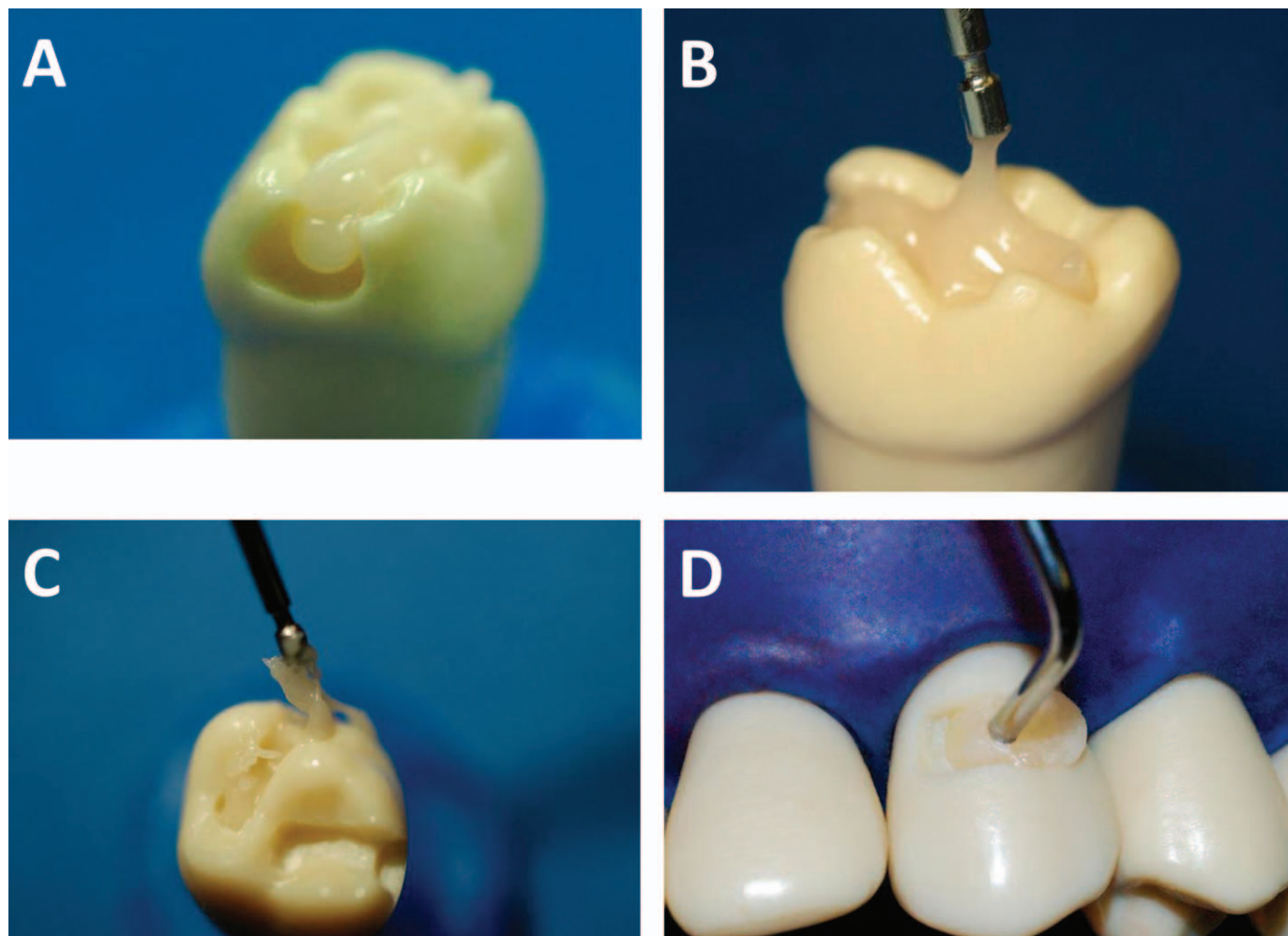


Figure 6. Restorative material shown (A) sagging after extrusion into a tooth preparation, (B) clinging to the placement instrument, (C) sticking to surfaces outside the preparation potentially capturing voids, and (D) being condensed more controllably into place after the IPP step.

medium for the reaction and is incorporated into the cement structure.²³ If the restoration is exposed to excessive water prior to hardening fully, the matrix-forming ions (Al and Ca) can be washed out and result in disintegration of the surface structure, discoloration, and increased surface roughness.²³ Dehydration of the material before it is fully set can result in shrinkage and crazing.²⁴ The dehydrated restoration is also more prone to staining and loss of adhesion.²⁴

One side effect of precuring Fuji II LC can be developing fine craze lines or a chalky, rough surface texture following contouring and manipulation. Placing a slight excess of material allows the practitioner to remove this layer, while finishing and polishing the restoration. Applying Fuji Coat LC after the restoration has been polished also fills in and repairs any surface defects that may have

existed. Final restorations using the IPP method were not distinguishable in appearance from those placed conventionally.

Individual practitioners would need to calibrate their light curing systems to determine the optimum length of time and light-tip proximity to achieve the desirable handling characteristics of a doughy, moderately packable state.

While this study was able to demonstrate that there may be significantly less microleakage following the experimental IPP protocol, future research might further describe the nature of the bonding interface between RMGI materials and tooth structure. Other studies could examine potential changes in surface wetting, density of material, depth of material penetration into the tooth structure, and changes to the ionic layer plus ionic crosslinks.

Investigations are also recommended to evaluate results of this technique in the actual clinical environment.

By employing the 1-second IPP step, Fuji II LC became easier to handle and manipulate during placement and was less prone to sagging or being drawn by gravity from the restorative preparation. It also resulted in apparently less microleakage than the manufacturer's currently specified instructions. This method used along with the recommended finishing varnish might help practitioners place light-polymerizable Fuji II material with greater control and possibly improved restorative integrity.

CONCLUSIONS

1. Initial partial polymerization of Fuji II LC is associated with less microleakage than placing the material without this step.
2. Applying Fuji Coat LC following finishing and polishing of the RMGI material results in significantly less microleakage.
3. The combination of controlled initial partial polymerization of Fuji II LC and using Fuji Coat LC produces significantly less microleakage than all other conditions tested.
4. Cervical margins of Fuji II LC restorations are more prone to microleakage than occlusal margins.

Acknowledgement

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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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***In Vitro* Evaluation of the Effect of Different Endodontic Sealers on Retentive Strength of Fiber Posts**

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Clinical Relevance

Eugenol-based sealers significantly reduced the bond strength of prefabricated fiber posts luted with resin cement.

SUMMARY

Purpose: There is limited information in the literature regarding the effect of different endodontic sealers on the bond strength of fiber posts luted with core buildup materials. The purpose of this study was to evaluate the

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effect of three different root canal sealers on the retentive strength of prefabricated fiber posts luted with a composite resin cement.

Materials and Methods: Fifty-four extracted single-rooted mandibular premolar teeth were prepared and randomly divided into three groups. The first two groups were obturated with gutta-percha and one of two eugenol-based root canal sealers (Endofil, Tubli-Seal). The third group (control) was obturated with gutta-percha and a resin-based root canal sealer (AH26). Prefabricated fiber posts were luted into the prepared post spaces with a composite resin cement (Multicore Flow). The pullout forces required for dislodgment of posts from their prepared post spaces were recorded. Data were collected and statistically analyzed.

Results: The AH26 group had significantly greater retentive strengths for the posts when compared with the Endofil and Tubli-Seal (eugenol-based sealers) groups ($p < 0.0001$).

There was no significant difference between the means of the retentive strengths for the Endofil and Tubli-Seal groups ($p=0.745$).

Conclusion: The chemical formulation of root canal sealers significantly affected the retentive strength for prefabricated fiber posts luted with a resin cement. Eugenol-based sealers significantly reduced the bond strength of prefabricated fiber posts luted with resin cement.

INTRODUCTION

The use of posts in endodontically treated teeth may be required in order to aid in the retention of a core and final coronal restoration.¹ The retentive capacity of the post is critical for the long-term survival of the final restoration.² Retention of a post can be influenced by its shape and design,³ its length and diameter, the type of luting agent used to cement it, the coronal tooth preparation after cementation, and the endodontic obturation sealer.⁴⁻⁶

With increasing demands for esthetic restorations, the use of tooth-colored endodontic posts have become more popular in recent years.⁷ Tooth-colored posts, such as fiber-reinforced posts, have been advocated in retaining the core restoration because of their purported favorable physical properties and biocompatibility.⁸

The influence of dental cements on post retention has been investigated.^{9,10} Fiber posts commonly are bonded into the root canals with the use of dual-polymerizing or self-polymerizing resin-based cements. Endodontic sealers are as influential as the luting medium in the loss of retention of the post.¹¹ Sealers based on epoxy resin are preferred because of their good physical properties and adequate biological performance.^{11,12} Calcium hydroxide-based endodontic sealers may stimulate a biological closure of the apical region, thereby increasing treatment success.¹³ Eugenol-containing sealers remain the most commonly used root canal sealer because of their long history of clinical success.¹⁴ However, eugenol, like all phenols, has considerable radical scavenging properties, and this is thought to inhibit composite resin polymerization.¹⁵⁻²³ There is little agreement between studies on whether this interaction is clinically relevant,^{15,16,18} and it is unclear if the presence of eugenol and other components of root canal sealers, remnants of pulp tissue, and/or a residual smear layer impair post retention.²⁴

MultiCore® Flow (Ivoclar Vivadent, Schaan, Liechtenstein) is a dual-polymerizing, fluoride-containing composite resin designed for core buildup restorations of vital and nonvital teeth and luting of fiber posts. It appears from the literature review that there is limited information regarding the effect of eugenol-based sealers on the bond strength of endodontic posts luted with core buildup materials. This *in vitro* study was undertaken to evaluate the influence of two eugenol-based root canal sealers (Endofil or Tubli-Seal) and a resin-based root canal sealer (AH26) on the bond strengths of prefabricated fiber posts luted with Multicore® Flow. The null hypothesis was that the type of root canal sealer used had no negative effect on the retentive bond strength of cemented fiber posts.

MATERIALS AND METHODS

Fifty-four extracted single-rooted, human permanent mandibular first premolars of approximately the same size were selected for this study. Radiographs were taken to ensure the presence of a straight, single main root canal and completely formed apex in each tooth. The teeth were stored in a container in 0.5% chloramine T at 4°C and used within six weeks after extraction. Teeth were sectioned 1 mm coronal to the midfacial cemento-enamel junction by using a low-speed diamond saw (Isomet 2000, Buehler Ltd, Lake Bluff, NY, USA) under copious water coolant.

The pulpal tissues were removed with a barbed broach of an appropriate size (Dentsply Maillefer, Ballaigues, Switzerland). Working length was established at 1 mm from the root apex. The canals were prepared with a rotary system (X-Smart, REF A 1004, Dentsply Maillefer) according to the manufacturer's instructions. Cleaning and shaping of the root canals were performed with Protaper Ni-Ti rotary instruments (sizes S1, S2, and S3, Dentsply Maillefer) following the crown-down technique. One milliliter of sodium hypochlorite (NaOCl; 5.25%) was reintroduced into each root canal after every instrument. After preparation, each root canal was irrigated with 2 mL of distilled water (pH 7), and the teeth were then randomly divided into three equal groups ($n=18$ in each group). The root canals were obturated with laterally condensed gutta-percha (Kerr/Sybron Corp, Romulus, MI, USA) and one of three different root canal sealers: AH26 (Dentsply DeTrey GmbH, Konstanz, Germany), an epoxy resin sealer that is free of eugenol; Endofil (Promedica, Neumünster, Germany), a sealer containing eugenol; and Tubli-

Seal (Kerr Italia S.p.A., Salerno, Italy), a sealer containing eugenol. All obturated teeth were then stored in 100% relative humidity at 37°C for seven days.

Gutta-percha was removed, and post spaces were prepared using a no. 5 peeso reamer (Pulpdent Corporation, Watertown, MA, USA) at low speed to a depth of 8 mm. Radiographs confirmed that 5 mm of the gutta-percha root canal obturation always remained in each specimen. A no. 6 parallel-sided Parapost twist drill (Parapost Black P-42, Whaledent International, New York, NY, USA) was then used at low speed to prepare standardized post spaces (1.5 mm diameter and 8 mm long), and 2 mL of 5.25% NaOCL irrigation was performed in each post space. After preparation, each post space was irrigated with 2 mL of distilled water (pH 7).

Parallel-sided, size 6 prefabricated fiber posts (PF-1716, ParaPost Fiber Lux, Coltene/Whaledent, Altstätten, Switzerland) were used. The Parapost posts were checked for a passive fit in their respective canals before luting. To maintain moistness, teeth were held in a gauze sponge soaked in saline throughout all root canal therapy and post space preparations. Carbide burs were used to notch the roots. Specimens were then mounted with autopolymerizing resin (Ortho Resin, Dentsply DeTrey) in a short length of PVC pipe, and a dental surveyor (J.M. Ney Co, Bloomfield, CT, USA) was used to orientate the post space to the vertical axis of the tooth.

After canal irrigation with the 5.25% NaOCL and then irrigation with the distilled water (pH 7), the canals were dried with absorbent paper points. The posts were then luted with Multicore® Flow (Ivoclar Vivadent), a dual-polymerizing resin cement. Acid etching of the root canal walls was performed with 37% phosphoric acid (Ivoclar Vivadent) for 15 seconds, followed by thorough water rinsing and removal of excess surface moisture with paper points. AdheSE (Ivoclar Vivadent) bonding material was applied to the canal using a microbrush for 10 seconds, and excess adhesive was removed using paper points. Finally, the luting cement material was applied directly from the tip of syringe into the prepared post space in the root canal. Each fiber post was also coated with the luting cement without any surface pretreatment and then inserted into the canal using slight pressure. Excess cement was removed and then light polymerized for 40 seconds. The posts remained passive in the canals during the setting of the cement.

Table 1: Means and Standard Deviations (SD) of Forces (Newtons) Required to Dislodge Posts ($n=18$)^a

Sealers	Mean $\pm$ SD
AH26	271.5 $\pm$ 78.4 A
Endofil	92.1 $\pm$ 31.8 B
Tubli-Seal	105.6 $\pm$ 45.3 B
^a Mean values designated with the same letter are not significantly different ($p>0.05$).	

The specimens were stored in 100% relative humidity at 37°C for 24 hours before testing. Each tooth specimen was vertically secured in the universal testing machine (Instron, Model 8500 Plus Dynamic Testing System, Instron Corp, High Wycombe, England). The force required to dislodge the post was determined using pneumatic grips that grasped the post head at its long axis. A constant loading rate of 0.5 mm/min was applied until cement failure was achieved. The peak force at the point of extrusion of the post segment from the test specimen was taken as the point of bond failure and was recorded in newtons (N).

Statistical Analyses

Statistical analyses of data were performed by using a statistical software package (SPSS v16.0, SPSS Corp, Chicago, IL, USA). A one-way analysis of variance (ANOVA) was applied to the mean retentive strengths of posts in canals with different sealers. A Tukey multiple comparison test was performed to determine which groups were significantly different. All statistical analyses were performed at a 0.05 level of significance ($\alpha=0.05$).

RESULTS

The means and standard deviations (SD) of the results are summarized in Table 1. The highest mean force needed to dislodge the post was recorded for the posts obturated with gutta-percha and AH26 sealer (271.5 N), while the lowest force was recorded for the group of Endofil sealer (92.1 N). One-way ANOVA demonstrated that there were significant differences between the three root canal sealers ($p>0.0001$). The Tukey multiple comparison test revealed statistically significant differences between the AH 26 group and Endofil group as well as between the AH26 group and the Tubli-Seal group ($p>0.0001$ and $p>0.0001$, respectively). However,

there was no significant difference with the post retention between the Endofil and Tubli-Seal groups ($p=0.745$).

DISCUSSION

Several studies have shown that the cementation of fiber posts with an adhesive resin cement provides better retention, less microleakage, and a higher resistance to tooth fracture.^{25,26} The present study assessed the influence of eugenol- and noneugenol-based root canal sealers on the retention of fiber posts cemented with MultiCore flow, a dual-polymerizing, filled, fluoride-containing composite resin designed for core buildup restorations of vital and nonvital teeth and luting of fiber posts.

All teeth were selected with relatively equal size and having the same canal configuration and a standardized post space was prepared for all canals. All post spaces were prepared with a relatively large ParaPost drill (1.5 mm in diameter), and all the posts were of the same size.

Retention of cemented fiber posts into prepared root canals relies on the interface resistance.^{9,10,27} It has been reported that resin-based root canal sealers were more effective in sealing root canals than the zinc oxide–eugenol-based sealers.¹¹ AH26 is claimed not to shrink during setting and to adhere to dentin, ensuring a permanent seal.¹¹

On the other hand, and despite their wide use, eugenol-based sealers (Endofil and Tubli-Seal) used for root canal obturation might cause a significant reduction in the adhesive effectiveness or modify the polymerized resin's surface,¹⁹ resulting in decreased bond strength of the resin cement. In addition, the phenolic components are free radical collectors and delay the polymerization reaction when interacting with resin.¹⁹ In the present investigation, the null hypothesis has been partially rejected since fiber posts cemented in canals filled with zinc oxide–eugenol-based sealers (Endofil and Tubli-Seal) presented the lowest tensile bond strength values, and no significant difference was found between the means of post bond strength for the Endofil and Tubli-Seal groups.

Although there is no consensus on the effect of eugenol on the polymerization of composite resin, some studies demonstrated that eugenol could inhibit the polymerization process.^{6,19,20} In the current study, higher mean bond strength values were needed for vertical dislodgment of the fiber posts luted after the AH26 sealer had previously

been used as part of the root canal obturation compared with those canals where Endofil and Tubli-Seal sealers had previously been used as part of the root canal obturation. In addition, Carvalho and others²¹ observed that a temporary sealing cement containing eugenol reduced the bond strength of adhesive systems. On the other hand, Hagge and others²² concluded that the chemical formulation of endodontic sealers did not affect significantly the retention of posts cemented with resin cements. Other authors have also reported that eugenol had no deleterious effect on resin cements.^{5,23}

The intracanal removal of the residual eugenol might be necessary to improve the effectiveness of the adhesion process. A previous study⁴ reported the negative effect of eugenol on the retention of posts cemented with Panavia cement; however, the irrigation of the canals with alcohol or acid conditioning restored the lost retention. This result was also verified by Schwartz and others⁵, who reported no changes in the bond strength of posts luted with Panavia cement in canals filled with eugenol and previously treated with acid. On the other hand, Hagge and others⁶ reported significant differences in groups treated with eugenol. Etching with 37% phosphoric acid has been found to be effective in restoring the retention that had been affected by eugenol.²⁸ The use of 37% phosphoric acid as the etching agent for most of the etch-and-rinse systems has been reported to eliminate the contaminated smear layer and results in demineralization of dentin to a depth of 9 to 10 μm . Studies have demonstrated that etch-and-rinse systems allow more effective bonding to the eugenol contaminated dentin surfaces, compared to the self-etch approach, due to the nonremoval of the sealer's debris entrapped within the smear layer. In the present study, there was no special canal treatment performed before post cementation, such as irrigation and disinfection with 70% ethanol, which might explain the reduced bond strength for the eugenol groups.

Tjan and Nemetz⁴ investigated the effect of eugenol-containing endodontic sealer on the retention of prefabricated posts cemented with an adhesive resin technique and found that the presence of eugenol within the root canal resulted in significant loss of retention. However, they also found that residual eugenol in the root canal could be removed without any effect on retention of the post by irrigating the canal with ethyl alcohol (ethanol) or etching with 37% phosphoric acid; irrigation with

ethanol produced more consistent and reliable results. A substitute for ethanol irrigation is to use a 10-second phosphoric-acid irrigation to remove residual eugenol and rinse and dry the canal of excess moisture using paper points and a micro-aspirator tip within the canal.⁴

Push-out tests lead to a shear stress, which is comparable to the stress under clinical conditions at the interface between dentin and luting cement, as well as between the post and luting cement.²⁹ Considering the relative weakness of the post-root bond, Goracci and others³⁰ noticed that the push-out test was a more reliable technique in the determination of bond strengths between fiber posts and post space dentin due to the high number of premature failures occurring during specimen preparation and due to the large data distribution associated with microtensile testing. Nonuniform stress distribution is a disadvantage of the push-out test when it is performed on thick root sections.³¹ To overcome this problem, original push-out test design was modified by slicing the posted root into 1-mm-thick specimens.³⁰ Therefore, this testing model was preferred for the present study to obtain two measurements for each third and to simplify calculations on the bonded area. The pullout test has been used by several studies to determine the values required to remove the post from the root canal.^{4,31-33} It can be assumed that the posts that exhibit the higher retentive values would be less likely to loosen when subjected to stress. In the current study, although teeth were selected with similar size and canal shapes and received standardized post preparations, a wide range of strengths and relatively large standard deviations were obtained for some of the groups. However, comparison of the values reported in some earlier studies dealing with the retention of root canal posts that used extracted human teeth also revealed wide ranges in their measurements.^{3,31,33} One possible explanation is that the size and shape of the root canals differ and/or the texture and properties of the inner surfaces of the root canals differ among the teeth used. This variability, however, also occurs in clinical situations. In addition, the diameter of the individual root canal preparation could affect how much of the canal was still covered with some eugenol-containing sealer. For example, if some AH26 remained in the canal around the post, then this would be more rigid than if some of either of the two eugenol-containing sealers were left filling that space.³³

Within the limitations of this study, it was determined that the type of root canal sealer affected the retention of a fiber post cemented with resin cement. The findings should be considered by clinicians. Controlled prospective long-term clinical trials evaluating the use of fiber posts luted with resin cements after the use of various root canal sealers would provide information to help address this dilemma.

CONCLUSIONS

Within the limitations of this study, it was concluded that prefabricated fiber posts luted with multicore flow resin in canals previously obturated with gutta-percha and eugenol-based sealers (Endofil and Tubli-Seal) had significantly reduced bond strength compared to fiber posts luted with the same resin cement in canals previously obturated with gutta-percha and AH26 resin sealer.

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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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Prolonged Curing Time Reduces the Effects of Simulated Pulpal Pressure on the Bond Strength of One-step Self-etch Adhesives

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Clinical Relevance

Prolonged light-curing procedures improve the bond strength of simplified self-etch adhesives, in particular when bonded to deep dentin in the presence of physiological pulpal pressure.

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SUMMARY

The aim of this study was to evaluate the effects of extended light-curing procedures on the microtensile bond strength (μ TBS) of one-step self-etch adhesives (1-SEAs) submitted to simulated pulpal pressure. Coronal deep-den-

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tin specimens were bonded using Clearfil S3 Bond (S3), Adper Easy Bond (EB), or G-Bond Plus (GB) following the manufacturers' recommendations and light-cured for 10 seconds or 40 seconds. The dentin-bonded specimens were stored in distilled water for 24 hours without pulpal pressure (control) or submitted to 20 cm H₂O simulated pulpal pressure for 24 hours. The specimens were cut into matchsticks and subjected to μ TBS testing. The data were statistically analyzed using the three-way analysis of variance and Tukey's tests ($p < 0.05$). Debonded sticks were investigated through scanning electron microscopy. EB obtained higher bond strengths than GB and S3. However, prolonged light activation (40 seconds) provided higher μ TBS for all adhesives when submitted to pulpal pressure. Conversely, pulpal pressure caused a drop in μ TBS in EB and S3 when light-cured for 10 seconds. A mixed failure mode was mainly attained for the control groups, whereas the specimens submitted to pulpal pressure failed in the adhesive mode. The μ TBS of GB was not affected by pulpal pressure when light-cured for 10 seconds. Adhesive was the most prevalent failure mode, except when light-cured for 40 seconds, which showed predominantly cohesive failure. Extended curing times improved the resistance of 1-SEAs to simulated pulpal pressure.

INTRODUCTION

One-step self-etch adhesives (1-SEAs) and two-step self-etch adhesives can be considered more user-friendly and less technique sensitive than classic three-step etch-and-rinse adhesives because there are fewer clinical application steps. Nevertheless, some of these simplified adhesives are affected by severe water permeability, especially when bonded in the presence of simulated pulpal pressure.¹ Conversely, multistep dentin bonding agents (DBAs) have shown lower permeability and bond strength reduction because of the application of a more hydrophobic solvent-free adhesive resin.^{2,3}

Direct water aging is considered a suitable degradation-promoting strategy to challenge resin-dentin bonds.⁴ However, in the presence of simulated physiological pulpal pressure, the water transudation through hybrid and adhesive layers may be increased and provide faster reduction in bond strength.^{5,6} This may also provide more polymer hydrolysis and plasticization, jeopardizing the long-

term durability of resin-dentin interfaces.^{7,8} Hence, the aging strategy based on the use of pulpal pressure is considered a reliable and an effective approach to challenge the resin-dentin bonds in a more relevant clinical situation.^{9,10}

It has been demonstrated that simplified 1-SEAs behave as permeable membranes^{11,12} because they contain large amounts of hydrophilic monomers and solvents to prevent phase separation and maintain the mixture in a stable solution over time. Nevertheless, because of their hydrophilic nature, these types of DBAs are more prone to water transduction,³ which compromises the polymerization ratio and the final degree of conversion.¹³⁻¹⁵

Researchers have suggested alternative strategies to improve the bonding performance of 1-SEAs, such as double adhesive application and/or the use of a more hydrophobic resin-bond layer.^{2,16,17} Although these procedures have shown great improvements in bonding, they convert the simplified DBAs into multistep bonding systems. Further clinical procedures to improve the performance of 1-SEAs are 1) agitation during application to improve the monomer infiltration,¹⁸ 2) use of a warm airstream to remove more solvent and water during the drying procedure,¹⁹ and 3) extended drying time to increase solvent evaporation.²⁰ However, there is little information on the effects of prolonged light-curing on the microtensile bond strength (μ TBS) of simplified DBAs applied on deep dentin in the presence of simulated pulpal pressure.

The objective of this *in vitro* study was to evaluate the bonding performance through μ TBS and scanning electron microscopy (SEM) failure pattern analysis of three 1-SEAs submitted to 24 hours of simulated pulpal pressure (20 cm H₂O) and light-cured in accordance with the manufacturer's recommendations (10 seconds) or with extended exposure time (40 seconds). The null hypothesis to be tested was that extended light-curing procedures have no effect on the μ TBS and failure pattern of 1-SEAs applied in the presence of simulated pulpal pressure.

MATERIALS AND METHODS

Sample Preparation

Sixty extracted caries-free human third molars (from patients aged 18–35 years) extracted for periodontal reasons under approval of the appropriate Research Ethics Committee (protocol 167/2009) were used in this study. The teeth were stored (4°C) in a 0.5% chloramine water solution for a period not exceeding two months.

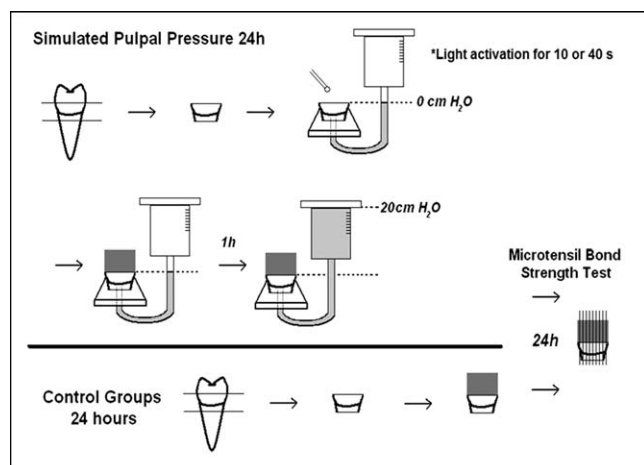


Figure 1. Experimental design (simulated pulpal pressure and control groups). Both groups were bonded without hydrostatic pulpal pressure. For pulpal pressure groups, the pressure was undertaken during 24 hours by using the classic method described by Sauro and others.¹¹

The roots were removed 1.5 mm below the cement-enamel junction (CEJ), and a parallel cut was made on the occlusal surface 1.5 mm above CEJ using a slow-speed water-cooled diamond saw (Isomet 1000, Buehler, Lake Bluff, IL, USA) to expose a deep dentin with a remaining dentin thickness (the dentin thickness between the flat occlusal surface and the pulpal wall on the highest pulp horn) of 0.9–1.0 mm. The dentin surface was wet-polished for 30 seconds with 600 grit SiC papers to create a flat surface with a standardized and more clinically relevant smear layer.

Subsequently, the specimens were randomly divided into 12 groups according to light-curing time (10 seconds or 40 seconds), DBA (Clearfil S3 [S3], Kuraray Medical Inc; G-Bond Plus [GB], GC Corporation; or Adper Easy Bond [EB], 3M-ESPE), and simulated pulpal pressure (no pulpal pressure for the control or 20 cm H₂O pulpal pressure) (Figure 1). The compositions, application procedures, and batch numbers are summarized in Table 1.

Bonding Procedures and Simulated Pulpal Pressure

The DBAs selected for this study were applied on the entire exposed dentin surface per manufacturers' recommendations (Table 1) and light-cured for 10 seconds (manufacturer's recommendation) or 40 seconds (prolonged time) at a standardized distance of 3 mm. A quartz-tungsten-halogen lamp (XL2500, 3M ESPE, St Paul, MN, USA) with 600 mW/cm² irradiance and emission in the 400–500 nm range was selected for the light-curing procedures as the

optimum wavelength for polymerization of an ideal light-curing system should lie within the 450–490 nm range for light-curable resin materials containing camphorquinone as the initiator.²¹ The irradiance was measured periodically with a calibrated Demetron Radiometer (Model 100, Demetron Research, Danbury, CT, USA). Composite build-ups (Filtek Z350, batch N124853, 3M-ESPE) were made in three or four layers (each layer 1–2 mm thick) to a height of 6 mm; each layer was light-cured for 40 seconds. Subsequently, half of the specimens were stored in distilled water at 37°C for 24 hours, and the remaining half of the specimens was submitted to simulated pulpal pressure (24 hours). All samples were bonded and restored with 0 cm H₂O water pressure.¹¹ The pulpal pressure was delivered one hour after the bonding procedures to simulate a clinical situation where local anaesthesia induces vasoconstriction and decreases the pulpal pressure.^{22,23}

The simulation of the pulpal pressure was undertaken following a previously published protocol.¹¹ Briefly, the crown segments were fixed using cyanoacrylate glue to a Plexiglas surface perforated by an 18-gauge stainless steel, which permitted communication between the pulp chamber and the hydraulic pressure device. For samples in simulated pulpal pressure groups, the hydraulic pressure device was filled with water to reproduce a pressure of 20 cm H₂O at the bonded dentin surface (Figure 1).

Microtensile Bond Strength

The samples were serially sectioned into slabs approximately 1-mm thick with a diamond saw (Isomet, Buehler) after the storage period. Each slab was further sectioned to produce resin-dentin matchsticks with approximately 1 mm² in cross-section. The matchsticks from the most peripheral area showing remnant enamel were excluded from the test.²⁴

The specimens were fixed to a jig using a cyanoacrylate glue (Super Bonder gel, Loctite, Henkel, Rocky Hill, CT, USA) in a universal testing machine (EZ-test, Shimadzu, Kyoto, Japan) and tested until failure under tensile tension (0.5 mm/minute). The cross-sectional area of each tested stick was measured with a digital micrometer after debonding. Means and standard deviations were calculated and expressed in megapascals. Five restored teeth (experimental unit, n=5) were evaluated in each group, the bond strength of the matchsticks from the same restored tooth were averaged, and the mean bond strength value was used for the statistical analysis. The μ TBS data were

Table 1: <i>Materials Composition and Application Procedures Used in Restorations</i>				
Materials	Composition	Application Procedure	Batch No.	Manufacturer
Clearfil S3 Bond (S3)	10-MDP, BisGMA, HEMA, dimethacrylates, photoinitiator	Apply adhesive for 20 s.	127A	Kuraray Medical, Tokyo, Japan
		Air-dry for 5 s to evaporate solvent.		
		Light cure for 10 s.		
Adper Easy Bond (EB)	HEMA, BisGMA, Vitrebond copolymer, methacrylated phosphoric ester, nanofiller, ethanol, water, photoinitiator	Apply adhesive for 20 s.	376899	3M ESPE, St Paul, MN, USA
		Air-dry for 5 s to evaporate solvent.		
		Light cure for 10 s.		
G-Bond Plus (GB)	4-MET, phosphate ester monomers, UDMA, acetone, water, microfiller, photoinitiator	Apply adhesive for 10 s.	1007061	GC Corporation, Tokyo, Japan
		Air-dry for 5 s to evaporate solvent.		
		Light cure for 10 s.		
Abbreviations: 4-MET, 4-methacryloxyethyl trimellitic acid; 10-MDP, 10-methacryloyloxydecyldihydrogenphosphate; BisGMA, bisphenol A glycidyl methacrylate; HEMA, hydroxyethyl methacrylate; UDMA, urethane dimethacrylate.				

statistically analyzed using three-way analysis of variance (ANOVA; DBA, pulpal pressure, and light-curing time) to identify differences among groups. Statistical differences were compared using Tukey’s test ($p<0.05$).

Analysis of Fracture Pattern

The failure pattern was verified after the μ TBS test using a stereomicroscope at 60 $\times$ magnification. Ten representative fractured dentin and composite surfaces from each group, those exhibiting the most frequently observed failure pattern and the μ TBS close to the mean, were processed for SEM. The specimens were placed on aluminum stubs, gold-coated (Balzers model SCD 050 sputter coater, BAL-TEC Aktiengesellschaft, Balzers, Liechtenstein), and examined using an SEM (JEOL JSM-5600LV, Tokyo, Japan) operated at 15 kV in secondary electron mode. The failures were classified as follows: adhesive failure (A); mixed failure (M); cohesive failure in composite (C); cohesive failure in dentin (D).

RESULTS

Three-way ANOVA showed that the three factors (dentin bonding agent, pulpal pressure, light-curing time) were statistically significant ($p<0.001$). The

interactions were also statistically significant ($p<0.001$), but not for the interaction of the three factors ($p=0.211$). Mean values of μ TBS (in megapascals) and standard deviations are shown in Table 2. Each bonded tooth yielded 15–20 matchsticks for the μ TBS survey. The specimens that received extended light-curing time (40 seconds) attained significantly higher bond strengths than those light-cured for 10 seconds ($p<0.001$). The only exception was when S3 and EB were not subjected to simulated pulpal pressure. Simulated pulpal pressure induced bond-strength reductions for S3 and EB when light-cured for 10 seconds ($p=0.002$), but not for S3 and EB when light-cured for 40 seconds ($p=0.113$). The bond strength of specimens bonded using GB and light-cured for 10 seconds were not affected by pulpal pressure ($p=0.207$).

The percentages of failure pattern from debonded specimens are shown in Table 3, and some representative images are presented in Figures 2, 3, and 4. Groups without simulated pulpal pressure presented a predominance of mixed failures (Figures 2A,B and 3A,B), and groups with simulated pulpal pressure showed more adhesive failures for the hydroxyethyl methacrylate (HEMA)–rich adhesives EB and S3. For GB, the predominant fractures were adhesives (Figure 4A,B), except in the group of GB light-cured for 40 seconds and subjected to simulated

Table 2: Means (Standard Deviations) of Microtensile Strength (MPa) of DBA Photoactivation Time^a

DBA	No Pulpal Pressure	20 cm H ₂ O Pulpal Pressure
S3 (10 s)	41.4 (3.9) ^{A,a}	34.7 (4.5) ^{B,b}
S3 (40 s)	45.9 (4.3) ^{A,a}	44.7 (6.3) ^{A,a}
EB (10 s)	52.1 (4.2) ^{A,a}	42.2 (3.4) ^{B,b}
EB (40 s)	52.5 (4.7) ^{A,a}	49.6 (3.5) ^{A,a}
GB (10 s)	31.2 (5.6) ^{B,a}	29.9 (3.0) ^{B,a}
GB (40 s)	49.3 (4.3) ^{A,a}	45.6 (4.7) ^{A,a}

^a Different capital letters in columns represent statistically significant differences between the light activation times ($p < 0.05$). Different lowercase letters in rows represent statistically significant difference between absence and presence of simulated pulpal pressure ($p < 0.05$). The differences among DBAs are presented only in the Results section to facilitate the comparison of photoactivation times and presence of simulated pulpal pressure. Abbreviation: DBA, dentine bonding adhesive; EB, Adper Easy Bond; GB, G-Bond Plus; S3, Clearfil S3 Bond.

pulpal pressure in which the predominant failures were cohesive in composite (Figure 4C,D). Regarding groups submitted to hydrostatic pulpal pressure bonded with S3 and EB (10 seconds and 40 seconds), failures in 10-second groups mainly occurred between the adhesive layer and resin composite (Figures 2C and 3C). Conversely, the 40-second groups mostly presented fractures between the hybrid layer and adhesive layer or into the hybrid layer (Figures 2D and 3D).

DISCUSSION

It is well known that simplified 1-SEAs have an intrinsic ability to absorb water in wet environments because of the high amount of hydrophilic monomers (ie, HEMA) and solvents (eg, water, ethanol, or acetone) contained within their composition.^{2,16} This particular ability to absorb a drastic amount of water also induces an important fluid transudation within the resin-dentin interface, which contributes to degradation of the hybrid layer.^{3,25,26} Indeed, hydrophilic monomers such as HEMA are able to imbibe large amounts of water, which jeopardizes the mechanical properties of the polymers,²⁷ such as the modulus of elasticity,²⁸ and the ultimate tensile strength.²⁹ Additionally, the degree of conversion of HEMA-containing 1-SEAs is reduced because of the intrinsic water entrapped within the polymer network during evaporation procedures.¹⁴ These factors

Table 3: Fracture Type After Microtensile Bond Strength

Groups	Fracture Type (%) ^a			
	A	M	C	D
S3 + 10 s + no pulpal pressure	30	37	26	7
S3 + 10 s + pulpal pressure	46	31	23	0
S3 + 40 s + no pulpal pressure	23	47	24	6
S3 + 40 s + pulpal pressure	55	39	5	1
EB + 10 s + no pulpal pressure	38	55	7	0
EB + 10 s + pulpal pressure	61	39	0	0
EB + 40 s + no pulpal pressure	29	57	14	0
EB + 40 s + pulpal pressure	53	41	6	0
GB + 10 s + no pulpal pressure	64	36	0	0
GB + 10 s + pulpal pressure	78	22	0	0
GB + 40 s + no pulpal pressure	42	34	15	9
GB + 40 s + pulpal pressure	25	31	39	5

^a Type A, adhesive failure; type M, mixed failure; type C, cohesive failure in resin composite; type D, cohesive failure in dentin. Abbreviations: EB, Adper Easy Bond; GB, G-Bond Plus; S3, Clearfil S3 Bond.

may justify the drop in bond strength attained in the specimens created with the EB and S3 light-cured for 10 seconds and submitted to pulpal pressure. In contrast, the specimens created with GB (HEMA-free adhesive) and light-cured for 10 seconds showed no bond strength reduction after 24 hours of pulpal pressure. The absence of HEMA within the composition of GB may have provided less immediate water sorption/transudation,³⁰ greater polymerization,¹⁴ and more cross-linked polymer chains²⁶ along with the usage of the more volatile solvent acetone; this may have reduced the negative effects of pulpal pressure on the bond strengths.

The extrinsic water uptake is more evident in deep dentin, which is a highly permeable substrate and may supply excessive amounts of water to polymerized adhesives after the vasoconstrictive effect of local anesthetic solutions.³¹ Therefore, deep dentin

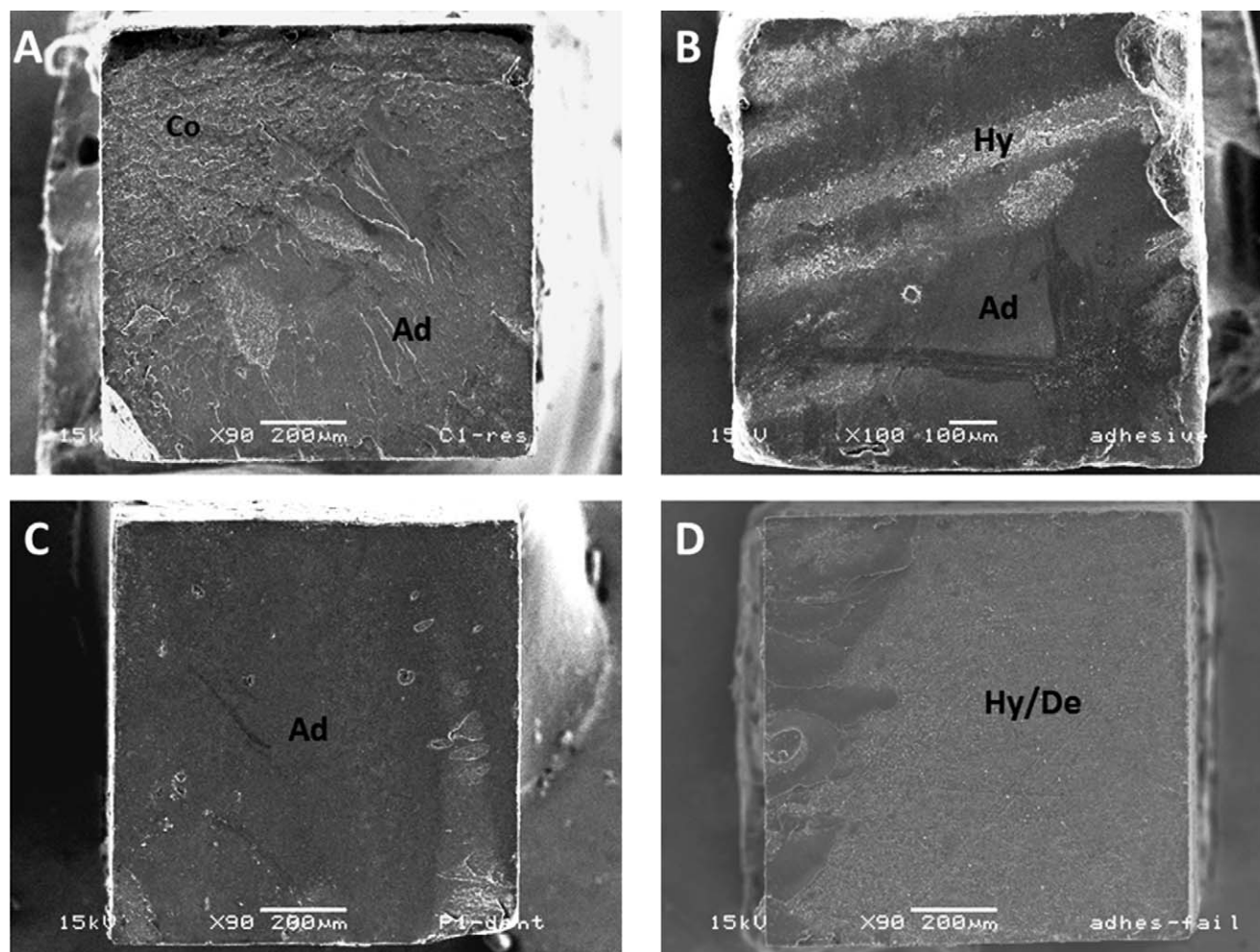


Figure 2. Representative SEM images showing the most frequent failure modes of S3. (A): Group control with 10-second light activation. A mixed failure among hybrid layer, adhesive layer, and resin composite may be observed. (B): Group control with 40-second light activation. The micrograph shows a mixed failure between hybrid layer and adhesive layer (the predominant failure mode). (C): Group with 10-second light activation subjected to simulated pulpal pressure. The image shows an adhesive failure between the adhesive layer and resin composite (failure often observed in this group). (D): Group subjected to pulpal pressure and 40-second light activation. Note the adhesive failure between the dentin and hybrid layer, with slight vestiges of adhesive layer (predominant failure observed in this group). Abbreviations: Ad, adhesive resin; Hy, hybrid layer; Co, resin composite; De, dentin.

with a mean thickness of 0.9 mm is currently chosen as the remaining dentin thickness for permeability and pulpal pressure investigations; it results in a suitable substrate for testing more permeable DBAs.^{3,11,32-35}

The results of this study showed that the prolonged light-curing time (40 seconds) may improve bonding performance of 1-SEAs and provide higher bond strength in presence of pulpal pressure (Table 2). These findings are in accordance with previous studies that showed a positive correlation between pulpal pressure and μ TBS.^{3,11,21}

In Table 2, it is possible to observe (control groups) that the bond strength of S3 and EB did not increase with prolonged curing time, whereas the bond

strength of GB significantly increased. This may be explained with the different solvents in the adhesive composition.^{13,15} For S3 and EB, the solvents are water/ethanol, while for GB they are acetone/ethanol. Indeed, with a prolonged light-curing, the evaporation of solvents (components that jeopardize the polymerization) is improved for acetone-based adhesive, which has a higher vapor pressure, but not for the ethanol-based adhesives with lower vapor pressure. For the latter adhesives, a longer time may be necessary to achieve more evaporation of solvents and an increase in bond strength.

Furthermore, the improvements observed when extended light-curing time was used also corroborate with previous findings^{15,36} that showed that pro-

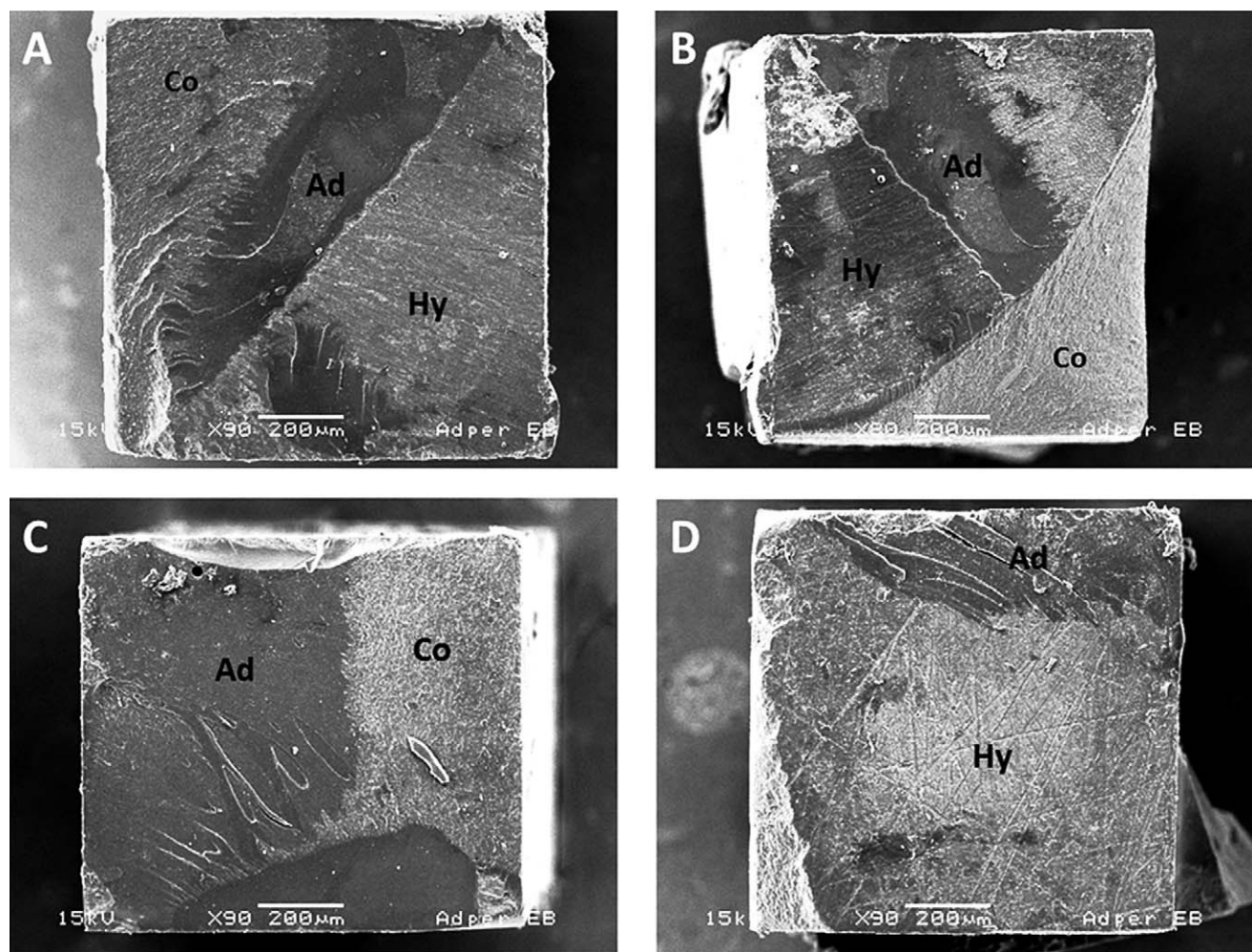


Figure 3. Representative SEM images showing the most frequent failure modes of EB. (A): Group control with 10-second light activation. A mixed failure among hybrid layer, adhesive layer, and resin composite may be observed. (B): Group control with 40-second light activation. The micrograph reveals the resin side of fractured stick, showing mixed failure between hybrid layer, adhesive layer, and partial cohesive failure in resin composite. (C): Group with 10-second light activation subjected to simulated pulpal pressure. The image shows an adhesive failure between adhesive layer and composite resin with slight vestiges of resin composite (failure often encountered in this group). (D): Group subjected to pulpal pressure and 40-second light activation. Note the adhesive failure between the dentin and hybrid layer, with vestiges of adhesive layer. Abbreviations: Ad, adhesive resin; Hy, hybrid layer; Co, resin composite.

longed photopolymerization exceeding 40 seconds improves the degree of conversion, creates a more homogeneous and less porous polymer network, and decreases the adhesive permeability and interface nanoleakage of 1-SEAs.^{15,36} Indeed, prolonged curing times may improve the physicochemical properties (such as modulus of elasticity, water sorption, and solubility) because of the higher degrees of conversion and more cross-linked polymeric structure.

The results of this study also showed that subjecting specimens to pulpal pressure had a detrimental effect on bond strength for EB and S3, in particular when light-cured for 10 seconds. Pulpal pressure may have promoted water seepage through

the adhesive layer to the composite interface (Figures 2C and 3C) because of the osmotic pressure created by uncured monomers at the interface.³⁷ This may explain the predominance of failures between the adhesive layer and resin composite for EB and S3 in groups light-activated for 10 seconds and submitted to pulpal pressure (Figures 2A and 3A,B).

Conversely, HEMA-rich adhesive systems (EB and S3) light-cured for 40 seconds and subjected to pulpal pressure showed, under SEM analysis, a few failures between adhesive layer and resin composite (Figures 2D and 3D). This confirms that an extended photoactivation of 1-SEAs may diminish the adhesive permeability and the fluid accumulation be-

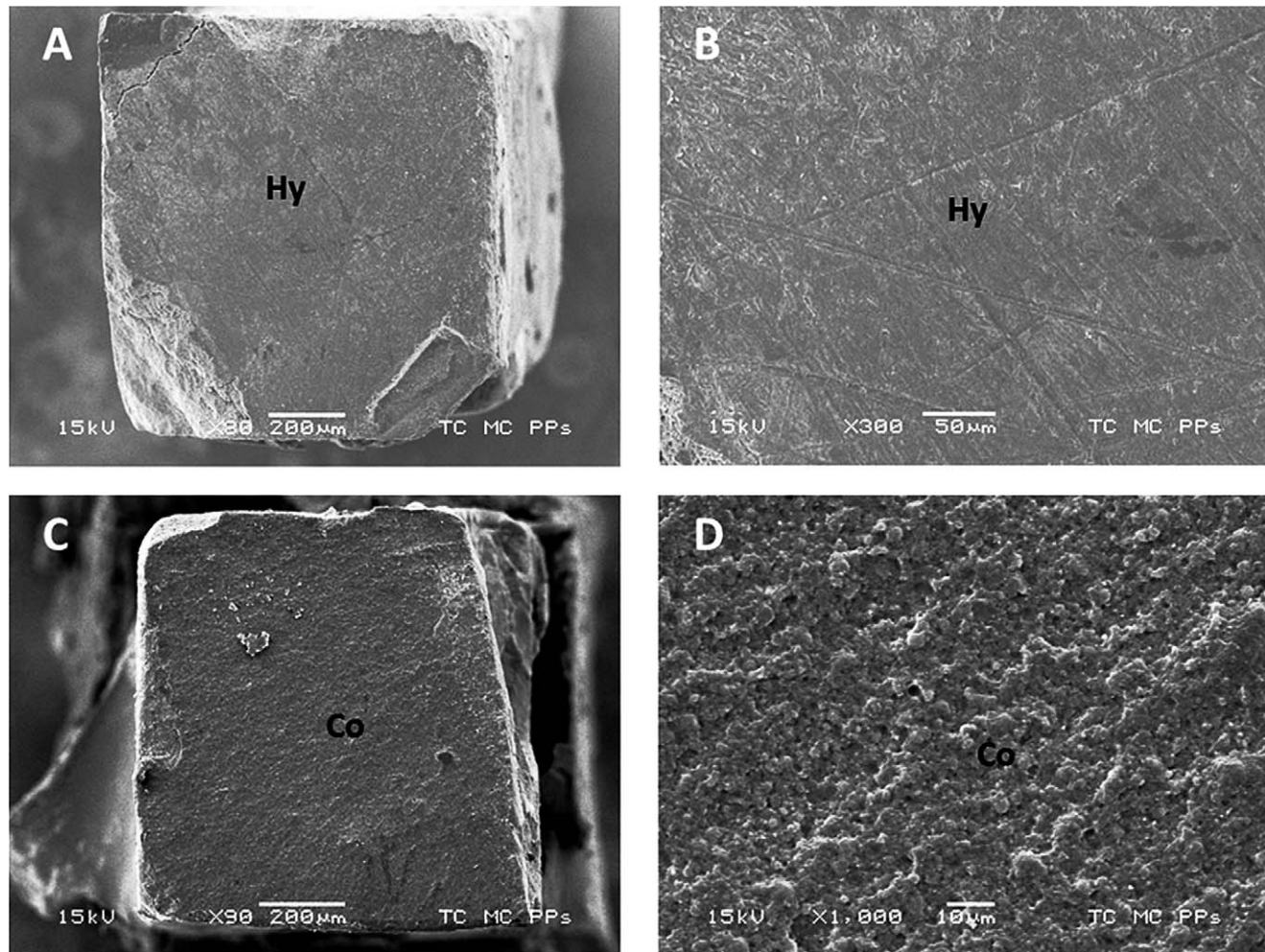


Figure 4. Representative SEM images showing the most frequent failure modes of GB. (A): Debonded stick from group control with 40-second light activation. A mixed failure among the hybrid layer, adhesive layer, and resin composite may be observed. (B): High magnification of A. The micrograph reveals the resin side of fractured stick, showing adhesive failure in the hybrid layer. Note the vestiges of SiC abrasion undertaken before the bonding procedures. (C): Debonded stick from the group with 40-second light activation subjected to 24-hour simulated pulpal pressure. The image shows a cohesive failure in composite resin (predominant failure in this group). (D): High magnification of C. Note the absence of adhesive resin and hybrid layer vestiges. Abbreviations: Hy, hybrid layer; Co, resin composite.

tween the adhesive layer and resin composite.^{15,36} However, remarkable differences were found between adhesives, light-curing times, and presence of pulpal pressure; therefore, the study hypothesis has to be rejected.

CONCLUSION

In conclusion, under the conditions of this study, 24 hours of simulated pulpal pressure had an adverse effect on μ TBS with 10 seconds of photoactivation time, especially for the HEMA-containing adhesives. No difference was encountered when the adhesives were light-cured for 40 seconds. Extended light-curing should be recommended to improve bonding performance of 1-SEAs, especially when bonded in

vital deep dentin and in presence of simulated pulpal pressure.

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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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Effect of Operator Experience on the Outcome of Fiber Post Cementation With Different Resin Cements

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Clinical Relevance

RelyX U100 (commercially available outside Brazil as RelyX Unicem) was shown not to be affected by the operator's experience and therefore seems to be more suitable for use by less experienced clinicians.

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SUMMARY

Objectives: To evaluate the influence of operator experience (dentist vs student) and cementation system (Adper Scotchbond Multi-Purpose [SBMP] + RelyX ARC [1]; Adper Single Bond 2 [SB] + RelyX ARC [2] and RelyX U100 [3]) on the push-out bond strength (BS) of fiber post to radicular dentin.

Materials and Methods: The roots of 48 extracted human maxillary central incisors were prepared and divided into six groups (n=8), according to combination of the above factors. Glass fiber posts were cemented in accordance with the instructions of the manufacturer of each cementation system. After water storage at 37°C for one week, the roots were cross-sectioned into six 1-mm thick slices and the push-out test was performed (0.5 mm/min). Data were statistically analyzed by two-way analysis of variance and Tukey tests ($\alpha=0.05$). The BS results obtained by dentist and student

for each cementation system were compared using the Student *t*-test ($\alpha=0.05$).

Results: Higher BS means were observed for the expert operators, irrespective of the cementation system used ($p=0.006$). RelyX U100 showed the highest bond strength, but it did not differ from SBMP + RelyX ARC. The Student *t*-test revealed that only RelyX U100 was not affected by the operator's experience.

Conclusion: Within the limitations of this *in vitro* study, it can be concluded that the self-adhesive cement RelyX U100 showed the highest bond strength to the root canal in the student's group, and its performance was not affected by the operator's experience.

INTRODUCTION

Teeth with extensive loss of dental structure frequently require endodontic treatment, and in the majority of cases, this leads to the use of intraradicular retainers and filling cores to retain the final restoration.¹ Moreover, to restore these teeth, an interesting option has been to use materials with a modulus of elasticity similar to that of dentin resulting in biomimetism between the properties of dentin and the post/cement set. This favors a more uniform stress distribution in the root structure and thus reduces the risk of root fractures.²⁻⁴ However, bonding posts to root walls is compromised by many factors such as timing of post space preparation and cementation,⁵ type of post and its adaptation to the post space,^{6,7} type of adhesive and cementation system,^{8,9} and operative procedures.¹⁰ Furthermore, it is difficult to achieve direct irradiation by light in deep regions of the root canal, and to overcome this, it is necessary to use resin cements with chemical or dual activation.¹¹

As this procedure is technically complicated, the operator's experience may directly affect the quality of this restorative procedure. It has indeed been proved that there is a variability in the results of adhesive procedures resulting from the operator.^{12,13} Other authors have demonstrated that failure to follow the manufacturers' recommendations also affects the bond strength results.^{14,15} Nevertheless, there is little related information in the literature, on how the operator's experience may influence the success or failure of procedures for adhesive cementation of intraradicular posts.¹⁶

One may hypothesize that materials/techniques with fewer bonding steps may be less sensitive to technique variables. Differently from the traditional

resin cements, self-adhesive materials require no previous treatment of the dental substrate, since the stages of acid etching and adhesive system application have been eliminated.¹⁷ Based on this, the aim of this study was to evaluate the influence of the operator's experience and three different cementation systems on the push-out bond strength to dentin. Two null hypotheses were tested: 1) no significant difference would be detected among the push-out bond strengths to dentin produced by different cementation systems, and 2) the operator's experience would not affect the push-out bond strength to dentin for different cementation systems.

MATERIALS AND METHODS

Forty-eight extracted human maxillary central incisors were stored in distilled water at 4°C and used within 6 months after extraction (ISO/TS 11405).¹⁸ The inclusion criteria were absence of root caries and cracks, absence of restorations and previous endodontic treatments, posts or crowns, absence of severe root curvatures, and a root length measured from the cemento-enamel junction (CEJ) of 14 ± 1 mm.

Specimen Preparation

Teeth were cross-sectioned immediately below the CEJ using a low-speed diamond saw (Isomet 1000, Buehler, Lake Bluff, IL, USA). A crown-down technique was used for instrumentation with Gates Glidden drills No. 2 to No. 4. Apical enlargement was performed to size 40 and .06 taper. Roots were dried with paper points, filled with AH Plus (DeTrey, Dentsply, Konstanz, Germany) and tapered gutta-percha points, using the warm vertical condensation technique. The root access was temporarily filled with Vitro Fil (DFL, Rio de Janeiro, RJ, Brazil). The roots were stored for one week at 37°C in 100% humidity.

After one week, the gutta-percha was removed, leaving 4 mm of the apical seal. The post space was then prepared with a low-speed bur provided by the post manufacturer (Tenax Fiber Trans Drills, Coltène/Whaledent, Cuyahoga Falls, OH, USA) up to a fixed depth of 10 mm from the CEJ. One bur was used for only five preparations. All specimens were prepared by one experienced operator in a standardized procedure. The canals were irrigated with 10 mL of distilled water and dried with paper points. To make sure that there was no residual gutta-percha on the walls of the post space preparation, a radiographic evaluation was performed (Figure 1).

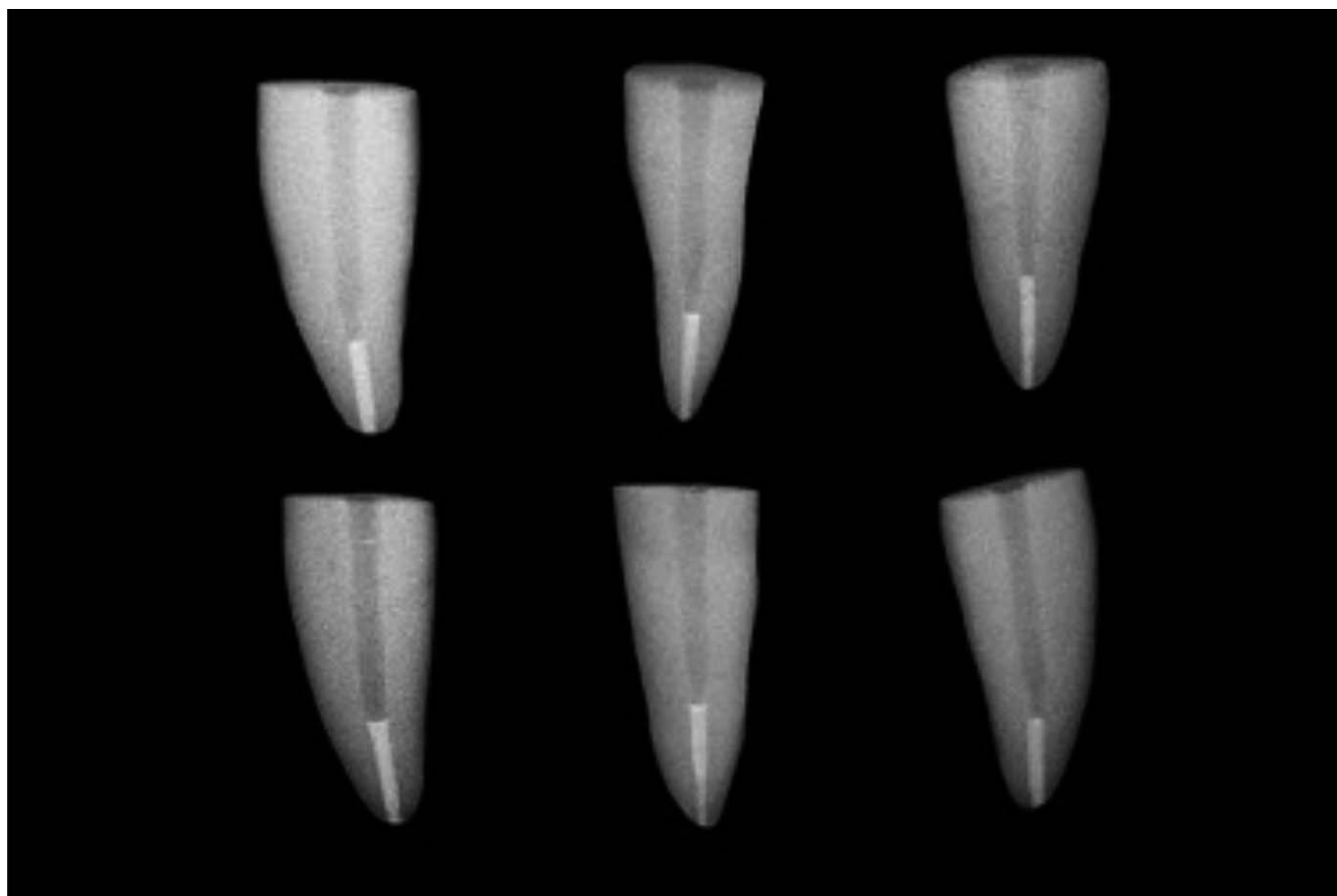


Figure 1. Radiographic evaluation of the radicular canals.

Six experimental conditions resulting from the combination of the main factors, operator experience (two levels) and cementation system (three levels), were evaluated. Expert dentists (eight dentists specialized in Restorative Dentistry) and undergraduate students (eight undergraduate students in the fourth year of the course) were selected to perform the fiber post cementation. Students from the fourth undergraduate year were selected because they had been taught restorative dentistry one year earlier and had learned to perform fiber post cementation procedures. They were given the three cementation systems shown in Figure 2. Three glass fiber posts, one of each material, were luted by each operator. Before cementation procedures, each glass fiber post (cylindrical with tapered end [Tenax Fiber Trans Esthetic Post System, Coltène/Whaledent]) was marked at a distance of 13 mm from the apical end and was horizontally sectioned at this point, using a water-cooled diamond rotary cutting instrument. Ten millimeters of the post were cemented inside

the root canal, while the other cervical 3 mm served as a guide to standardize the distance of the light curing device from the cervical root region. The posts were tried in, cleaned with alcohol, and cemented in accordance with the instructions provided by the manufacturer of each cementation system described in Table 1, which were given to all operators, who were instructed to follow them strictly. All bonding procedures were performed on the same mannequin, with the purpose of simulating a clinical setting. The composition of the materials used for the cementation procedure is described in Table 2.

The adhesive systems (Table 1) were applied by means of microbrushes (Vigodent, Rio de Janeiro, RJ, Brazil), and the resin cements were applied with a Centrix syringe (DFL, Rio de Janeiro, RJ, Brazil). A LED light curing device (L.E.Demetron I/Kerr Corporation, Orange, CA, USA) was used for activation purposes (800 mW/cm^2). Specimens were then stored in water at 37°C for one week.

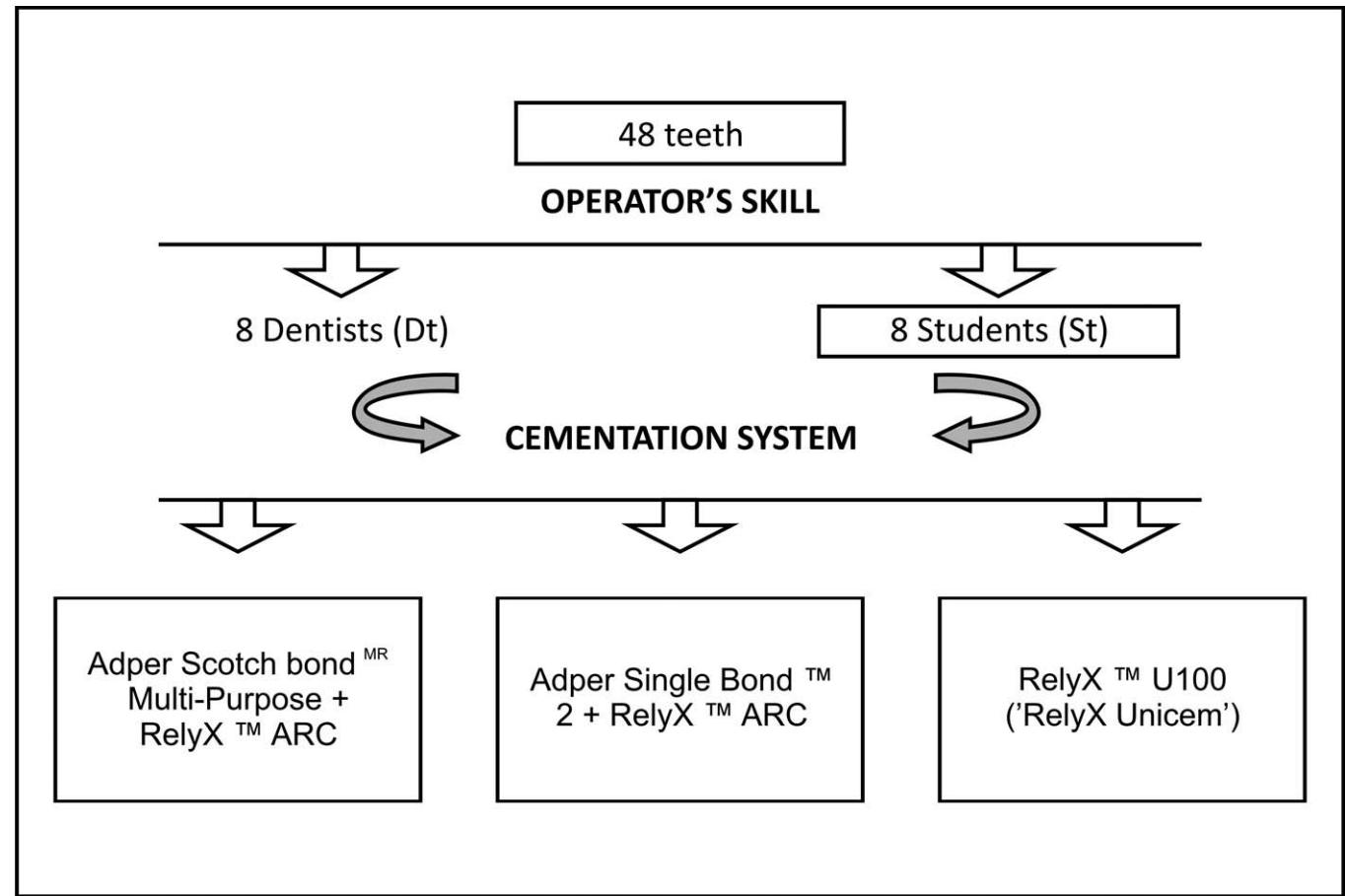


Figure 2. Experimental flowchart.

Preparation of Sections for Push-Out Bond Strength Test

After this, the roots were embedded in polyvinyl chloride tubes using acrylic resin, and the portion of each root was sectioned perpendicular to the long axis into six 1-mm serial slices. Subsequently, all specimens were observed with a light stereomicroscope at 10× magnification to discard slices with artifact defects.

The coronal side of each slice was identified and its thickness measured with a digital caliper (Mitutoyo, Tokyo, Japan). Images from both sides of the slides were recorded with an optical microscope (Olympus, model BX 51, Olympus, Tokyo, Japan) at 40× magnification to measure the coronal and apical post diameters and allow the bond area to be calculated using UTHSCSA ImageTool 3.0 software (Department of Dental Diagnostic Science at The University of Texas Health Science Center, San Antonio, TX, USA).

Each slice was subjected to a push-out test using a universal loading device (AG-I, Shimadzu Autograph, Tokyo, Japan) at 0.5 mm/min with the load applied in the apical-coronal direction until the post was dislodged. The maximum failure load was recorded in Newton (N) and converted into MPa by dividing the applied load by the bonded area (S_L). The latter, being the lateral surface of a truncated cone, was calculated by the formula: $S_L = \pi(R + r)[(h^2 + (R - r)^2)^{0.5}]$, where $\pi = 3.14$, R = coronal post radius, r = apical post radius, and h = root slice thickness.

Failure Mode Analysis

The failure modes of all specimens were evaluated under a stereomicroscope (40× magnification), and approximately 30% of the specimens from each group were randomly selected and processed for scanning electron microscopy (SEM) evaluation. Slices were rinsed in a 95% alcohol solution for one minute, air-dried, mounted on a metal stub and

Table 1: Bonding Procedures

Cementation System/ Manufacturer/ Abbreviation	Mode of Application (Batch Number)
Adper Scotchbond Multi-Purpose/3M ESPE + RelyX ARC/3M ESPE (SBMP + ARC)	1) Apply 35% phosphoric acid (lot: 7KU) for 15 s; 2) rinse with water for 15 s followed by air drying (2 s); 3) remove excess moisture with a paper point; 4) apply activator (lot: 7KY) of the adhesive system in canal and remove excess with air drying (5 s); 5) apply primer (lot: 7BJ) of the adhesive system in canal and remove excess with air drying (5 s); 6) apply catalyst (lot: 7BA) of the adhesive system in canal; 7) dispense cement (lot: GN8JA) onto a mixing pad and mix for 10 s; 8) apply cement in and around canal; 9) place a thin layer of mixed cement on post and seat the post; 10) remove excess cement while holding post in place; and 11) light-polymerize for 40 s from an occlusal direction.
Adper Single Bond 2/3M ESPE + RelyX ARC/3M ESPE (SB + ARC)	1) Apply 35% phosphoric acid (lot: 7KU) for 15 s; 2) rinse with water for 15 s followed by air drying (2 s); 3) remove excess moisture with a paper point; 4) apply two consecutive coats of the adhesive (9WH) in canal and remove excess with air drying (5 s); 5) remove excess (if any) with a dry paper point; 6) light-polymerize for 10 s; 7) dispense cement (lot: GN8JA) onto a mixing pad and mix for 10 s; 8) apply cement in and around canal; 9) place a thin layer of mixed cement on post and seat the post; 10) remove excess cement while holding post in place; and 11) light-polymerize for 40 s from an occlusal direction.
RelyX U100 (RelyX Unicem)/3M ESPE (U100)	1) Irrigate the canals with NaOCl 2.5% and with distilled water; 2) remove excess moisture with a paper point; 3) dispense cement (338618) onto a mixing pad and mix for 20 s; 4) apply cement in and around canal; 5) place a thin layer of mixed cement on post and seat the post; 6) remove excess cement while holding post in place; and 7) light-polymerize for 20 s from an occlusal direction.

sputter-coated with gold-palladium (Polaron SC7620, Quorum Technologies Ltd, East Sussex, UK) for five minutes at 10 mA. Each specimen was examined by SEM (JSM 6360LV, Jeol Ltd, Tokyo,

Japan) at a 15-kV accelerating voltage at different magnifications (40× to 200×) and photographs were taken. Two independent operators evaluated the failure modes according to the following criteria: 1)

Table 2: Composition of the Materials

Material	Composition
Adper Scotchbond Multi-Purpose (SBMP)	Activator: ethanol-based solution of a sulfinic acid salt and a photoinitiator component.
	Primer: aqueous solution of HEMA (hydroxyethyl methacrylate) and polyalkenoic acid copolymer.
	Catalyst: HEMA and Bis-GMA (bisphenol-A-glycidyl methacrylate).
Adper Single Bond 2 (SB)	Bis-GMA, HEMA, dimethacrylates, ethanol, water, photoinitiator system, and a methacrylate functional copolymer of polyacrylic and polyitaconic acids.
RelyX ARC (ARC)	Paste A: Bis-GMA, triethyleneglycol dimethacrylate, zircon/silica filler, photoinitiators, amine, pigments.
	Paste B: Bis-GMA, triethyleneglycol dimethacrylate, benzoic peroxide, zircon/silica filler.
RelyX U100 (U100)	Paste base: glass fiber, methacrylated phosphoric acid esters, dimethacrylates, silanated silica, sodium persulfate.
	Paste catalyst: glass fiber, dimethacrylates, silanated silica, p-toluene sodium sulfate, calcium hydroxide.

Table 3: Means and Standard Deviations (MPa) of Push-Out Bond Strength Values for the Experimental Groups

Cementation System	Operator		Student <i>t</i> -Test*
	Dentist (A)	Student (B)	
SBMP + ARC (a,b)	13.2 ± 8.2	10.3 ± 6.6	≠
SB + ARC (b)	11.3 ± 6.7	8.3 ± 7.0	≠
U100 (a)	14.4 ± 7.9	13.3 ± 6.7	=
* Similar lowercase letters indicate statistically similar means within each row. Similar capital letters indicate statistically similar means within column. Symbol ≠ indicates different means for each cement; symbol = indicates similar means.			

adhesive failure between dentin and luting cement, 2) adhesive failure between luting cement and post, 3) cohesive failure within luting cement, 4) cohesive failure within the post, 5) cohesive failure within dentin, and 6) mixed failure.

Statistical Analysis

The mean bond strength (BS) (MPa) of all slices originating from the same tooth was first averaged in order to provide one mean for each tooth. These values were then evaluated by a two-way analysis of variance (ANOVA) and Tukey test ($\alpha=0.05$) for pairwise comparisons.

A second statistical analysis with a more powerful statistical test was performed to evaluate the effect of the operator's experience on the BS data of each cementation system, which was compared using the Student *t*-test ($\alpha=0.05$). Thirdly, the pairwise comparison of the fracture patterns was analyzed by Fisher exact test ($\alpha=0.05$).

RESULTS

None of the specimens observed presented artifacts caused by the sectioning procedure; therefore, all slices were tested. The mean cross-sectional areas ranged from 3.0 to 6.0 mm², and no difference was detected among groups ($p>0.05$).

The main factors operator experience and cementation system ($p=0.006$ and $p=0.0006$, respectively) were significant. Higher push-out BS means (MPa) were observed for expert operators (12.9 ± 7.6) in comparison with the undergraduate students (10.6 ± 6.7) (Table 3) irrespective of the cementation system used ($p=0.006$). With regard to the cement,

Table 4: Distribution of the Fracture Pattern (%) Among the Different Experimental Groups

Cementation System	Operator			
	Expert Dentist		Student	
	Adhesive Dentin-Cement	Mixed	Adhesive Dentin-Cement	Mixed
SBMP + ARC	73	27	23	77
SB + ARC	60	40	47	53
U100	13	87	23	77
^a No cohesive failure in dentin and post or adhesive failure between cement and the post were observed. Significantly more mixed failures occurred for U100 in the expert dentist group ($p<0.02$, Fisher exact test).				

higher BS means were observed for U100 (13.9 ± 7.3) irrespective of the operator's experience. The lowest means were observed for SB + ARC (9.8 ± 6.8) ($p<0.05$). SBMP + ARC (11.8 ± 7.4) had an intermediate performance and it was similar to the other groups ($p>0.05$). The Student *t*-test revealed that the push-out means of U100 were not affected by the operator's experience ($p>0.05$).

No significant difference in the fracture pattern was observed among materials in the undergraduate student group (Table 4). With regard to the expert operators, U100 showed more mixed failures than the other two materials. Most of the mixed failures (70%) occurred between resin cement and dentin with cohesive failure of the cement. A representative image of the most prevalent fracture mode can be seen in Figure 3.

DISCUSSION

In this study, it was observed that the use of a simplified etch-and-rinse (ER) adhesive SB together with ARC produced lower bond strength in comparison with U100, which led to rejection of the first null hypothesis. An adverse chemical interaction has been reported between unpolymerized acidic resin monomers in the oxygen inhibition layer of simplified ER adhesives and the tertiary amine present in auto/dual-cured composites, which may be responsible for incompatibility among these systems.¹⁹⁻²¹ Although the materials evaluated in this study (SB and ARC system) were not tested in the cited studies,¹⁹⁻²¹ one cannot rule out the possibility that this may be a plausible explanation, especially in the apical region of the root canal where the conversion of the dual

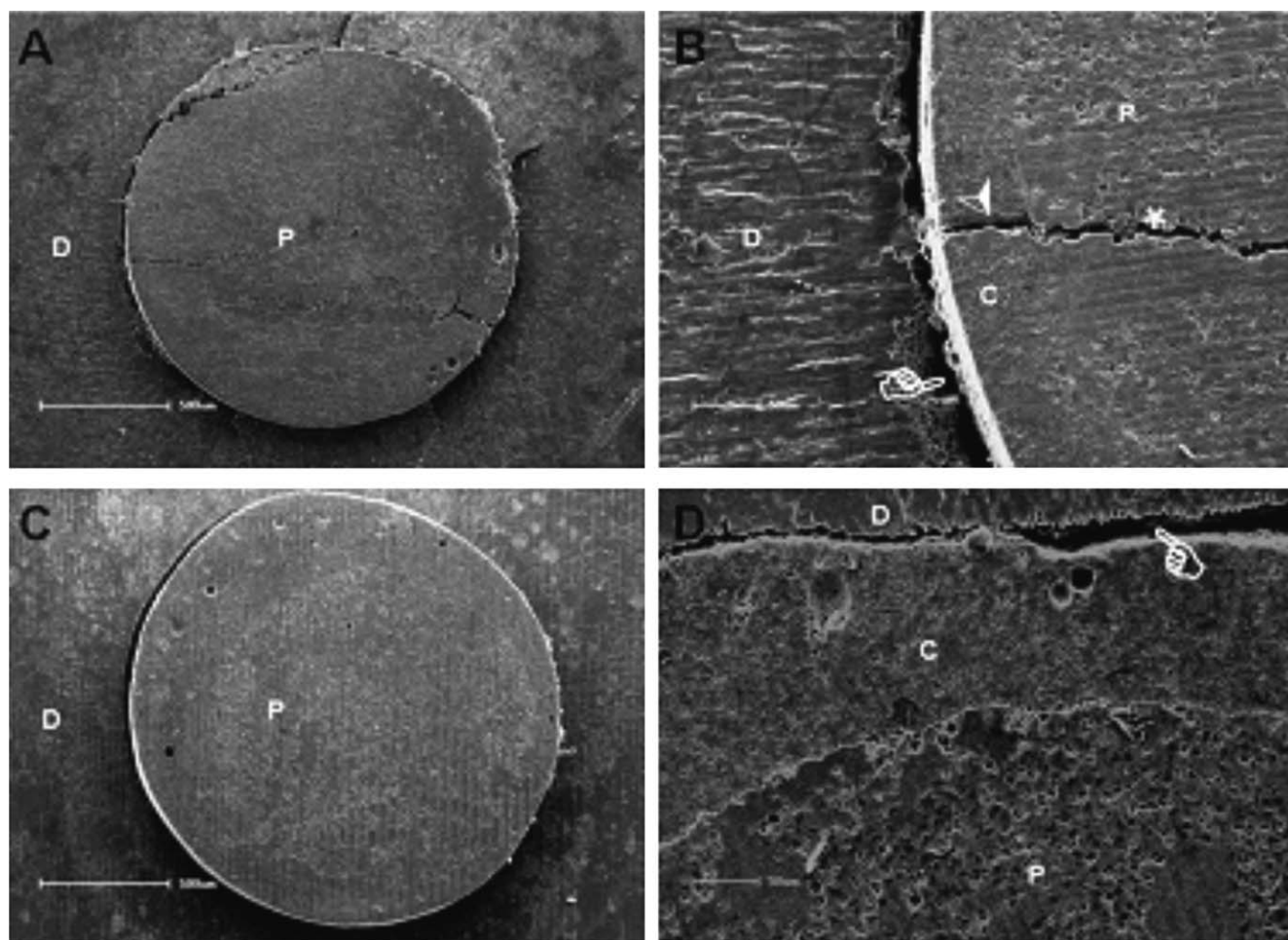


Figure 3. Scanning electron micrographs of representative fracture patterns. A mixed failure mode can be seen in low (A) and high (B) magnification. In (B) one can observe the adhesive failure between the cement and the dentin interface (pointer) along with a cohesive failure within cement (arrow head) and a fissure in the post (asterisk). An adhesive failure mode can be seen in low (C) and high magnification (D). In (D) one can observe that the failure occurred between the cement and dentin (pointer). Abbreviations: C, cement; D, dentin; P, post.

resin cement practically relies on chemical activation, as light does not reach this area properly.^{22,23} Moreover, simplified ER systems have been shown to function as permeable membranes,²¹⁻²⁴ allowing water movement across their structure even after polymerization,^{25,26} which may adversely affect the coupling of auto/dual-cured resin cements to the dentin surface.^{24,25}

To attain proper polymerization in such situations, a chemically activated component of a dual-catalyst system was shown to be effective.²⁷ This was partially confirmed in this study since the use of three-step ER with the self-cure bottle of the SBMP system allowed intermediate push-out BS values to be obtained, a finding previously demonstrated in others studies.⁸⁻²⁸ The additional chemical polymerization of the three-step ER self-cure adhesive system may also compensate for the light attenua-

tion that occurs during the light polymerization step in a root canal.^{29,30}

Despite the tendency of SBMP to obtain high BS values, the foregoing reasons do not explain why this system was similar to SB. The use of chemical coinitiators in the SBMP completely eliminates the adverse chemical interaction reported for simplified ER adhesives (such as SB) and self/dual-cured composites, but the inherent permeability of the polymerized adhesive still precludes optimal coupling to bonded hydrated dentin.³¹ Furthermore, these two adhesives rely on the same bonding strategy, the ER approach, which requires the dentin substrate to be kept moist after acid conditioning.³² Due to limited access, it is difficult to control moisture within the root canal, and this makes the procedure more critical. Furthermore, the ideal degree of moisture varies widely among the

manufacturers' instructions and also depends on the solvent used in each system.³³

The foregoing discussion makes the two ER adhesives sensitive to the operator's experience, as observed in the present investigation, leading to rejection of the second null hypothesis, since expert operators achieved higher BS results than undergraduate students. This finding has been observed in the literature when bonding to coronal dentin.^{12,13} However, contrary to the results of the present study, Simonetti and others¹⁶ did not observe any influence of the operator's experience on the push-out BS of a dual-cured resin cement associated with Prime&Bond NT (Dentsply). It is speculated that the low number of operators (only one in each experimental condition) and specimens used by the authors reduced the power of the study to an extent that prevented the authors from observing a significant effect of the operator's experience on the BS. As data from push-out BS present high standard deviations, usually exceeding 50% of the means,^{1,5,6,16,28,34} the sample size should be high enough to detect subtle differences between groups.

The self-adhesive cement U100 does not require rinsing, solving the problem of substrate moisture control and thus simplifying the clinical procedure. The high BS values observed for U100 in this study and in others^{1,7-9,28,35-37} can be attributed to the chemical interaction between monomer acidic phosphate groups and dentin/enamel hydroxyapatite¹⁷ and to low shrinkage of the material,^{38,39} leading to closer contact of the resin cement with the root canal walls and higher frictional resistance.^{40,41} Unfortunately, there is no consensus in the literature with regard to the superiority of this material when compared with conventional bonding strategies.^{5,6,37,41,42} The reason for this controversy should be further investigated.

With regard to the influence of the operator's expertise on the success or failure of self-adhesive cements used for post cementation, little information is available in the literature. The reduced number of clinical steps and no need to keep the dentin substrate moist before application of the material might explain why U100 was not sensitive to the operator's experience in the present investigation. It may be said that for different operators, reducing the number of steps in the bonding procedure is an important factor in obtaining a more reliable and stronger bond between the resin and dentin. It is worth pointing out that the fact that U100 was not affected by the operator's experience in an *in vitro* setting, does not necessarily mean that this will be

the case in a clinical scenario. Further clinical studies should be conducted to evaluate this aspect.

The high number of operators in the present study was a favorable condition for the greater reliability of the data. However, this study also has some limitations. The test specimen crowns were not completely restored and no thermal cycling or mechanical stressing was applied. These factors may limit the direct application of the study results to clinical conditions.

CONCLUSIONS

Within the limitations of this *in vitro* study, it may be concluded that:

- Higher BS means were observed for expert operators in comparison with the undergraduate students, irrespective of the cementation system used.
- RelyX U100 showed the highest bond strength, but it did not differ from that of SBMP + RelyX ARC.
- The self-adhesive cement used (RelyX U100) was not sensitive to the operator's experience.

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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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Comparison of Enamel Microabrasion with a Combined Approach to the Esthetic Management of Fluorosed Teeth

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Clinical Relevance

Although enamel microabrasion improves the appearance of teeth with brown stains or white opaque areas, the combination of enamel microabrasion and in-office bleaching results in better esthetics.

SUMMARY

Objective: To compare *in vivo* the efficacy of enamel microabrasion alone or in combination with vital tooth bleaching for the management of tooth discoloration caused by fluorosis.

Methods: A total of 118 maxillary and mandibular fluorosed incisors and canines in 10

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patients, scored from 1 to 7 according to the Tooth Surface Index of Fluorosis, were included in this study. All of the teeth were initially treated with enamel microabrasion (Opalustre, Ultradent Products Inc, South Jordan, UT, USA), and after 24 hours, an in-office bleaching technique (Opalescence Boost, Ultradent) was utilized (n=118). Standardized images of the teeth were taken using a digital camera prior to treatment and 24 hours after the enamel microabrasion and after the in-office bleaching therapy. The study groups were assigned according to evaluation time: a) after enamel microabrasion (Group 1) and b) after the combined approach (enamel microabrasion and in-office bleaching) (Group 2). Two calibrated and blinded examiners scored Group 1 and Group 2 images by comparing each with baseline images for “improvement in appearance,” “changes in brown stains,” and “changes in white opaque areas” using the visual analogue scales (VAS) that range from 1 to 7.

“Patient satisfaction,” “tooth sensitivity,” and “gingival problems” were also recorded. The data were analyzed using two sample paired Wilcoxon signed-rank, Kruskal-Wallis, and Mann-Whitney *U*-tests ($\alpha=0.05$).

Results: The combined therapy revealed significantly higher scores than the enamel microabrasion procedure in terms of all of the evaluated criteria ($p<0.001$). Enamel microabrasion provoked less tooth sensitivity but led to lower patient satisfaction scores than the combined therapy ($p<0.001$); however, in terms of gingival problems, no differences were found between both groups.

Conclusion: The combined therapy, including enamel microabrasion and in-office bleaching, was more effective than enamel microabrasion alone in the esthetic management of fluorosed teeth.

INTRODUCTION

Dental fluorosis is a form of enamel dysplasia caused by excessive fluoride intake during enamel formation. Teeth affected by fluorosis have white opaque areas or discoloration ranging from yellow to dark brown, together with porosity on the enamel surface. The white opaque areas and stains caused by fluorosis lead to mild to severe esthetic problems, and studies^{1,2} conducted on the health-related quality of lives and the psychosocial aspects of fluorotic staining revealed that esthetic treatment is needed in cases of dental fluorosis.

In the past, fluorosed teeth were restored with direct or indirect restorative techniques. Although satisfactory results have been obtained with veneers or crowns, the main problem with these invasive procedures is that most patients referred to clinics to treat fluorosis are young adults, and the use of invasive procedures results in excessive loss of tooth structure, thereby increasing the likelihood of tooth destruction at an early age. Thus, there has been a tendency toward conservative approaches, even in severely fluorosed teeth.³⁻⁵

Two primary conservative approaches have been proposed to remove the white opaque areas and stains caused by dental fluorosis: the microabrasive method^{6,7} and vital bleaching,⁸ along with a combination of both methods.⁹ Enamel microabrasion removes the porous subsurface enamel layer, including entrapped stains, when a gel that includes hydrochloride acid (HCl) is used. It is the first treatment option in cases involving teeth that have

white opaque areas, staining, and surface irregularity because it not only removes the white opaque areas and brown stains but it also smoothens surface irregularities and results in a more regular, lustrous enamel surface.¹⁰ However, depending on the concentration of HCl, the type of abrasive contained in the gel, and the application duration of the gel, the microabrasive method only removes the outer enamel surface (10 to 200 μm); it cannot eliminate deep, intrinsic stains and porosities.^{10,11} Some authors reported a darker or yellowish color on teeth subjected to enamel microabrasion. This was attributed to the fact that teeth become thinner and the underlying dentin changes color after treatment.¹⁰ In addition, some studies^{12,13} claim that this technique is more successful in removing brown stains than white opaque areas.

Vital bleaching techniques are also used in the treatment of fluorosed teeth as a way to change the perception of the white opaque areas and stains. Vital tooth bleaching can be performed at home or in the dental office. In-office bleaching agents contain high concentrations of carbamide peroxide (35%-37%) or hydrogen peroxide (30%-35%), while at-home agents consist of low concentrations of both peroxides and are employed in a custom tray under the supervision of a dentist.¹⁴ These techniques remove brown stains and they change the perception of white opaque areas by lightening the adjacent enamel surface, but they cannot eliminate irregularities on the tooth's surface.¹⁵ Thus, a combination of enamel microabrasion and vital bleaching is generally preferred to both reduce the contrast between the white opaque areas and the surrounding tooth surface and to eliminate surface irregularities.^{9,15}

Performance of a combination of enamel microabrasion and vital bleaching techniques to esthetically manage fluorosed teeth has been studied since 1986,¹⁶ wherein applying a mixture of hydrochloric acid was proposed to remove intrinsic enamel stains. All of the proposed techniques improved the esthetics to some degree, depending on the type of technique used or the severity of the fluorosis.^{6,7,9,12,17} However, most of the articles on this topic are case reports, and many questions exist related to concerns, such as the following: 1) Are all methods effective in the esthetic management of fluorosed teeth; 2) Which method is the best: enamel microabrasion, vital bleaching, or a combination of both methods; 3) Do all methods eliminate white opaque areas and brown stains; and 4) Do all methods eliminate the mottled surface of teeth and improve the appearance perfectly?

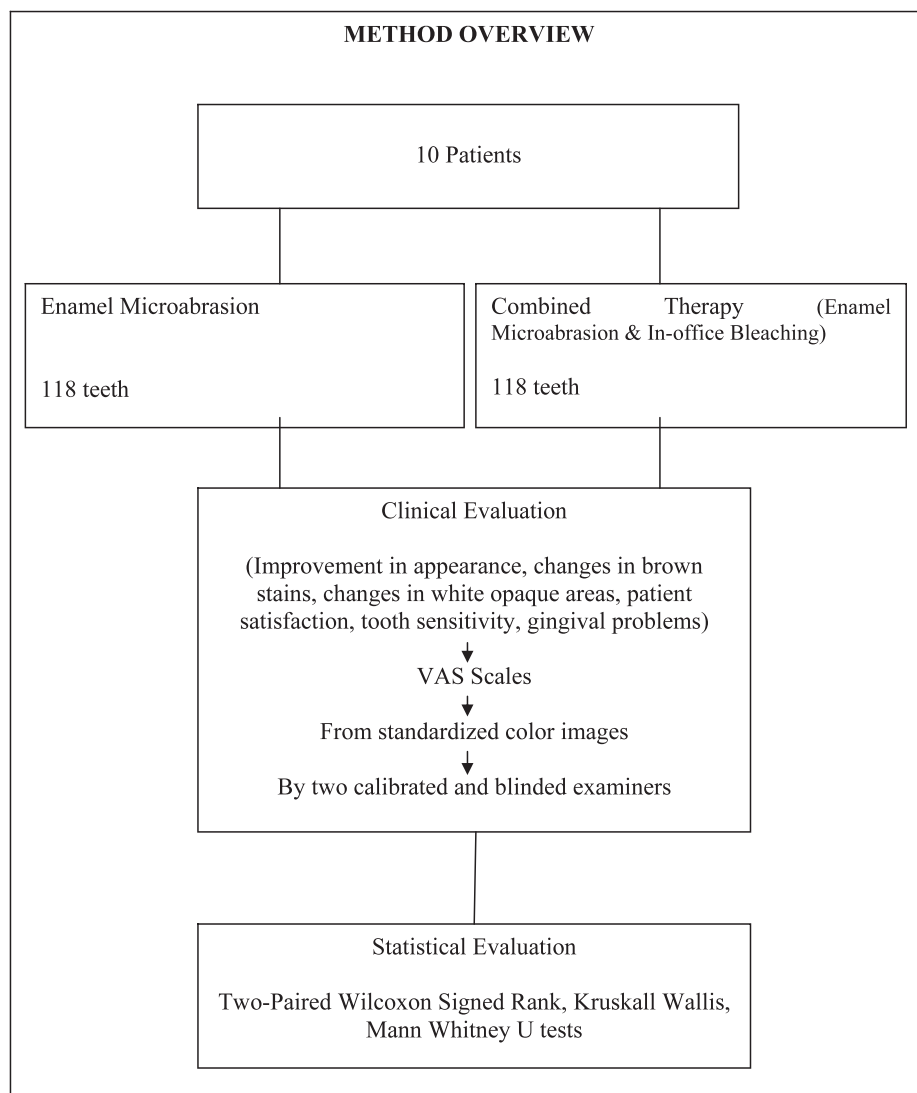


Figure 1. Method overview of the clinical study.

The aim of this study was to compare *in vivo* the efficacy of enamel microabrasion alone or in combination with vital tooth bleaching for the management of tooth discoloration caused by fluorosis using clinical photographs and a visual analogue scale (VAS). The null hypothesis tested was that there were no differences between the clinical performance of enamel microabrasion and the combined approach in the esthetic management of fluorosed teeth.

MATERIALS AND METHODS

Study Design

All patients were subjected to both enamel microabrasion and in-office bleaching therapy. The study groups were assigned according to evaluation time, as follows: 1) after enamel microabrasion (Group 1) and

2) after the combined approach (enamel microabrasion and in-office bleaching) (Group 2) (Figure 1).

Sample Size and Power Analysis

The G*Power (G*Power Ver 3.0.10, Franz Faul, Universität Kiel, Kiel, Germany; <http://www.psych.uni-duesseldorf.de/aap/projects/gpower>) program was used to determine the sample size. At least 102 teeth from each group were required to determine the $f = 0.30$ effect difference between study groups with 90% power and $\alpha = 0.05$ type I error and $\beta = 0.05$ type II error rates.

Patient Selection

Ten patients (three males and seven females) with 118 fluorosed teeth, ranging in age from 18 to 41

years (with a mean age of 25 years), recruited from the university hospital, were included in this clinical trial. The committee for medical ethics of Cumhuriyet University Sivas Province, Turkey, approved the study protocol (No. 2011-04/19). Each patient signed an informed consent form after the nature and objectives of the clinical trial had been explained at the beginning of the study. The distribution of patients according to gender, age, oral hygiene status, and Tooth Surface Index of Fluorosis (TSIF) scores is presented in Table 1.

The inclusion/exclusion criteria were the following. Participants had to

- Have at least eight fluorosed maxillary and mandibular incisors and canines with scores of 1-7, according to the TSIF.
- Have no caries or restorations on the teeth to be treated.
- Be able to return for periodic recalls.

The exclusion criteria included the following:

- Poor general or dental health.
- Any fixed orthodontic appliances.
- Hypersensitive teeth.
- Smoking habit.
- Current or previous use of bleaching agents.
- Status as a pregnant or lactating woman.
- Tetracycline-stained teeth.
- A history of allergies to tooth-whitening products.
- Age of less than 18 years.
- Symptoms of pulpitis, such as spontaneous pain or sensitivity to pressure.

Enamel Microabrasion

Even though only maxillary and mandibular fluorosed incisors and canines were included in the current study, all fluorosed teeth visible during smiling, laughing, or speaking were treated in this trial. The teeth were cleaned with pumice before treatment. Initial photographs of the teeth were taken (Figure 2). They were isolated with a rubber dam and then a fine-grit, water-cooled diamond bur was applied to the stained and white opaque enamel region for five to 10 seconds to enable penetration of the gel into the enamel. An approximately 1-mm-thick layer of 6.6% hydrochloric acid slurry with silicone carbide microparticles (Opalustre, Ultradent Products Inc, South Jordan, UT, USA) was applied to the affected tooth surfaces. OpalCups™ prophylaxis cups (Ultradent Products Inc) attached to a gear-reduction contra-angle were used to microabrade the

Table 1: Distribution of Patients According to the Gender, Age, Oral Hygiene Status, and Tooth Surface Index of Fluorosis (TSIF) Scores		
	Number of Patients	Number of Teeth
Gender		
Male	3	36
Female	7	82
Age		
18-25 y	7	82
25-35 y	1	12
35-50 y	2	24
Oral hygiene		
Good	6	70
Moderate	4	48
Poor	—	—
TSIF score		
0	0	0
1	0	0
2	3	7
3	7	37
4	8	48
5	3	6
6	2	8
7	3	12

surfaces of the teeth using slight pressure for 60 seconds. The teeth were then rinsed, and this procedure was repeated five times for mild lesions and 10 times for moderate and severe lesions during the same session.¹⁸ Fluoride gel (Sultan Topex Neutral Fluoride gel, Englewood, NJ, USA) was



Figure 2. Pretreatment view of a patient with fluorosed teeth.

applied for five minutes. Photographs were taken 24 hours after treatment (Figure 3).

In-office Bleaching

Patients received the in-office bleaching treatment 24 hours after the enamel microabrasion procedure. All patients returned for in-office bleaching. Gingival protector gel (OpalDam, Ultradent Products Inc) was applied 4-6 mm high and 1.5-2.0 mm thick along the gingival margin, overlapping approximately 0.5 mm onto the enamel. It was light-cured for 20 seconds per arch using a scanning motion. After mixing two syringes, a 0.5-1.0-mm-thick layer of 38% hydrogen peroxide gel (Opalescence Boost, Ultradent Products Inc) was applied to the labial surfaces of the teeth. The gel was allowed to remain on the teeth for 20 minutes and then it was removed using suction. The teeth were then cleaned with water. These steps were repeated up to three times per visit, depending on tooth sensitivity. The treatment was repeated in three- to five-day intervals until no differences were observed between two consecutive visits. The mean application duration of gels in both groups is given in Table 2. After in-office bleaching, the teeth were polished with abrasive discs, and fluoride gel was



Figure 3. View of patient after microabrasion.

Table 2: Mean Application Duration of Gels in Both Groups		
Material	Mean Number of Visits	Mean Duration, min
Opalustre	1	9.7
Opalescence Boost	2.5	96

applied for five minutes. Photographs were taken 24 hours after treatment (Figure 4).

Evaluation

Standardized images of the teeth were taken with a digital camera (Coolpix 8800, Nikon, Tokyo, Japan) before each treatment and 24 hours after the enamel microabrasion and in-office bleaching therapy. The images were taken at the same distance in a dark room under controlled lighting conditions. The same background, camera, light source, and exposure were used. Two calibrated and blinded examiners scored the Group 1 and Group 2 images by comparing each with pretreatment images for “improvement in appearance,” “changes in brown stains,” and “changes in white opaque areas,” using VAS ranging from 1 to 7 (Figure 5). “Patient satisfaction,” “tooth sensitivity,” and “gingival problems,” ranging from 1 to 7, were also evaluated using VAS (Figure 5). Five pairs of pretreatment–Group 1 or pretreatment–Group 2 images were randomly selected and used to test for intra- and interexaminer reliability.

Statistical Analysis

The statistical analysis was processed with the SPSS 15.0 software system (SPSS Inc, Chicago, IL, USA). The Shapiro-Wilk test was used to assess the



Figure 4. View of patient after microabrasion and in-office bleaching.

VISUAL ANALOGUE SCALES						
Improvement in Appearance						
1	2	3	4	5	6	7
1=No Improvement				7=Exceptional Improvement		
Changes in Brown Stains						
1	2	3	4	5	6	7
1=Not at All				7=Totally Removed		
Changes in White Opaque Areas						
1	2	3	4	5	6	7
1=Not at All				7=Totally Disappeared		
Patient Satisfaction						
1	2	3	4	5	6	7
1= Totally, expectations not fulfilled				7=Complete Satisfaction		
Tooth Sensitivity During or After Bleaching						
1	2	3	4	5	6	7
1=Not acceptable				7=No side effects		
Gingival Problems During or After Bleaching						
1	2	3	4	5	6	7
1=Not acceptable				7=No side effects		

Figure 5. Visual analogue scales.

likelihood that the given data set came from a normal distribution. The data could not be assumed to be distributed normally; thus, median and Interquartile Range (IQR) values were used to display the descriptive statistics. Differences in the “improvement in appearance,” “changes in brown stains,” and “changes in white opaque areas” scores for Group 1 and Group 2 were respectively tested with the two-sample paired Wilcoxon signed-rank test.

The Mann-Whitney *U*-test was used to analyze 1) differences between the maxillary and mandibular teeth in terms of their “improvement in appearance,” “changes in brown stains,” and “changes in white opaque areas” scores in Group 1 and Group 2; 2) differences between the “improvement in appearance,” “changes in brown stains,” and “changes in white opaque areas” scores of Group 1 and Group 2 in maxillary and mandibular teeth; and 3) differences between the “tooth sensitivity,” “gingival prob-

Table 3: Descriptive Values and Statistical Results of Group 1 and Group 2 Comparisons

	Group 1			Group 2			Group 1 vs Group 2	
	Minimum-Maximum	Median (IQR)	Mean (SD)	Minimum-Maximum	Median (IQR)	Mean (SD)	Z	p
Improvement in appearance	1.0–6.0	3.0 (2.0)	3.4 (1.4)	1.0–7.0	6.0 (2.0)	5.8 (1.4)	9.241	<0.001
Changes in brown stains	1.0–7.0	5.0 (2.0)	4.8 (1.5)	3.0–7.0	7.0 (1.0)	6.5 (0.9)	9.107	<0.001
Changes in opaque white areas	1.0–7.0	4.0 (2.0)	4.2 (1.4)	1.0–7.0	5.0 (1.0)	5.5 (1.2)	8.294	<0.001

Abbreviations: IQR, interquartile range; SD, standard deviation.

lems,” and “patient satisfaction” scores for Group 1 and Group 2.

The Kruskal-Wallis test was used to analyze differences among the scores of “improvement in appearance,” “changes in brown stains,” and “changes in white opaque areas” criteria in both groups. For all tests, the probability level for statistical significance was at $\alpha = 0.05$.

RESULTS

The test of intraexaminer and interexaminer agreement resulted in Cohen’s Kappa statistics of 84 and 81, respectively. The mean (standard deviation [SD]) and median (interquartile range [IQR]) scores of Group 1 and Group 2 were given for “improvement in appearance,” “changes in brown stains,” and “chang-

es in white opaque areas” in Table 3. Group 1 revealed significantly lower scores than Group 2 in terms of all of the evaluated criteria ($p < 0.001$).

In Group 1 and Group 2, no differences were found between the maxillary and mandibular teeth in all evaluated criteria, except for “changes in white opaque areas” scores in Group 1. Maxillary teeth had higher scores than mandibular teeth in terms of “changes in white opaque areas” in Group 1 ($p < 0.001$). In maxillary and mandibular teeth, Group 1 had significantly lower scores than Group 2 related to all evaluated criteria ($p < 0.001$) (Table 4).

Both groups revealed the highest scores in “changes in brown stains” ($p < 0.001$). The “changes in white opaque areas” scores of Group 1 were higher than

Table 4: Statistical Results of Comparisons Between Maxillary and Mandibular Teeth

	Tooth	Group 1	Max vs Man	Group 2	Max vs Man	Group 1 vs Group 2	
		Median (IQR)	Z (p)	Median (IQR)	Z (p)	Z	p
Improvement in appearance	Max	3.0 (2.0)	0.662 (0.508)	6.0 (1.3)	1.411 (0.158)	6.669	<0.001
	Man	3.0 (3.0)		6.0 (2.8)		6.449	<0.001
Changes in brown stains	Max	4.0 (1.0)	1.327 (0.185)	6.0 (1.0)	1.495 (0.135)	6.523	<0.001
	Man	6.0 (3.0)		7.0 (1.0)		6.498	<0.001
Changes in opaque white areas	Max	4.0 (1.0)	4.521 (<0.001)	5.5 (1.0)	0.892 (0.373)	5.655	<0.001
	Man	3.0 (2.0)		5.0 (1.0)		6.135	<0.001

Abbreviations: IQR, interquartile range; Man, mandibular; Max, maxillary.

the “improvement in appearance” scores ($p < 0.001$), while the “improvement in appearance” scores of Group 2 were higher than the “changes in white opaque areas” scores ($p < 0.05$).

Group 1 experienced less tooth sensitivity and reflected lower patient satisfaction scores than Group 2 ($p < 0.001$); however, no differences were found between both groups in terms of gingival problems.

DISCUSSION

In the current study, VAS ranging from 1 to 7 was preferred to evaluate “improvement in appearance,” “changes in brown stains,” and “changes in opaque white stains,” in lieu of any dental spectrophotometer evaluation. This was similar to the study by Price and others,⁶ even though it was a subjective technique for shade measurement. Shade evaluation by spectrophotometers depends on the CIELAB color difference, which is determined by calculating the Euclidean distance (ΔE) between the two colors in the CIELAB color space. In the formula used to find the color difference, the squared differences among the L^* , a^* , and b^* measures are summed up.¹⁹ Although it is a quantitative technique, esthetic management related to determining any change in color parameters is not enough in fluorosed teeth, as the primary aims are to remove all stains and improve the mottled surface. Knösel and others²⁰ used the CIE $L^*a^*b^*$ evaluation to report the effects of bleaching therapy on fluorotic enamel stains. Using this evaluation method, these authors could only report the rate of all fluorotic areas that showed detectable color change ($\Delta E > 3.7$) after bleaching. They could not comment on the stain removal performance, improvement in mottled appearance, and esthetic management level that resulted from this quantitative technique.

Two different conservative approaches, enamel microabrasion and a combined therapy (enamel microabrasion and in-office bleaching), were evaluated to esthetically manage mild to severely fluorosed teeth in this trial. In order to eliminate the patient-dependent variable, the current study was designed to apply enamel microabrasion and in-office bleaching therapy onto the same teeth, respectively. Thus, Group 1 included scores from images taken after enamel microabrasion, and Group 2 included scores from images taken after in-office bleaching, followed by enamel microabrasion.

Although both methods improved the appearance of and removed stains and white opaque areas at

different levels, enamel microabrasion revealed significantly lower scores than did combined bleaching therapy in terms of all of the evaluated criteria. In the literature, there is no article that compares the effectiveness of enamel microabrasion to vital bleaching techniques. In case reports that evaluated the effectiveness of microabrasion, it was considered an effective and minimally invasive procedure.²¹ On the other hand, in clinical articles, this technique removed stains and white opaque areas from the outermost layer of enamel and improved the appearance of teeth to some degree; however, similar to the results of the current study, the technique could not entirely improve esthetics. Price and others⁶ reported that enamel microabrasion resulted in a score of 5.38 for “improvement of appearance” and a 5.06 score for “stain removal,” according to the VAS scale, which ranged from 1 to 7. Loguercio and others²² obtained scores of 3.4 and 2.4, respectively, for “improvement of appearance” using different products for enamel microabrasion. This technique claims to remove the outermost layer of enamel and change the optical properties of the enamel surface. When the enamel surface is abraded with an acid gel, a densely compacted prism-free layer is formed on the enamel surface. This prism-free layer reflects and refracts light in such a way that underlying stains are believed to be camouflaged.¹⁰

Vital bleaching techniques, including in-office and at-home bleaching, were mostly used together or with enamel microabrasion to esthetically manage fluorosed teeth, except as demonstrated in some early articles.^{8,23} A sufficient amount of esthetic management was mainly provided by using a combined approach (in-office and at-home bleaching, enamel microabrasion and in-office and at-home bleaching or enamel microabrasion, in-office and at-home bleaching). Knösel and others²⁰ applied in-office bleaching to 18 subjects using 30% hydrogen peroxide, followed by 14 days of at-home bleaching. They reported that in-office bleaching does not lead to a significant change in the color and luminosity of fluorotic teeth, whereas the application of at-home bleaching therapy after an in-office bleaching regime provided detectable color change in fluorotic areas. Ardu and others³ reported successful results after the application of enamel microabrasion followed by the at-home bleaching technique on a patient with severe dental fluorosis. Ng and Manton⁵ could reduce dark brown stains using a combination of enamel microabrasion and in-office and at-home bleaching techniques in a severe fluorosis case;

however, they required the use of composite veneers to achieve further improvement in the esthetics of the patient. Pontes and others⁹ used an enamel microabrasion technique followed by in-office bleaching. They revealed that enamel microabrasion was an efficient method for removing white opaque areas, whereas dental bleaching can be used to obtain a uniform tooth shade. Similar to previous articles, an in-office bleaching regime conducted after enamel microabrasion increased the efficacy of the current study's therapy, as was used for the esthetic management of fluorosed teeth in the present research.

In the current trial, when the efficacy of both methods of "improvement in appearance," "changes in brown stains," and "changes in white opaque areas" were compared, it was observed that utilizing both methods to remove brown stains offered the best solution. Enamel microabrasion revealed the worst performance in "improvement in appearance," probably because it could not achieve a uniform tooth shade, similar to bleaching techniques. Similar to the current study, previous articles^{15,21} on enamel microabrasion documented being successful in removing fluorosis stains, while bleaching methods were preferred as a way to harmonize the shade of the tooth and provide a more esthetic appearance.

CONCLUSIONS

With regard to our results, the hypothesis was rejected. To some degree, enamel microabrasion improves the appearance of teeth and removes brown stains or white opaque areas; however, the combination of enamel microabrasion and in-office bleaching techniques results in better performance in all of the evaluated criteria and provides a better esthetic appearance.

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Note

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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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Laboratory Research

Physical Property Evaluation of Four Composite Materials

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Clinical Relevance

A clinician should customize the choice of a composite material to the location and preparation of the cavity. When surface hardness and flexural strength are required, the results of this study indicate that Aelite LS had superior properties compared with the other materials. When polymerization shrinkage is of more importance, Filtek LS had significantly lower volumetric shrinkage.

SUMMARY

Purpose: The purpose of this study was to evaluate the physical properties of current formulations of composite resins for polymerization shrinkage, surface hardness, and flexural strength. In addition, a comparison of Knoop and Vickers hardness tests was made to determine if there was a correlation in the precision between the two tests.

Materials and Methods: Four composite resin materials were used: Filtek LS (3M-ESPE), Aelite LS (Bisco), Kalore (GC America), and

Empress Direct (Ivoclar). Ten samples of each composite (shade Vita A2) were used. Polymerization shrinkage was measured with the Kaman linometer using 2-mm-thick samples, cured for 40 seconds and measured with digital calipers for sample thickness. Surface microhardness samples were prepared (2-mm thick $\times$ 12-mm diameter) and sequentially polished using 600-grit silicone carbide paper, 9 μ m and 1 μ m diamond polishing solutions. After 24 hours of dry storage, Knoop (200 g load, 15 seconds dwell time) and Vickers (500 g load, 15 seconds dwell time) hardness tests were conducted. Flexural strength test samples (25 $\times$ 2 $\times$ 2 mm) were stored in 100% relative humidity and analyzed using a three-point bending test with an Instron Universal Testing Machine (Instron 5565, Instron Corp) applied at a cross-head speed of 0.75 $\pm$ 0.25 mm/min. Maximum load at fracture was recorded. One-way analysis of variance and Tukey multiple comparison tests were used to determine significant differences in physical properties among materials.

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Results: Filtek LS had significantly lower shrinkage (0.45 [0.39] vol%). Aelite LS demonstrated the greatest Knoop surface hardness (114.55 [8.67] KHN), followed by Filtek LS, Kalore, and Empress Direct (36.59 [1.75] KHN). Vickers surface hardness was significantly greater for Aelite LS (126.88 [6.58] VH), followed by Filtek LS, Kalore, and Empress Direct (44.14 [1.02] VH). Flexural strength (MPa) was significantly higher for Aelite LS and Filtek LS (135.75 [17.35]; 129.42 [9.48]) than for Kalore and Empress Direct (86.84 [9.04]; 92.96 [9.27]). There is a strong correlation between results obtained using Knoop and Vickers hardness tests ($r=0.99$), although Vickers values were significantly greater for each material.

Conclusion: Results suggest that Aelite LS possesses superior hardness and flexural strength, while Filtek LS has significantly less shrinkage compared with the other composites tested.

INTRODUCTION

Manufacturers of dental materials have attempted to distinguish their products by adjusting composite formulations to find a market niche. In an effort to identify which composition will have adequate clinical performance and meet minimum standards, physical property tests are used to evaluate the materials.

Polymerization shrinkage of a dental composite is of significant clinical importance because shrinkage leads to mechanical stresses on enamel and dentin at the adhesive interface.¹ The degree of shrinkage of a composite is related to the molecular weight of the monomer, the amount of monomer in the composite, and the degree of polymer conversion. The polymerization shrinkage of low-molecular-weight monomers is more pronounced than that of high-molecular-weight monomers.¹ Shrinkage can lead to marginal leakage when the restoration does not adhere to the tooth structure or when the stress generated at the restoration-tooth interface causes the composite to debond from the tooth structure.² Marginal leakage and cohesive failures have been generated by stresses of as little as 2% of volume shrinkage of typical composites.³

There are two general methods to test polymerization shrinkage: non-volume dilatometry and volume dilatometry.⁴ Non-volume dilatometric methods include the use of a linometer^{5,6} and video

imaging of a sample as it undergoes polymerization.⁷ A mercury dilatometer⁸ and a water-filled dilatometer² are common methods of volumetric measurements for shrinkage. A significant consideration in the use of a mercury or water dilatometer is that the fluids are very sensitive to ambient temperature. Thermal control is mandatory; otherwise, the expansion or contraction of the fluids will affect the results.⁸ In addition, application of light to polymerize an experimental resin is difficult because of the opacity of mercury.

Strength (tensile, shear, compressive, or flexural) values are often relied on as indicators of structural performance for brittle dental materials, including composites.⁹ The three-point flexural strength test has been used to measure mechanical properties of a composite material and has been selected by the International Standards Organization (ISO) for screening resin-based filling materials.^{9,10} Flexural strength is defined as the failure stress of a material as measured in bending.¹¹ Composite restorations are subjected to flexural stresses, especially in stress-bearing cavities (Class I, Class II, and Class IV).¹² Flexural strength has been shown to be a more discriminating test and more sensitive to subtle changes in a materials substructure than compressive strength.¹³ Currently, continuous loading machines are employed in flexural strength testing, which can be conducted using either three-point or four-point loading.^{14,15}

The satisfactory clinical performance of a restorative material is partially determined by its adaptability to prepared tooth structure and its resistance to degradation in the oral environment.¹⁶ Degradation is the result of a combination of effects including abrasive wear, masticating forces, and damage by oral fluids. The hardness of a composite is a quality of the material that resists the degradation forces and improves the function of the restoration. The use of hardness tests has become prevalent because of their relatively simple testing method and the reliability of the results.¹⁷ Another advantage that has been cited is the correlation between hardness values and degree of conversion.¹⁸ In general, Knoop hardness is the most commonly indicated method for evaluation of polymeric materials, such as resin composites, because it minimizes the effect of elastic recovery. However, other authors have used the Vickers hardness test as an indicator of the degree of resin polymerization.^{19,20} The Vickers indentation involves a larger surface area and is more representative of the surface of multiphase materials.

Table 1: Descriptive Table of Materials Used			
Composite	Manufacturer	Filler Type	Filler Content
Aelite LS	Bisco Inc. (Schaumburg, IL) Lot No. 1000006337	Microhybrid (glass, amorphous silica)	88%
Filtek LS	3M ESPE (St Paul, MN) Lot No. N182605	Microhybrid (quartz, yttrium fluoride)	76%
Kalore	GC America Corp (Chicago, IL) Lot No. 0907141	Nanohybrid (fluoroaluminosilicate glass, strontium glass, prepolymer-HDR, silicon dioxide)	82%
Empress Direct	Ivoclar Vivadent (Amherst, NY) Lot No. M68450	Nanohybrid (barium glass, ytterbiumtrifluoride glass, silicon dioxide)	79%

This study was designed to compare flexural strength, polymerization shrinkage, and surface hardness of four composites, selected on the basis of filler content and resin composition: Filtek LS (3M-ESPE), Aelite LS (Bisco), Kalore (GC America), and Empress Direct (Ivoclar). In addition, a comparison of the Knoop and Vickers hardness test was made to determine if there was a correlation in the precision between the two. The null hypotheses tested were that there were no differences in each of the physical properties among the four composites and that there is not a significant direct correlation between Knoop and Vickers hardness tests.

MATERIALS AND METHODS

This study was divided into three parts to evaluate the following physical properties: polymerization shrinkage, surface hardness using Knoop and Vickers and flexural strength. For each part, 10 samples of each composite were made in shade A2 as listed in Table 1.

Polymerization Shrinkage

Measurements for linear polymerization shrinkage were performed with a linometer as described by Herrero and others⁶ and are shown as a schematic representation in Figure 1. The setup consisted of a noncontact displacement transducer (Kaman Instrumentation Corp, Colorado Springs, CO) with the sensor placed in a vertically oriented quartz tube. The target and samples are positioned at the required offset distance of 0.13 mm and within the 1-mm range below the sensor. The Kaman linometer was calibrated at the beginning of each measurement period with a fixed sensor, and the aluminum target was placed at 0, 500, and 1000 μm

distances, such that each unit = 1 μm on a standard micrometer gauge.

The samples of disk-shaped uncured composite were approximately 5 mm in diameter and between 1.5- and 2.0-mm thick. All the procedures were performed at room temperature. A cylinder-shaped specimen of each composite resin was extruded from the syringe and preflattened on the mixing pad to

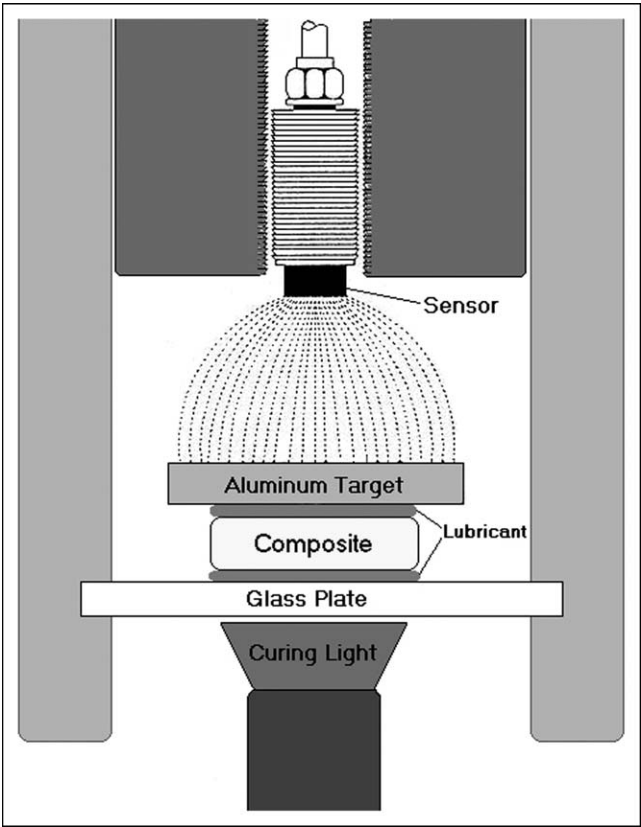


Figure 1. Linometer with the composite specimen placed between the lubricated glass plate and the aluminum target disk.

the desired thickness. The samples were transferred to a glass slide that was coated with a separating medium (Al-Cote, Caulk, Dentsply, Milford, DE) to allow the composite to shrink free of surface adhesion.

The top of the sample was covered by a flat aluminum target (10-mm diameter $\times$ 1-mm thick) placed parallel to the glass slide and coated with a lubricant. The entire assembly was mounted in a vertical position to use gravity to maintain the aluminum target position on the top surface of the sample (Figure 1). Once in position, the composite specimens were polymerized for 40 seconds using a Smartlite iQ2 (Model No. 200, Dentsply). Linear shrinkage data were recorded as ΔL after 40 seconds of light exposure. The percentage of shrinkage was calculated using the formula proposed by de Gee and others⁵ and used by Herrero and others⁶:

$$Lin\% = \Delta L / (L + \Delta L) \times 100$$

in which ΔL is the recorded displacement in micrometers and L is the thickness of the specimen in micrometers after polymerization. The $Lin\%$ is converted to a volumetric value using the following formula^{5,6} in which the last term is negligible:

$$Vol\% = 3Lin\% - 0.03(Lin\%)^2 + 0.001(Lin\%)^3$$

Surface Hardness

A metal mold, lubricated with Al-Cote, was used to fabricate composite samples that were 14 mm in diameter and 2 mm in thickness. Under low-light conditions, composite was placed in the mold, and the excess was removed using a wax spatula. A lubricated glass slide was placed on top of the sample, and finger pressure was applied to achieve a smooth surface and good adaptation of the composite in the mold. Each sample was light cured for 40 seconds through the glass slide using the Smartlight iQ2. The samples were removed, and the bottom or the side of the sample that was against the base was labeled using a permanent marker.

The light-cured side of each sample was polished for 5 seconds in an elliptical pattern with 600-grit wet silicon carbide paper (MAGER Scientific, Dexter, MI) to remove the resin-rich surface. A rotary grinder-polisher (Micro Star 2000, Concord, Ontario, Canada) was used at a rotation speed of 102 rpm to polish the samples. Each sample was first polished with a 9- μ m polycrystalline diamond suspension on a polishing cloth for four minutes, followed by a 1- μ m diamond suspension for two minutes on a finer

polishing cloth (PC-532 Pan, MAGER Scientific). Each sample was rinsed with tap water and kept in an envelope in a dark drawer for 24 hours at room temperature prior to testing. Following the storage period, a Tukon 2100B (Wilson Instrument, Norwood, MA) was prepared and calibrated for the microhardness testing.

For Knoop hardness, a 200-g load was applied to the sample surface with a dwell time of 15 seconds. After removal of the load, the microscopic indentation obtained from this procedure was evaluated for length and/or width as a function of penetration. For Knoop hardness, the diamond is rhombic shaped, and measurements are performed on the longest diagonal of the impression.

Three indentations were made on each sample, and the filar readings were measured using 20 $\times$ magnification (Figure 2A). The three readings were averaged to produce a single hardness value for each sample. Knoop hardness is the ratio of the load applied to the area of the indentation calculated from the following formula¹⁵:

$$KHN = \frac{L}{I^2 C_p}$$

where L = the applied load in kilograms, I = the length of the long diagonal of indentation (mm), and C_p = a constant related to the area of the indentation (0.07028). Means and standard deviations were then calculated.

Vickers indentations were made with a 500-g load, applied for 15 seconds. The diamond indenter is pyramidal, and hence a square-shaped indentation is obtained. Measurements were made on both diagonals, and mean values were obtained. The first measurement was made by positioning the filar lines at the tips of the horizontal indentation. For the second measurement, the eyepiece assembly was

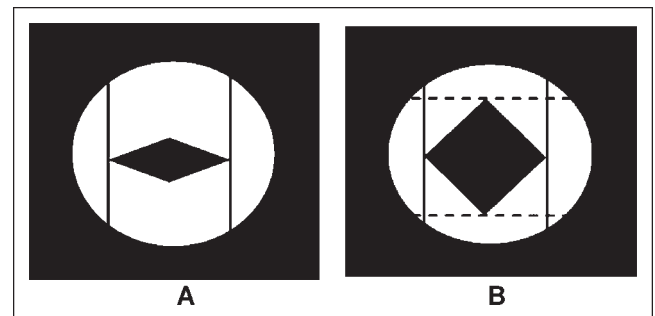


Figure 2. Eyepiece view of hardness indentations with filar lines in place for hardness measurement. (A): Knoop indenter. (B): Vickers indenter.

rotated 90° clockwise, and the filar lines were placed on the tips of vertical axis of the Vickers indentation (Figure 2B). Three readings were made, and they were averaged to represent a Vickers hardness value for each sample. The Vickers hardness number is computed from the following equation¹⁵:

$$HV = (1000P)/A$$

where P = test force in kg and A = surface area of indent in mm². Means and standard deviations were then calculated.

Flexural Strength

Samples of each composite were prepared in a split aluminum mold 25 ± 2 mm × 2 ± 0.1 mm × 2 ± 0.1 mm in accordance with ISO specification No. 4049/2000 and ANSI/ADA specification No. 27. The base and mold were lubricated with a thin layer of Al-Cote. Under low-light conditions, sufficient composite was applied to fill the mold, and the excess composite was removed using a wax spatula. A thin coat of Al-Cote was applied to a clean glass slide, and the slide was placed on top of the sample. Finger pressure was applied to achieve a smooth surface and good adaptation of the composite. Each sample was light cured for 40 seconds through the glass slide using the Smartlight iQ2. Since the length of the rectangular bars for the three-point flexure test exceeded the diameter of the curing-light tip, three overlapping curing times were employed until the entire length of the samples was covered. During all sample preparation, light intensity (620 mW/cm²) was checked periodically with the Cure Rite radiometer (Efes Inc, Mississauga, Ontario, Canada). After polymerization, the specimens were finished using 600-grit wet silicon carbide paper and stored in distilled water at room temperature for 24 hours prior to testing.

The specimens were mounted on a jig, and the load was applied with an Instron Universal Testing Machine (Instron 5565, Instron Corp, Norwood, MA) at a crosshead speed of 0.75 ± 0.25 mm/min until the sample fractured. The maximum load exerted on the samples was recorded, and the flexural strength at failure was calculated by the following formula:

$$FS = \frac{3PS}{2BH^2}$$

where P = maximum load in Newtons, S = distance between supports (20 mm) accurate to ±0.01 mm, and B and H are the width and thickness of the

Table 2: Volumetric Shrinkage for Each Material: Range, Mean, and Standard Deviation (n=10) ^a		
Composite	Range	Shrinkage (Vol %)
Aelite LS	1.12 (1.16-2.28)	1.59 (0.39) ^A
Filtek LS	0.45 (0.24-0.69)	0.45 (0.17)
Kalore	0.76 (1.24-2.0)	1.65 (0.27) ^A
Empress Direct	2.12 (0.88-3.0)	1.83 (0.62) ^A
^a Values followed by the same superscript are not significantly different, p>0.05.		

sample (2 mm) measured immediately prior to testing.

Statistical Analysis

Multiple comparisons of material group means for each property were made using a one-way analysis of variance (ANOVA). A Tukey’s multiple comparison test was then used to determine significant differences between the means at 95% confidence (p<0.05). A Pearson correlation coefficient was calculated to test for correlation between the Knoop vs Vickers hardness tests (p<0.05).

RESULTS

Four commercially available resin composites were evaluated for polymerization shrinkage, flexural strength, and surface hardness (n=10). Products were selected based on resin composition and filler particle size. In addition, a comparison of Knoop and Vickers hardness tests was made to determine if there was a correlation between the two tests.

Polymerization Shrinkage

Table 2 illustrates the range, means, and standard deviations for volumetric shrinkage. Filtek LS had a significantly lower shrinkage value than the other materials, based on a one-way ANOVA test (p=0.001) and a Tukey multiple comparison test (p<0.05). Aelite LS, Kalore, and Empress Direct have statistically similar but higher shrinkage values.

The distribution of volumetric shrinkage values for the 10 samples within each material showed that Empress Direct exhibited the highest variation in values among samples (range=2.12) compared with the other material groups. On the other hand,

Table 3: Knoop Microhardness (KHN) for Each Material: Range, Mean, and Standard Deviation ($n=10$)^a

Composite	Range	Surface Hardness (Knoop)
Aelite LS	31.63 (99.9-131.53)	114.55 (8.67)
Filtek LS	5.70 (51.73-57.43)	54.36 (2.05)
Kalore	5.84 (44.43-50.27)	46.57 (1.60)
Empress direct	5.10 (34.17-39.27)	36.59 (1.75)

^a Statistically significant differences found between each material ($p>0.05$).

Filtek LS showed the most consistent values (range=0.45).

Surface Hardness: Knoop

Table 3 illustrates the range, means, and standard deviations for Knoop hardness. Aelite LS exhibited a significantly higher mean value compared with the other materials. Filtek LS was significantly lower than Aelite LS; Kalore was significantly lower than Filtek LS, and Empress Direct exhibited the lowest value. Statistical analysis demonstrated significant differences between all the materials ($p<0.05$).

The distribution of Knoop hardness values for the 10 samples within each material showed that Aelite LS had greater variation in values (range=31.63) than the other materials. Filtek LS, Empress Direct, and Kalore all had similar variation (ranges=5.10-5.84).

Table 4: Vickers Microhardness for Each Material: Range, Mean, and Standard Deviation ($n=10$)^a

Composite	Range	Surface Hardness (Vickers)
Aelite LS	19.24 (115.73-134.97)	126.88 (6.58)
Filtek LS	7.03 (58.57-65.6)	62.23 (2.06)
Kalore	5.47 (50.63-56.10)	52.77 (1.59)
Empress Direct	3.20 (42.47-45.67)	44.14 (1.02)

^a Statistically significant differences found between each material ($p>0.05$).

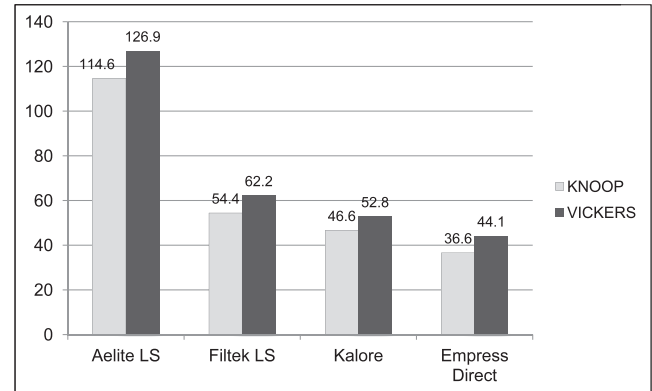


Figure 3. Comparison of values for Knoop and Vickers hardness for each material.

Surface Hardness: Vickers

Table 4 illustrates the range, means, and standard deviations for Vickers hardness. Aelite LS exhibited a significantly higher mean value than the other materials. Filtek LS was significantly lower than Aelite LS; Kalore was significantly lower than Filtek LS, and Empress Direct exhibited the lowest value. Statistical analysis showed significant differences between all the materials ($p<0.05$).

The distribution of Vickers hardness values for the 10 samples within each material again showed that Aelite LS had more variation in values (range=19.24) than the other materials. Filtek LS had less variation than Aelite LS (range=7.03), and Kalore had less variation than Filtek LS (range=5.47). Empress Direct had the least amount of variation (range=3.20).

Knoop and Vickers Hardness Compared

Figure 3 illustrates the comparison between the Knoop and Vickers hardness data for all materials. The Pearson correlation coefficient of the Knoop vs Vickers hardness tests showed that there was a very strong correlation between the two tests ($r=0.991$), with Vickers hardness values always significantly greater (independent t -tests, $p<0.01$).

Flexural Strength

Table 5 illustrates the range, means, and standard deviations for the flexural strength test. Aelite LS exhibited the highest value compared with other materials but was not significantly different from Filtek LS. Kalore and Empress Direct were similar but were significantly lower ($p<0.05$).

The distribution of flexural strength values for each material showed that Aelite LS had the

Table 5: Flexural Strength (MPa) for Each Material: Range, Mean, and Standard Deviation (n=10) ^a		
Composite	Range	Flexural Strength (MPa)
Aelite LS	55.01 (109.28-164.29)	135.75 (17.35) ^A
Filtek LS	25.28 (119.21-144.49)	129.42 (9.48) ^A
Kalore	30.00 (69.49-99.49)	86.84 (9.04) ^B
Empress Direct	29.43 (78.53-107.96)	92.96 (9.27) ^B
^a Values followed by the same superscript are not significantly different (p>0.05).		

greatest variation (range=55.01), while the other materials showed similar but lower variation (ranges=25.28-30.00).

DISCUSSION

This study tested the following hypotheses:

- Ho₁: There is no significant difference in polymerization shrinkage of different composite systems.
- Ho₂: There is no significant difference in flexural strength among different composite systems.
- Ho₃: There is no significant difference in surface hardness among different composite systems.
- Ho₄: There is no significant difference in the precision between Knoop and Vickers hardness tests.

There was a statistically significant difference among the materials tested for each physical property. Filtek LS had less shrinkage than the other composites. Aelite LS showed greater hardness for both Knoop and Vickers tests. Filtek LS had greater hardness than Kalore and Empress Direct. Aelite LS and Filtek LS had greater flexural strength than Kalore and Empress Direct. Therefore, the first three null hypotheses were rejected, and the fourth hypothesis was accepted. Composite shade A2 was selected for this study since it has a greater potential for full depth of cure at 2-mm thickness and has been used in prior research protocols.²¹

Polymerization Shrinkage

There are two general approaches for determining material shrinkage: volume dilatometry or non-

volume dilatometric methods.⁴ Dental composites polymerize from a viscous to a rigid material, and during the polymer conversion, the resin matrix produces a gel. It is at this gel point that the material can no longer provide viscous flow to keep up with the curing contraction. Therefore, the results of shrinkage determinations are dependent on the flow of the material. Conclusions regarding shrinkage values where the displacement transducer requires activation can monitor only the postgel part of the curing contraction because that is when the material is sufficiently strong to exert forces.²² In general, volumetric curing contraction determinations account for both the pregel and postgel curing contraction.² These are termed *free* shrinkage measurements. Non-volume dilatometric experiments are usually designed with either a contacting or noncontacting transducer. The dimensional change during contraction is considered “hindered” and is generally thought to account for only the postgel contraction.²² For this reason, the various linear shrinkage determinations are not standardized and are hard to compare.

The dental literature reports many devices in which volumetric polymerization contraction has been measured. Many experiments are designed with either a mercury dilatometer^{8,23} or a water dilatometer.² Dilatometry is arduous and protracted. It is also subject to data scattering when used for low-viscosity resins. Mercury dilatometry requires the handling of mercury (a toxic material), and as with water dilatometry, strict adherence to temperature control of the liquid medium is required. Maintaining a constant temperature environment for the water dilatometer is critical. To illustrate this point, the thermal expansion coefficient of water at 20°C is 20.7 × 10⁻⁴. For a dilatometer that contains 25 mL of water, a 0.1°C increase in water temperature will cause an increase of 2.67 mm in meniscus reading. A typical meniscus drop associated with the shrinkage in the work by Lai and Johnson² was 20 mm for the samples. Therefore, a 0.1°C temperature fluctuation could introduce 13.3% error. Considering the limitations of mercury and water dilatometry, these methods were not chosen for this experiment.

A more recent experimental design is the use of video imaging to measure volumetric shrinkage.⁷ Video imaging has been shown to produce volumetric shrinkage measurements of composites that are comparable to those obtained with mercury dilatometry.⁷ In addition, it is free of the hazards of handling toxic materials such as mercury. However, the

instrumentation is expensive and not readily available.

Non-volumetric dilatometric experiments measuring polymerization shrinkage can be determined linearly.²⁴ In 1991, Watts and Cash⁴ used a method to determine volumetric shrinkage indirectly by calculating the postgel linear displacement of a deflecting disk placed on composite. This technique measured the shrinkage between a glass microscope slide and a flexible glass diaphragm using a linear variable differential transformer displacement transducer. Grajower and Guelmann²⁵ determined the dimensional change of glass polyalkenoate cements by means of a linear displacement transducer. Feilzer and others²⁶ presented a modified technique for measuring the wall-to-wall shrinkage of composites. They used a linometer to determine the linear curing contraction from the start of the setting reaction. The linear contraction was determined by means of a noncontact displacement transducer. A thin layer of grease was needed to maintain contact between the two walls of the device and to ensure free shrinkage of the composite, thus determining the total (pregel and postgel) shrinkage. The current project methodology was patterned after the work of Herrero and others⁶ employing a K μ DA (Kaman Instrumentation Corp) contactless displacement instrument to measure the linear shrinkage of composite polymerized with an LED curing light.

One challenge in conducting the experiment was to reduce the amount of ambient light during the testing process. During each measurement, the laboratory lights were turned off, and the testing assembly was located in a remote area of the room to minimize the effect from air drafts. The composite was pliable and did not appear to set prior to the start of light exposure. Future shrinkage experiments should be done in total darkness or at least in a filtered environment that eliminates the ambient light that would cause the material to precure before polymer activation.

Another challenge in this experiment was the preparation of uniform uncured composite samples. To make the prepolymerization depth of 2 mm for each sample, approximately 2 mm of composite was expressed from the compule and placed on a glass slide in the center of a 2-mm-thick $\times$ 10-mm-wide Teflon ring. A second glass slide was lightly coated with Alcote and placed on the top of the composite. Finger pressure was applied to the top slide so that it eventually rested on the top of the ring. However, the composite tended to adhere to the top glass slide, and some manipulation was required to release it

from the sample. Thus, there was opportunity to develop voids and nonuniform sample thicknesses.

In the present study, Filtek LS had significantly less shrinkage than the other materials. Filtek LS was the only composite with the ring opening organic matrix, silorane. Aelite LS used ethoxylated Bis-GMA, Kalore employed urethane dimethacrylate and a proprietary matrix formula DX-511, and Empress Direct was composed of dimethacrylates. According to the manufacturer, silorane chemistry does not contain methacrylates, and the ring-opening monomers allow for lower polymerization shrinkage.

Surface Hardness

In this study, Aelite LS showed greater values for both Knoop and Vickers hardness, likely due to the high inorganic filler content of that material. Filtek LS had greater hardness than Kalore and Empress Direct, possibly due to the polymerization characteristic of the silorane matrix. Significant differences in hardness among the materials tested are related to the resin formulations, polymerization kinetics, and the type and loading of the filler particles.

For polymeric materials, an elastic recovery is present after removal of the load, and it could affect both measurements in the Vickers indentation. In a Knoop indentation, the elastic recovery would affect the shorter diagonal more than the longer diagonal. Consequently, since the Knoop measurement is based on the longest diagonal, the occurrence of elastic recovery will have less of an impact on the Knoop measurements than the Vickers measurements.¹⁷

When the results for the Knoop and Vickers hardness tests are compared, there was a strong correlation between results obtained using the two tests. The Vickers values were slightly higher than Knoop hardness measurements, and this could be due to the elastic recovery. The depth of the indentation is also related to the homogeneity of the surface being tested. One area of a sample may have higher filler content or larger particle sizes than another similar area and thus produce greater variation. This variation is most notable in Aelite LS, where the filler content is higher and the range of hardness values is much greater, especially for the Knoop test. Another factor is that the Knoop value is determined from a linear measurement, while the Vickers value is determined from an area measurement. Therefore, it is not possible to say which values are the most accurate. It would appear that

either test could be used to make material comparisons, but the Vickers test may be more relevant. As a result, the fourth null hypothesis can be accepted.

An alternative measurement involves the use of depth-sensing devices. These offer advantages because of their high resolution and ability to obtain information regarding the elastic properties of the tested material.²⁷ In this technique, the depth of the indentation is measured instead of a surface dimension. The depth-sensing device reports depth alterations under load and unload cycles. Therefore, the hardness and elastic modulus may be automatically reported. This is different from the visual measurement performed in a conventional hardness test. Lower loads are used, which produce much smaller indentations than Knoop and Vickers hardness tests. The Ultra Micro-Indentation System has been used to measure the hardness and elastic modulus of dental structures and is considered a reliable and reproducible method with relative operator ease in measuring.²⁸

Flexural Strength

Composite restorations are subjected to flexural stresses, especially in stress-bearing cavities (Classes I, II, and IV).¹² The flexural three-point bending test has been used to measure mechanical properties of a composite material and for predicting clinical performance of restorative materials (ISO specification 4049).¹⁰ It is stated that ISO specifications for height and width are acceptable because the dimensions of the specimens permit effective polymerization.⁹

In this experiment, the sample bars (25 × 2 × 2 mm) were prepared in accordance with the ISO 4049 specification. The length of the bar-shaped specimen exceeded the exit window diameter of the curing-light tip, so an overlapping light-curing exposure was required as curing progressed down the length of the bar. Recent studies have questioned the effect of the overlapping method on the flexural properties of dental composites, whereby the overlapped regions of bar-shaped specimens are subject to an increased light energy density, resulting in specimens that are cured inhomogeneously.⁹ It was also observed that the ISO 4049 standard is not relative to clinical placement of composite restorations since the geometry of the large bar-shaped specimen is disparate to that of actual direct fillings.

A possible solution is the use of biaxial flexure strength tests. This process has been recognized for the evaluation of dental ceramics²⁹ and has advantages over uniaxial, diametral tensile, and compres-

sive strength tests.³⁰ One study showed that biaxial flexure strength tests provided a more reliable testing method than did three-point flexure tests.³¹ The shape for a biaxial test disk (12-mm diameter × 2-mm thick) allows for a complete reproducible single-exposure cure without the need for overlapping curing light exposures.

In the present study, the flexural strength of Aelite LS and Filtek LS were not significantly different, but both were significantly greater than Kalore and Empress Direct, which were not significantly different. Increasing the load of reinforcing filler particles has enhanced the mechanical properties of composites. Aelite LS has a higher filler content than the other three materials, and this could account for the greater amount of flexural strength and surface hardness. However, Filtek LS had the lowest filler content and yet high flexural strength. This could be due to the use of silorane as a matrix material, which may improve resin resistance to flexural stress.

CONCLUSION

Within the limits of this *in vitro* study, the following conclusions were drawn:

1. There were statistically significant differences in polymerization shrinkage, surface hardness, and flexural strength among composite materials. Therefore, the first three null hypotheses of this study were rejected.
2. For polymerization shrinkage, Filtek LS had significantly lower shrinkage than Aelite LS, Kalore, or Empress Direct, which were not significantly different.
3. For surface hardness, all materials were significantly different for both Knoop and Vickers tests. Aelite LS > Filtek LS > Kalore > Empress Direct for both tests.
4. For flexural strength, Aelite LS and Filtek LS had significantly greater flexural strengths than Kalore and Empress Direct. Aelite LS = Filtek LS > Kalore = Empress Direct.
5. The Vickers hardness values were significantly higher than Knoop hardness measurements for each material. There was a strong correlation ($r=0.99$) between the two hardness tests. The fourth null hypothesis was accepted.

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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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Laboratory Research

Interfacial Nanoleakage and Bonding of Self-Adhesive Systems Cured with a Modified-Layering Technique to Dentin of Weakened Roots

E Mobarak • R Seyam

Clinical Relevance

Self-adhering systems demonstrated better bonding to root dentin than self-etch systems. A modified-layering technique with high-intensity light-curing units can be recommended when restoring weakened roots with light-curable adhesive materials.

SUMMARY

Objective: The purpose of the study was to evaluate the nanoleakage and bond strength of different self adhesive systems cured with a modified-layering technique (MLT) to dentin of weakened roots.

Methods: Twenty-one maxillary incisors were decoronated and then root canals were instrumented and obturated with the cold lateral compaction technique. Weakened roots were simulated by flaring root canals

until only 1 mm dentin thickness remained. Teeth were distributed into three groups. The canals were backfilled with Vertise Flow (VF group), a self-adhering system, following a modified-layering technique using two light-transmitting posts, sizes 6 and 3. DT Light Post size 2 was cemented using the same material. Remaining roots were prepared and cured in the same way as the VF group. However, in the TS/MF group, Clearfil Tri-S Bond (TS) adhesive and Clearfil Majesty Flow (MF) composite were used, while in the ED/PF group, ED primer II (ED)/Panavia F2.0 (PF) were used. After one week of storage, each root was sectioned to obtain six slices (two slices from each root third: coronal, middle and apical) of 0.9 ± 0.1 mm thickness. Interfacial nanoleakage expression was analyzed using a field emission scanning electron microscope (FEG-SEM), and the micro push-out

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bond strength (μ POBS) was measured at different root regions. Modes of failure were also determined using SEM. Data were statistically analyzed using two-way analysis of variance with repeated measures and Tukey *post hoc* test ($p \leq 0.05$).

Results: With MLT, all adhesive systems showed nanoleakage. For μ POBS, there was a statistically significant effect for adhesive systems ($p < 0.001$) but not for root region ($p < 0.64$) or for their interaction ($p = 0.99$). Tukey *post hoc* test revealed that the bond strength of the VF group was significantly higher than the TS/MF and ED/PF groups for all root regions.

Conclusion: All of the tested self-adhesive systems cured using MLT had slight nanoleakage and were not sensitive to root regional differences. Self-adhering systems had higher bond strength than self-etch adhesives.

INTRODUCTION

In clinical situations, it is not uncommon for patients to suffer from vertical root fractures of endodontically treated teeth, even when the endodontic treatment has been successful.¹ Thus, thin dentinal walls due to instrumentation and post preparation of endodontically treated teeth remains a restorative problem. Therefore, when restoring such teeth, it would be advantageous to reinforce the roots aiming to increase their resistance to fracture. Researchers have tested the reinforcing effect of different materials, including glass ionomer cements, hybrids of glass ionomer cements, and resin composites with different post systems, including metal or fiber posts.²⁻⁴ Fiber posts have further extended the applications of adhesive dentistry in endodontics and have been advocated because of their advantages of corrosion resistance, esthetic appeal, single-visit office placement, and easier removal for endodontic retreatment.⁵ Additionally, fiber posts with resin composites that bond to dentin have surpassed other approaches in increasing the fracture resistance.⁴ Nevertheless, the presence of multistep adhesives with technique sensitivity, the difficulty in material application, and curing effectiveness and the high C-factor (ratio of bonded to unbonded surfaces) in root canals make bonding to root dentin a real challenge.

In coronal restorations, to overcome the problems of multistep adhesives and their technique sensitivity, adhesive application steps were simplified ending up with the most recent single-step self-

adhering resin composite.⁶ Also, the use of a layering technique increased curing effectiveness,⁷ decreased the volumetric shrinkage,^{7,8} and decreased the C-factor.⁹ Applying these approaches while restoring the root canal presents an attractive solution to manage the problem of bonding to weakened root canals.

The use of the new light-cured self-adhesive resin composites would allow for proper application and extend the working time for the restoration of weakened roots. In root canals, plastic light-transmitting posts and recently the newer versions of fiber post were developed to help in light transmission to increase the depth of resin cure.¹⁰ However, it is accepted that light curing from the top of post spaces is insufficient to optimally polymerize light-curing adhesives and resin cements.¹¹⁻¹³ Whether the use of the light-transmitting posts in successive sizes to apply resin material in layers would lead to decreased volumetric shrinkage and C-factor while achieving effective curing leading to homogeneous bonding throughout the root dentin has not yet been investigated. For bonding behavior of the adhesives inside the canal, nanoleakage at the root dentin-adhesive interface was analyzed and bond strength measured. Simultaneous measurements of nanoleakage and bond strength were taken by many researchers to investigate the adhesive-dentin interface for coronal restorations,¹⁴⁻¹⁷ whereas preparation for nanoleakage measurements prior to bond strength were proven to have no influence on bond strength.^{18,19} Adoption of this approach while evaluating bonding to root dentin can be of value, as this would allow measuring bond strength and the evaluation of the sealing at the interface.²⁰

Thus, the objective of this study was to examine the interfacial nanoleakage and regional push-out bond strength of different self-adhesive systems, cured with a modified-layering technique, to dentin of weakened roots. The null hypotheses tested were the following: 1) the tested adhesive systems cured with a modified-layering technique would not reveal significantly different micro push-out bond strengths (μ POBS) to root dentin, and 2) the micro push-out bond strengths of each tested adhesive system cured with the modified-layering technique would not be significantly different among root sections.

MATERIALS AND METHODS

Tooth Selection and Standardization

Intact human maxillary incisors were collected, cleaned, and disinfected and then stored in saline

until use.²¹ Root length and mesio-distal and bucco-lingual diameters at the cemento-enamel junction (CEJ) of the collected teeth were measured by digital caliper (Mitutoyo digital caliper, Mitutoyo Corp, Kawasaki, Japan).³ Teeth (n=21) with similar root sizes and lengths were selected. The overall mean (range) root dimensions of all selected teeth measured at the CEJ were 5 ± 1 mm mesio-distally and 6 ± 1 mm bucco-lingually. The root length was approximately 15 ± 1 mm.

Tooth Preparation and Weakened Root Simulation

The anatomical crowns of teeth were cut off perpendicular to the long axis of the roots, leaving 2 mm coronal to the CEJ of the buccal surfaces using a low-speed IsoMet saw (IsoMet, Lake Bluff, IL, USA) under water coolant. The root canals were instrumented using the step-back technique at a working length of 1 mm short of the apex to a master apical file size 60 K-file (Mani, Tochigi, Japan) using 2.5% NaOCl irrigation (Clorox, Egyptian Company for Household Products, 10th of Ramadan City, Egypt) and coronally flared using Gates Glidden drills sizes 2 and 3. The smear layer was removed with 3 ml 17% EDTA (Prevest Denpro Ltd, Jammu, India) for 1 min. Then the canals were dried with paper points (Diadent, Seoul, Korea) and filled with gutta-percha (Diadent) and AH Plus resin sealer (Dentsply DeTrey GmbH, Konstanz, Germany) using cold lateral compaction. After endodontic treatment, the teeth were sealed with Coltosol F temporary filling (Coltène/Whaledent AG, Altstätten, Switzerland) and stored at 37°C and 100% relative humidity for 48 hours.

Coronal gutta-percha was removed using Peeso reamers (size 2; Dentsply Maillefer, Ballaigues, Switzerland) to a depth of 12 mm, leaving about 4 ± 1 mm of obturating material apically. To simulate the weakened root canal walls, the canals were enlarged apically to a depth of 12 mm using Peeso reamers (Dentsply Maillefer) of ascending sizes from size 3 (1.1-mm diameter) to size 6 (1.7-mm diameter) in all teeth. The canal spaces were flared, leaving approximately 1 ± 0.2 mm of dentin thickness between the internal prepared root canal wall and the external root surface at the cervical region using high-speed tapered diamond burs (Dentsply Maillefer). The remaining thickness was confirmed with a digital caliper (Mitutoyo digital caliper, Mitutoyo Corp).²² After flaring, bucco-lingual and mesio-distal radiographs were taken to ensure the homogeneity of root flaring. The roots were then centrally

embedded in polyester (polyester #2121, Eternal Chemical Co., LTD, Hsien, Taiwan) along their long axis following the methodology described by Mobarak and others.²³ In each canal, the smear layer was removed using 5 mL of 17% EDTA followed by 5 mL of 5.25% NaOCl as an irrigant. Final irrigation was accomplished with 10 mL of distilled water,²⁴ then air-dried with high-pressure airflow for five seconds.

Specimen Grouping

The embedded specimens (n=21) were then equally divided into three groups (n=7) according to the reinforcing materials used (Table 1) as follows:

VF Group—Seven flared specimens received Vertise Flow (VF) material (Kerr Corp, Orange, CA, USA), a light-cure self-adhering flowable resin composite, in three layering applications. A light coat of VF was first agitated onto the canal walls using a disposable microbrush applicator (Microbrush International Co, Grafton, WI, USA). A light-transmitting plastic post size 6 (Luminex, Dentatus USA Ltd, New York, NY, USA) was then inserted centrally in the root canal at the level of the apical gutta-percha, leaving circumferentially approximately 0.5 mm of thickness of VF resin composite material. Curing was done through the light-transmitting post for 80 seconds using Elipar S10 (3M ESPE Dental Products, St. Paul, MN, USA). The light-curing unit had an intensity ≥ 1400 mw/cm² and was checked using a radiometer (Kerr Corp). After curing, the light-transmitting plastic post was removed. A second layer of VF was then applied and cured with the aid of a size 3 light-transmitting plastic post (Luminex, Dentatus USA) to obtain a circumferential resin composite of thickness less than 2 mm. This layer was also cured for 80 seconds in the same way as the first layer. After curing, the light-transmitting post was removed. The remaining space was then filled with VF, then a DT Light Post (size 2, Bisco Inc, Schaumburg, IL, USA) was placed slowly and an additional 80 seconds curing applied.

TS/MF Group—Specimens (n=7) were filled as group 1, but the light-cure single-step self-etch adhesive system Clearfil Tri-S Bond and flowable resin composite Clearfil Majesty Flow (Kuraray Medical Inc, Tokyo, Japan) were used instead. Clearfil Tri-S Bond was applied according to the manufacturer's instructions. Light curing through size 6 light-transmitting plastic post for 80 seconds was done. The canals were then filled with Clearfil Majesty Flow using the other successive light-transmitting posts and finally the DT Light Post

Table 1: *Materials Descriptions, Manufacturers, Compositions, and Batch Numbers*

Material (Manufacturer)	Description	Composition and Batch Number
Clearfil Tri-S Bond (Kuraray Medical Inc, Tokyo, Japan)	Light cure Single-step self-etch adhesive system	MDP, Bis-GMA, HEMA, photoinitiators, ethanol, water, silanated colloidal silica (061232)
Clearfil Majesty Flow (Kuraray Medical Inc., Tokyo, Japan)	Light cure flowable resin composite	TEGDMA, silanated barium glass filler, silanated colloidal silica, hydrophobic aromatic dimethacrylate, di-camphorquinone (00308A)
Vertise Flow (Kerr Corp, Orange, C)	Light cure self-adhering flowable resin composite	Matrix: GPDM and methacrylate co-monomers Fillers: (70wt%): prepolymerized filler, barium glass, nanosized colloidal silica, nanosized ytterbium fluoride (3358782)
Panavia F2.0 (Kuraray Medical)	Dual-cure single-step self-etch resin cement	ED primer II Liquid A: HEMA (30-50%), MDP, <i>N</i> -methacryloyl-5-aminosalicylic acid, water, accelerator (61185). ED primer II Liquid B: <i>N</i> -methacryloyl-5-aminosalicylic acid, accelerator, water, sodium benzene sulfinate (61185). Paste A: hydrophobic aromatic and aliphatic dimethacrylate, hydrophilic aliphatic dimethacrylate, sodium aromatic sulfinate (TPBSS), <i>N,N</i> -diethanol- <i>p</i> -toluidine, surface-treated (functionalized) sodium fluoride < 10%, silanated barium glass (61185). Paste B: MDP, hydrophobic aromatic and aliphatic dimethacrylate, hydrophilic aliphatic dimethacrylate, silanated silica, photoinitiator, dibenzoylperoxide (61185)
Abbreviations: MDP, 10-methacryloyloxydecyl dihydrogen phosphate; Bis-GMA, bisphenol-A glycol dimethacrylate; HEMA, 2-hydroxy ethyl methacrylate; TEGDMA, triethylene glycol dimethacrylate; GPDM, glycerol phosphate dimethacrylate; Bis-EMA, ethoxylated bisphenol A glycol dimethacrylate; UDMA, urethane dimethacrylate.		

(size 2) following the same protocol as in the VF group.

ED/PF Group—Specimens ($n=7$) were filled and cured following the previously mentioned protocol in VF and TS/MF groups but using dual-cure self-etch primer adhesive/cement ED primer II/Panvia F2.0 (Kuraray Medical), which was applied according to the manufacturer's instructions. All specimens were stored in distilled water at 37°C for one week before bond strength testing. From each specimen, six horizontal slices of 0.9 ± 0.1 mm thickness each were cut from coronal, middle, and apical thirds of each root (two slices from each third) using a low-speed saw (IsoMet) under water coolant. Each slice was coded, and the apical and coronal diameters of the post were measured using a stereomicroscope (SZ-PT, Olympus, Tokyo, Japan). The exact thickness of each slice was measured using a digital caliper with 0.01-mm accuracy.

Nanoleakage Analysis

Slices were immersed in 50% ammoniacal silver nitrate solution, which was prepared according to the protocol described by Tay and others.²⁵ The slices were left in the silver nitrate solution in darkness for 24 hours, rinsed thoroughly in distilled water, and

immersed in photo-developing solution for eight hours under fluorescent light to reduce silver ions into metallic silver grains within voids along the bonded interface. Slices were then polished using SiC paper of increasing grit size (1200, 2500, and 4000) and rinsed with water for 30 seconds. Slices were then mounted on aluminum stubs. The composite-dentin and composite-post interfaces were analyzed for nanoleakage²⁶ using field emission scanning electron microscopy (FEG-SEM, Quanta 250, FEI, Eindhoven, The Netherlands) operated in the backscattered-electron/low-vacuum mode. Micrographs were captured at two magnifications (500× and 2500×).

Push-Out Bond Strength Testing

Each root slice was fixed to a specially constructed loading fixture and then subjected to a compressive load via a universal testing machine (Lloyd LRXplus, Lloyd Instruments Ltd, Fareham, United Kingdom) at a crosshead speed of 1 mm/min using three plungers of different sizes (1.3, 1, and 0.75 mm) for coronal, middle, and apical slices, respectively. The plunger tip was positioned so that it contacted only the bonded post. The push-out force was applied in an apico-coronal direction until bond failure oc-

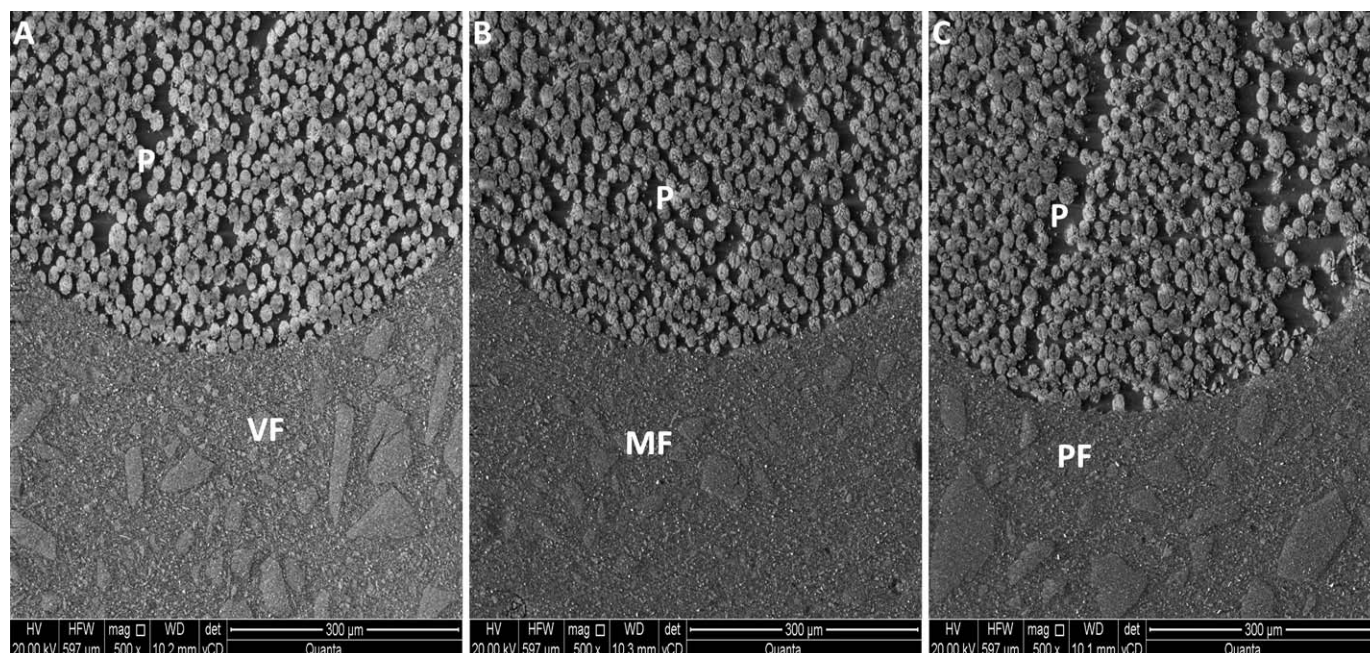


Figure 1. Representative scanning electron micrographs for the post (P) and resin materials interface: (A) VF, Vertise Flow; (B) MF, Majesty Flow; (C) PF, Panavia F2.0.

cured, which was manifested by extrusion of the post and a sudden drop along the load/time curve recorded by the testing machine. The maximum failure load was recorded in newtons and was used to calculate the micro push-out bond strength in megapascals (MPa) according to the following formula: Push-out bond strength (MPa) = Maximum load (N)/Post area (mm²). The post surface area (A) for each section was calculated as $\pi(r_1 + r_2) [(r_1 - r_2)^2 + h^2]^{0.5}$, where π is the constant 3.14, r_1 is the coronal radius, r_2 is the apical radius of the post, and h is the thickness of the slice in mm.²⁷

Two-way analysis of variance (ANOVA) with repeated measures was used to compare the effect of the adhesive system, canal region, and their interaction. This was followed by the Tukey *post hoc* test for pairwise comparison. The significance level was set at $p \leq 0.05$. Data were analyzed using the SPSS program for windows (Statistical Package for Social Sciences, release 15 for MS Windows, 2006, SPSS Inc, Chicago, IL, USA).

Failure Mode Analysis

Failed parts of the tested slices were mounted on an aluminum stub. Following sputter coating with gold, the slices were analyzed with a scanning electron microscope (SEM, XL30, Philips, Eindhoven, The Netherlands). Images were obtained with backscattered mode. Failure modes were evaluated at 50×

and classified as follows: 1) adhesive failure at dentin interface, 2) adhesive failure at the post interface, 3) cohesive failure within the adhesive material, 4) cohesive failure within the post, 5) cohesive failure within the dentin, and 6) mixed failure (adhesive at the dentin interface and cohesive in adhesive layer and/or in resin composite).

RESULTS

Nanoleakage

Representative images of the tested groups can be seen in Figures 1 through 4. Adaptation between the tested adhesives to the posts was confirmed. No silver nitrate deposits were seen for all groups at the resin composite–post interface after storage for one week (Figure 1). However, slight silver nitrate deposits were seen at the composite–dentin interfaces in all groups (Figures 2 through 4). An adhesive layer was detected in the TS/MF and ED/PF groups, where no silver uptake was detected at the interfaces between these adhesive layers and resin composites (Figures 3 and 4).

Push-Out Bond Strength

Two-way ANOVA with repeated measures revealed that there was a statistically significant effect for adhesive systems ($p < 0.001$) but not for root region ($p < 0.64$) or for their interaction ($p = 0.99$). Means and standard deviations of the μ POBS values of all

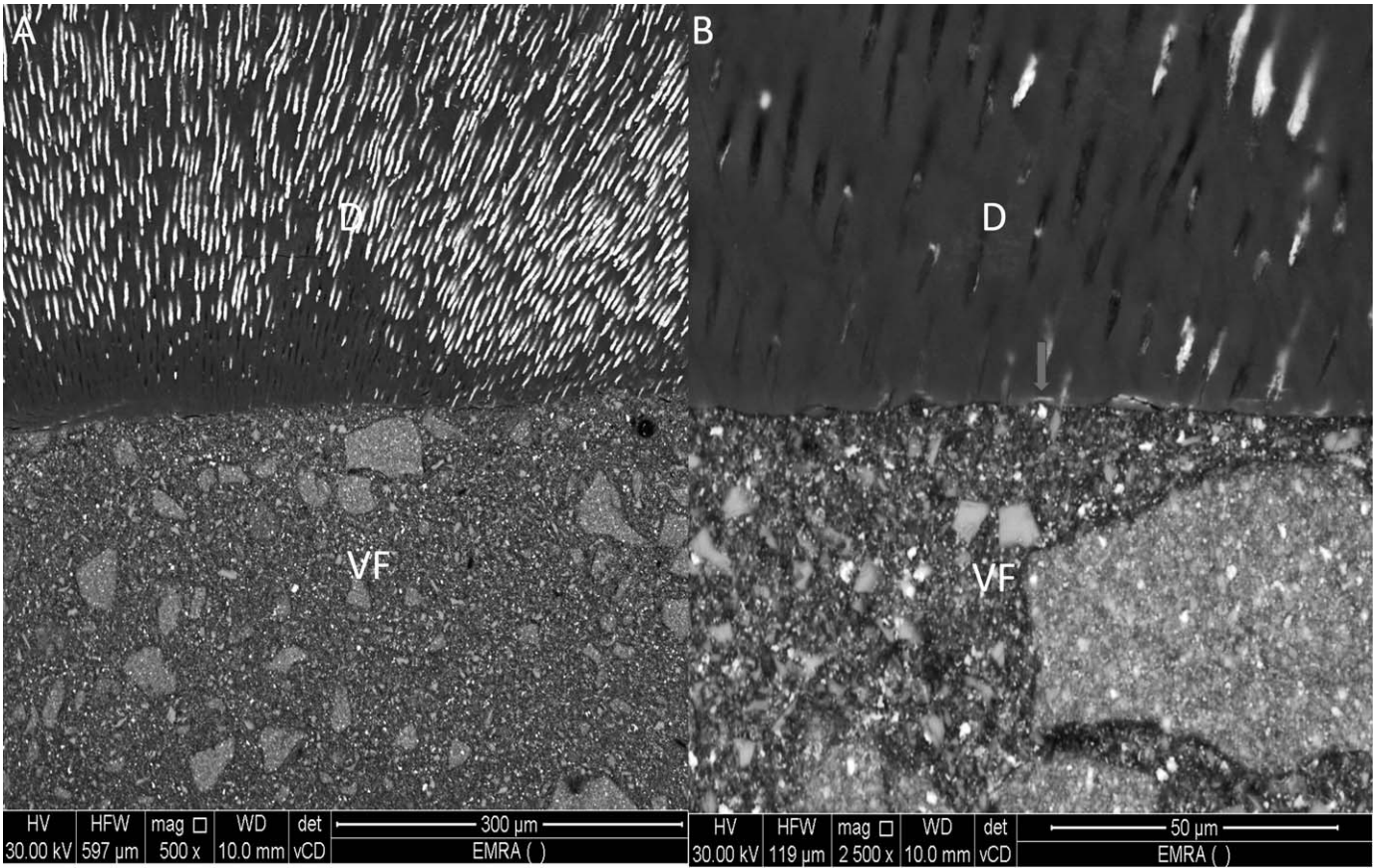


Figure 2. Representative scanning electron micrographs demonstrating the Vertise Flow (VF) and dentin interface with few silver nitrate uptake (solid arrows). No hybrid layer, adhesive layer, and resin tags were recorded.

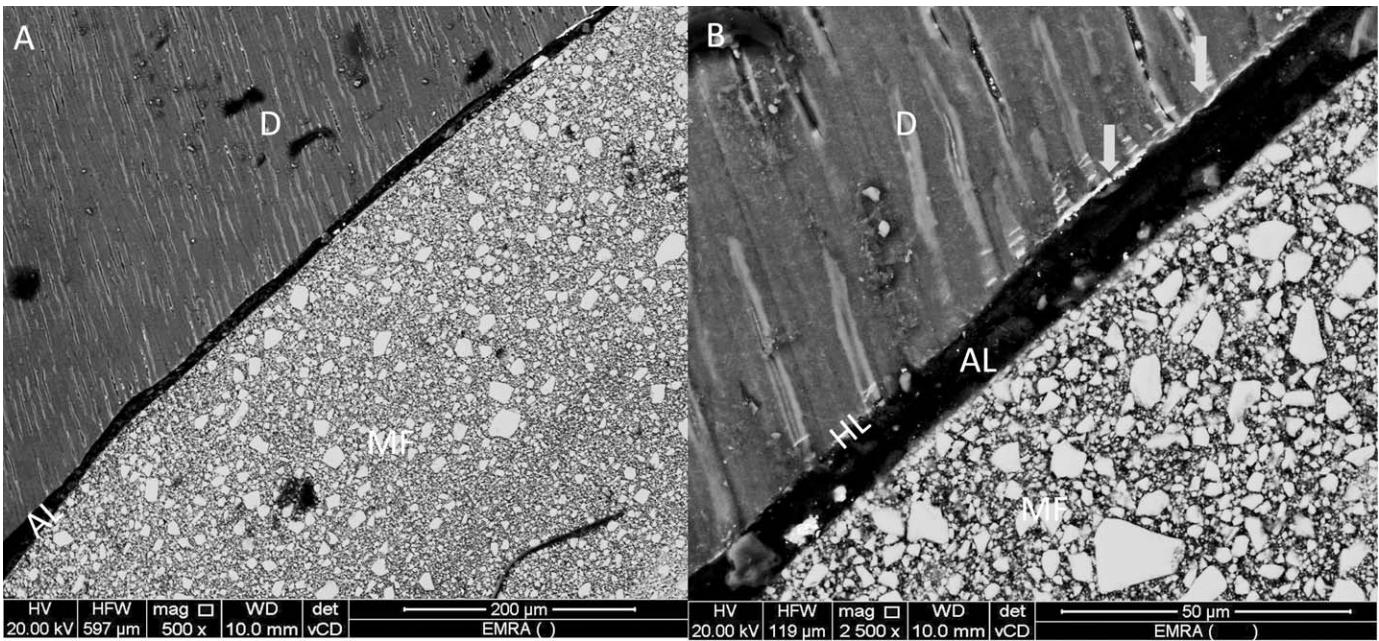


Figure 3. Representative scanning electron micrographs demonstrating the Clearfil Tri S Bond (TS)/Majesty Flow (MF) and dentin interface with few silver nitrate uptake (solid arrows). Hybrid layer (HL) as well as adhesive layer (AL) were detected, while no resin tags were recorded.

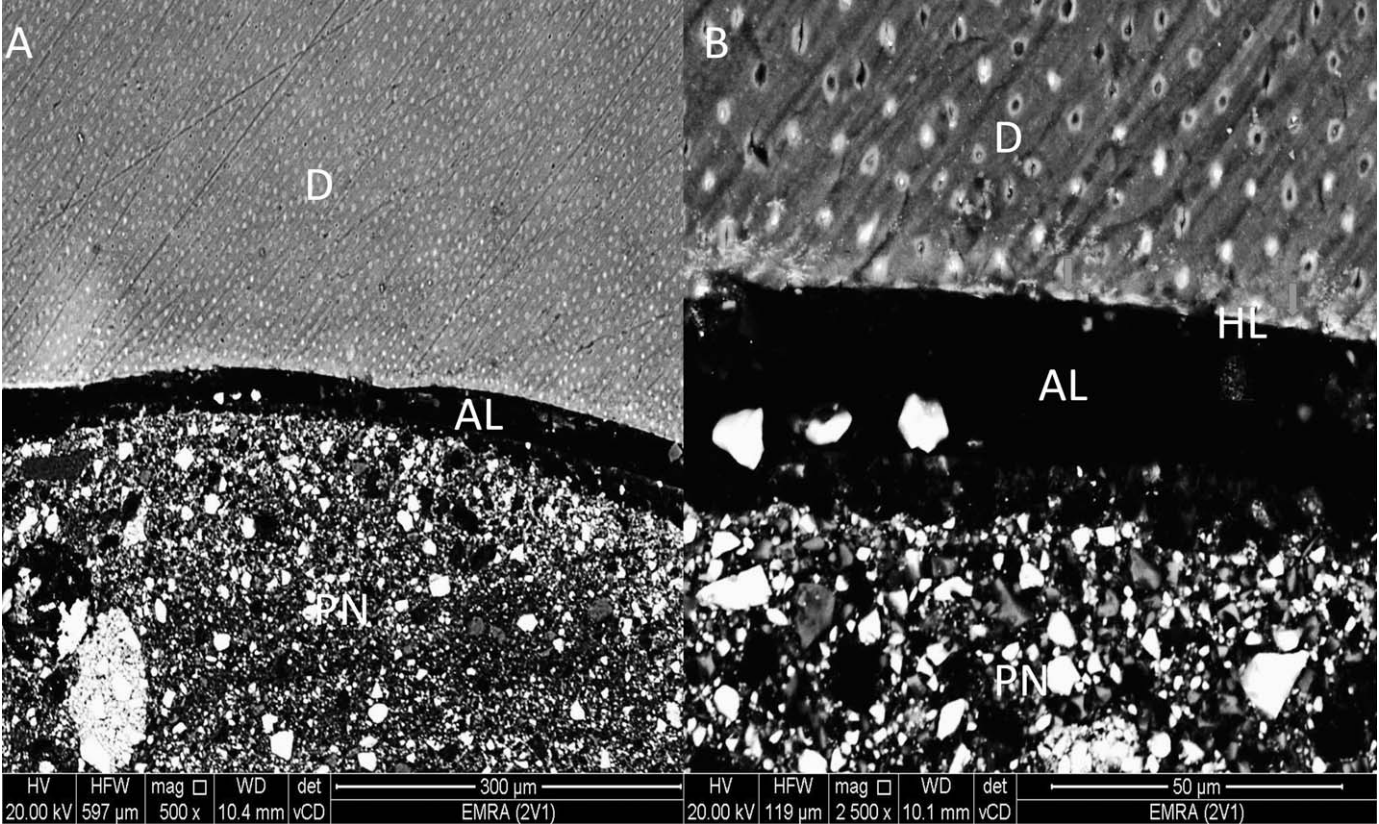


Figure 4. Representative scanning electron micrographs demonstrating the ED primer II/Panavia F2.0 (PF) and dentin interface with few silver nitrate uptake (solid arrows). Hybrid layer (HL) as well as adhesive layer (AL) were detected, while no resin tags were recorded.

tested groups are presented in Table 2. There was a significant difference among the adhesive systems for each root region (Table 2). As shown in Table 2, Tukey *post hoc* test revealed that the VF group was significantly higher than the TS/MF and ED/PF groups for all root regions.

Failure Mode Analysis

Failure mode analysis is shown in Figure 5. Exclusive cohesive fracture in the post or in the adhesive material was not seen. Overall, the majority of failures were mainly adhesive at the dentin side rather than mixed failure. Representative SEM

Table 2: Micro Push-Out Bond Strength (μ POBS) Values (Mean [SD]) in Mpa of Tested Groups ^a				
Root Region	Micro Push-Out Bond Strength Values (Mean [SD]) in (MPa)			
	VF group	TS/MF group	ED/PF group	p-Value
Coronal	19.1(5.3) aA	14.4(3.3) bA	13.2(4.2) bA	0.01
Middle	18.6(5.8) aA	13.1(4.3) bA	11.3(2.9) bA	0.00
Apical	18.0(5.5) aA	14.1(4.8) abA	12.8(3.1) bA	0.04
p-Value	0.90	0.78	0.47	
Abbreviations: VF, Vertise Flow; TS, Clearfil Tri S Bond; MF, Majesty Flow; ED, ED primer II; PF, Panavia F 2.0.				
^a Within rows, means with same small letters denote no statistical significant difference among restorative groups ($p>0.05$; Tukey test). Within columns, means with same capital letters indicate no statistical significant difference among root regions ($p>0.05$; Tukey test).				

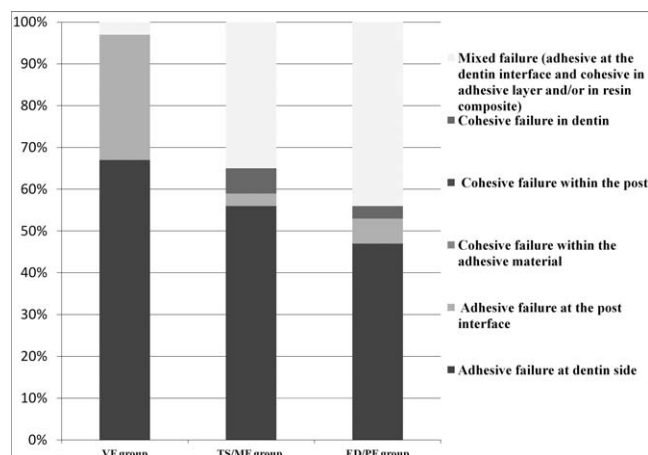


Figure 5. Modes of failure of tested groups. VF, Vertise Flow; TS, Clearfil Tri S Bond; MF, Majesty Flow; ED, ED primer II; PF, Panavia F2.0.

images for the detected modes of failure for each group are presented in Figure 6.

DISCUSSION

Achieving good bonding and sealing at the dentin-adhesive system interface are crucial criteria for a restoration to be considered successful, especially when used with weakened tooth structure. In the present study, nanoleakage was analyzed using FE-SEM, which was reported to reveal less accurate observation of nanoleakage within the hybrid layer than did the transmission electron microscope (TEM).²⁸ Yet FE-SEM enables the entire root slice to be observed without further preparation, reducing the risk of missing the presence of silver particles in areas not sectioned by the ultramicrotome used for TEM specimen preparation.²⁹ In addition, when FEG-SEM is used for analysis, low vacuum mode can be used. The slices require neither desiccation nor coating with gold-palladium. Thus, their original characteristics can be preserved for further testing. FEG-SEM micrographic pictures showed slight nanoleakage at the dentin interface with all tested adhesives. The slight nanoleakage recorded for the VF group could be attributed to the claimed chemical adhesion to hydroxyapatite of root dentin. The bonding mechanism of the VF is based primarily on the chemical bond between the phosphate functional group of GPDM monomer and calcium ions of the tooth. VF contains fluoride in the fillers. It has been speculated that minor nanoleakage could be related to the water repulsion effect of fluoride, which may help to reduce residual water in the bonding interface and improve its resistance to hydrolytic degradation.³⁰ There are no data in the available

literature concerning the nanoleakage behavior of VF. ED primer II and Clearfil Tri-S Bond, as previously mentioned, contain MDP, which tends to react with hydroxyapatite to form calcium salt.³¹ The MDP-calcium salt formed has low water solubility, rendering the interfacial bond hydrolytically stable.³² The present study results support the suggestion that the use of MLT may decrease the volumetric shrinkage, leading to better adaptation at the interface between dentin and the tested adhesive systems. This is similar to what happens with coronal restorations when the incremental layering technique is applied.⁸ However, it should be clearly stated that whether this favorable result would last over time requires further research. Bitter and others²⁹ recorded distinctive silver uptake with ED primer II/Panavia F2.0 after thermocycling.

In the current study, bond strength was measured using the μ POBS test. This testing method was preferred to other methods, such as pullout testing or microtensile bond strength, for several reasons. One reason is the ease in slice preparation and testing. Also, this testing method allows fabrication of several slices out of one root as well as testing for regional differences among root sections.^{24,33} In contrast to microtensile bond strength testing, the push-out design showed no premature failures and an acceptable variability of the data distribution.³⁴ It was suggested that the push-out bond strength method results in shear stress at the interface between post and cement, causing failures to occur parallel to the post-cement-dentin interface, which is comparable to clinical conditions.³⁵ However, another study suggested that forces during testing cannot be directly compared with functional forces that the post needs to withstand during clinical service. Also, the effect of friction seems to influence bond strength results.^{35,36} It is also possible that the sectioning process can induce artifacts that can result in a relatively high coefficient of variation.²⁷ In the present study, using the very thin slices (<1 mm thickness), the funnel-shaped preparation,³⁷ and the placement of slices in an apico-coronal direction during testing might have played a role in minimizing the frictional forces. The cautious sectioning using the slow-speed IsoMet saw prevented sectioning artifacts as confirmed during the inspection of the slices for nanoleakage analysis. A control group in which the tested adhesive materials were applied without MLT (ie, applied in bulk) was not included in the present study. The pilot study showed that this approach revealed a marked gap between the dentin and the adhesive material due to the large

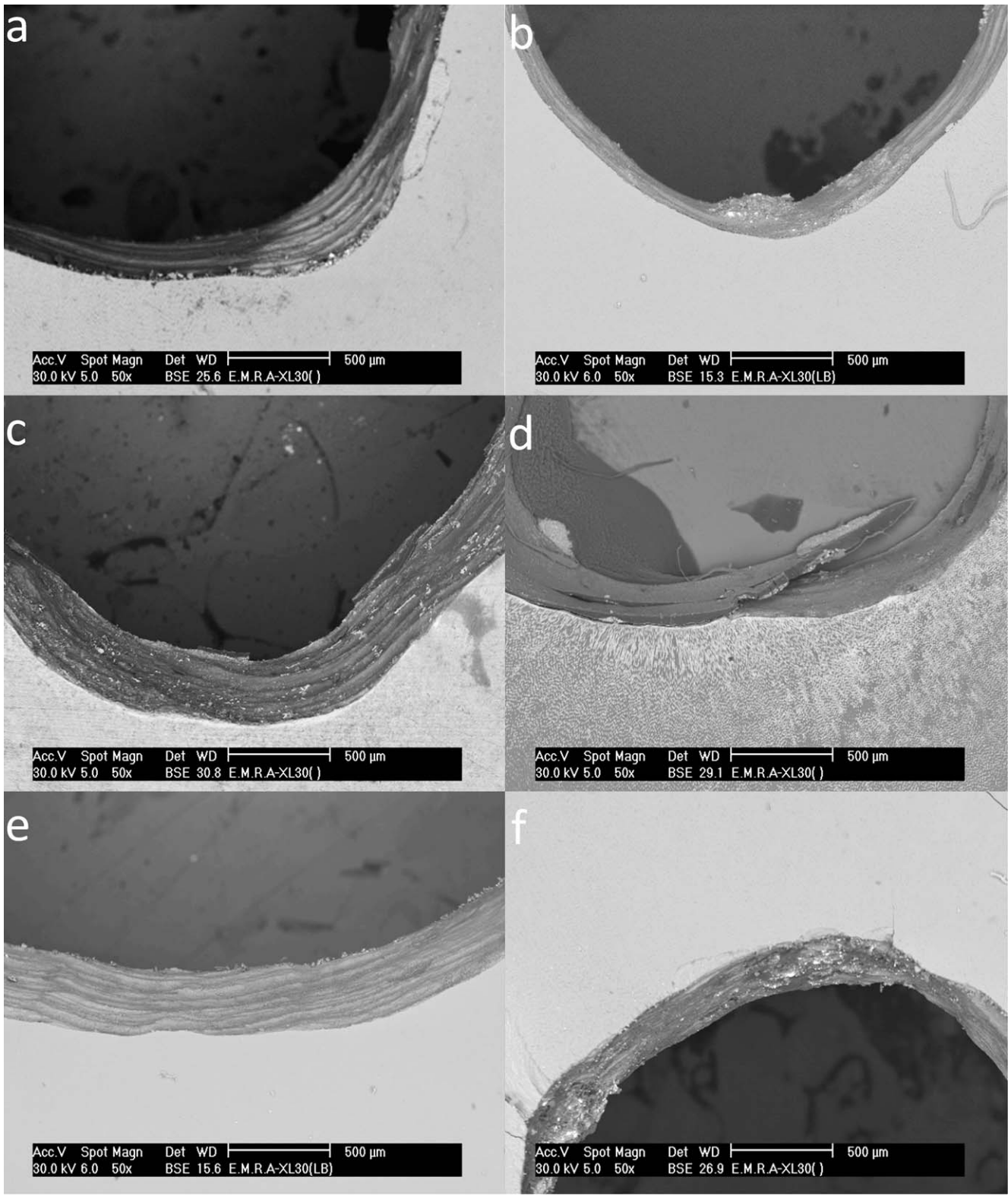


Figure 6. Representative scanning electron micrographs (SEM) for the most frequently detected mode of failures. a, c, and e show adhesive failure at the dentin interface, while b, d, and f show mixed mode of failure (adhesive at the dentin interface and cohesive in adhesive layer and/or in resin composite) for the VF group, TS/MF group, and ED/PF group, respectively. VF, Vertise Flow; TS, Clearfil Tri S Bond; MF, Majesty Flow; ED, ED primer II; PF, Panavia F2.0.

volume of the material required to be cured at once. Previous work proved that bulk application of direct resin results in a pulling away of resin from dentin walls, dramatically threatening the tooth-resin bond strength.³⁷

In the present study, VF, the self-adhering system, had statistically significant higher bond strength than self-etch systems (Clearfil Tri-S Bond/Majesty Flow as well as ED primer II/Panavia F2.0). This finding suggests the rejection of the second null hypothesis. Although previous studies did not test the same material, they reported statistically higher bonding performance of self-adhering than self-etch systems, which to a certain extent supports our findings.^{27,34,38,39} On the other hand, it should be mentioned that other studies contradicted this claim.^{33,40} Although the materials used in this study are common in their approach (ie, self-adhesive systems), other factors, such as application technique, chemical composition, and polymerization mode, could have affected their bonding. Panavia F was used after the application of ED Primer II, a two-bottle (Liquid A and Liquid B primers) self-etch adhesive system, while Majesty Flow was applied after Clearfil Tri-S Bond, a single-step self-etch adhesive system. VF is a self-adhering flowable composite. Panavia F2.0 showed the least bond strength. This might be due to its unfavorable cohesive strength,²⁷ which was manifested in the present study with a higher percentage of mixed mode of failure. For the polymerization mode, most studies have recommended the use of self-cured or dual-cured adhesives to guarantee adequate polymerization, especially in the apical part of the post space.^{11,12} Yet in our study, the dual-cured Panavia F2.0 did not perform better than the light-cured tested materials. Other investigators also found no difference⁴¹ or even better performance⁴² of light-cured to dual-cured adhesive systems. Interestingly, the current study result corroborated these studies despite the expected larger material volume that had to be cured as the canals were enlarged, simulating weakened roots. However, the use of MLT allowed the control of volume of material to be cured.

Bonding to root dentin is still a challenge because of root dentin regional differences in bond strength. Many studies have shown that the cervical bond strength was higher than the middle and apical ones.^{24,39,40} Regional differences in bond strength were attributed to the difficulty in visualization and access to the apical part.⁴³ Differences in polymerization degree throughout the root length as well as

the C-factor are also important factors.⁴⁴ Additionally, variation in quantity, volume, and orientation of the tubules toward the apical portion of the root canal might play a role, making it difficult for the adhesive system to penetrate and form resin tags.⁴² All materials used in this study showed no difference in bond strength at different root regions, thus corroborating the third hypothesis. The indifference in regional bond strength reported for VF echoed that of Giachetti and others.⁴¹ Also, the results of Panavia F2.0 agreed with other studies.^{33,34,42,43} No data could be retrieved regarding the regional bond strength of Clearfil Tri-S Bond to root dentin.

The present study results might be attributed to some factors: The funnel-shaped preparation might have allowed proper material application at the apical part even with VF, which required agitation according to the manufacturer's instructions. The use of the high-intensity LED light-curing unit, together with the new suggested modified-layering technique used in the present study, might have allowed proper polymerization even at the apical part of the post space. Other researchers who found no regional differences in bond strength values expected that the light passing through a light-transmitting post might be able to activate the thin resin layer surrounding the post surface, enabling the resin to cure promptly along the post.⁴⁴ The successive usage of light-transmitting post in the modified-layering technique might have also decreased the C-factor. The lack of adhesion between the light-transmitting posts and tested materials was confirmed by the ease of post removal after curing. Another reason for the insignificant difference among root regions might be the self-adhesive approach of all tested adhesive systems. The effect on bond strength due to regional difference seems to be more pronounced in the etch-and-rinse approach but has less effect on self-adhesive systems.⁴² Self-adhesive systems bond to the superficial layer of dentin and do not completely remove the smear plugs.^{42,45} Thus, their bonding efficacy may be more dependent on the formation of the hybrid layer than on resin tags, where the surface area of intertubular dentin plays a greater role rather than the number of dentinal tubules available for penetration. This was confirmed by FEG-SEM, where no resin tags were seen in the present study.

Analysis of the failure modes in the present study revealed that most failures occurred between dentin and tested adhesive systems, which is in accordance with the results of published investigations.^{27,33,34,43} In the present study, no silane pretreatment was

performed on the post surface, yet we had fewer adhesive failures at the post interface. For Panavia F2.0, this might be attributed to bonding between MDP and the epoxy matrix of DT Light post.⁴⁶ However, Clearfil Majesty Flow and VF have no MDP in their chemical composition. The current study, and other *in vitro* studies,^{35,40} support the general clinical finding that fewer failures were noted at the post interface, indicating that no post pretreatment is needed. On the other hand, since the weak point was at the dentin side, dislodgement would be the main problem in such instances. Meanwhile, direct application of the results of the present study to clinical situations should be done with caution, as the longer storage time and/or thermal cycling might give different results.

CONCLUSIONS

All of the tested self-adhesive systems that cured using MLT had slight nanoleakage and were not sensitive to root regional differences. Self-adhering systems had higher bond strength than the other self-etch adhesives.

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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***In Vitro* Performance of Class I and II Composite Restorations: A Literature Review on Nondestructive Laboratory Trials—Part I**

D Dietschi • A Argente • I Krejci
M Mandikos

Clinical Relevance

In vitro research remains of primary importance to selecting and validating the techniques and products to be used *in vivo*. However, the clinical predictive value of such tests needs to be appraised and ranked to provide meaningful help toward the clinical decision-making process.

ABSTRACT

Posterior adhesive restorations are a basic procedure in general dental practices, but their application remains poorly standardized as a result of the number of available options.

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An abundant number of study hypotheses corresponding to almost unlimited combinations of preparation techniques, adhesive procedures, restorative options, and materials have been described in the literature and submitted to various evaluation protocols. A literature review was thus conducted on adhesive Class I and II restorations and nondestructive *in vitro* tests using the PubMed/Medline database for the 1995-2010 period. The first part of this review discusses the selected literature related to photoelasticity, finite element analysis (FEM), and microleakage protocols. Based on the aforementioned evaluation methods, the following parameters proved influential: cavity dimensions and design, activation mode (light or chemical), type of curing light, layering technique, and composite structure or physical characteristics. Photoelasticity has various limitations and has been largely (and advantageously) replaced by the FEM technique. The

results of microleakage studies proved to be highly inconsistent, and the further use of this technique should be strictly limited. Other study protocols for adhesive Class II restorations were also reviewed and will be addressed in part II of this article, together with a tentative relevance hierarchy of selected *in vitro* methods.

INTRODUCTION

The use of posterior adhesive restorations as a primary treatment for caries or as a substitution for metal-based restorations remains a basic procedure in general dental practices.¹⁻³ However, it is presently a poorly standardized treatment as a result of the number of available options for nearly each clinical step involved. It generally is accepted that small cavities will be restored with a direct technique, likely using an incremental approach, and that multiple large cavities will be restored with an indirect technique.⁴ Anything in between these two opposite clinical situations currently lies in a gray zone, thus leading to countless "speculations" and concepts often founded on limited evidence.

The clinician must thus consider which is the ideal adhesive approach and system, whether or not to use a base or liner, which is the best restorative material, and which restorative approach (direct or indirect) should be used. When a direct approach is chosen, thought must then be given to what type of layering technique (if any) should be applied. This represents a substantial number of combinations, which tremendously complicates the clinical and operative choices. Searching for literature evidence neither leads to a straightforward answer nor helps in making easy decisions as a result of the overwhelming number of studies evaluating Class II restoration quality and behavior. This abundant literature deals with various *in vitro* and *in vivo* studies and requires a strategy to identify the most relevant information. While an evidence hierarchy has been established for *in vivo* studies in biomedical science,⁵⁻⁸ the same thinking process has not yet been applied to *in vitro* research.

While everyone agrees that clinical studies ultimately confirm the validity of any treatment option, the impact of *in vivo* research remains counterbalanced by many factors. These include the number of available restorative protocols and products but also by several other inherent limits and drawbacks related to patient selection, sample size, number and qualification of operators, evaluation criteria and methods, the significant resources required,

and, last but not least, the time frame.¹⁻³ In regard to this latter point, and despite the absence of a formal consensus, clinicians and researchers have logically suggested running medium- to long-term studies to ascertain operative protocols and material choices. Several authors have then proposed that evaluation periods should not be shorter than three to five years.^{9,10} Regrettably, the rapid turnover of dental product and application protocols tends to lessen the validity of otherwise-legitimate long-term studies. This is why a number of preclinical, *in vitro* evaluation protocols were developed to overcome the aforementioned clinical trial boundaries.⁹⁻¹¹ Recent literature reviews on the *in vivo* performance and longevity of various posterior restorations have identified mainly four kinds of failures (with the exception of early failures associated with faulty material handling), and these are marginal defects or secondary caries (interfacial failures) and restoration fractures or excessive wear (material failures).^{1,3,12,13} With regard to posterior composite restorations, interfacial failures appeared to prevail in a large number of studies.^{12,13} This actually explains why the majority of protocols applied to evaluate the *in vitro* performance of adhesive restorations focus on phenomena that influence adhesive interface quality and stability. However, the interest and real predictive value of the many laboratory tests should be discussed and their possible clinical relevance estimated more precisely.

Therefore, the purpose of this review was first to search for and select *in vitro* studies on Class I and II adhesive restorations using nondestructive tests, according to the research protocol and hypothesis. The second objective was to critically appraise selected articles and to propose a classification and hierarchy of laboratory protocols based on the quality, quantity, and consistency of the evidence, in particular, toward a likely clinical significance. The third resulting objective was to draw conclusions and recommendations in regard to the best restorative protocols and materials based on the results of nondestructive *in vitro* evaluations of adhesive posterior restorations. The first part of this review will detail the search strategy and classification of selected references according to study protocol and hypotheses as well as an appraisal of photoelasticity, finite element analysis (FEM), and microleakage studies.

MATERIALS AND METHODS

Search Strategy

The search strategy included a review of the PubMed/Medline database, with use of the following

primary key words: *in vitro*, Class II, posterior composites, inlays and onlays, tooth colored, and composite. Additional key words related to study hypothesis (such as cavity configuration, polymerization, or light-curing, or to study methodology, such as finite element analysis, photoelasticity, leakage and microleakage for part I of this review, and resistance to fracture or deformation, shrinkage stress, tooth deformation, bond strength and microtensile bond strength, marginal and internal adaptation for part II of this review) were used to identify all existing references. The search was conducted with the limit "Dental Journal." The review was conducted from 1995 to 2010. Perusal of the references of relevant articles allowed completion of the review (references of the references). A few older "major" references were used to supplement these aforementioned resources when appropriate. The selection and analysis process led us to study exclusion in cases of insufficient group description, undefined hypothesis, operative protocol, or results, including statistical analysis. The articles were first classified according to the experimental protocol, with each one corresponding to a specific review table, as follows:

- I. Photoelasticity,
- II. FEM (two dimensional [2D]/three dimensional [3D]),
- III. Microleakage,
- IV. Deformation resistance and fracture resistance to cyclic loading (mere fracture testing was not considered),
- V. Shrinkage stress and tooth deformation,
- VI. Bond strength (microtensile, tensile, and shear tests), and
- VII. Marginal and internal adaptation.

Subsequently, for each experimental protocol and table, selected references were then subclassified according to the parameters/hypotheses investigated. For microleakage, bond strength, and marginal adaptation protocols, the type of restoration was also taken into account (direct and indirect composite restorations only or comparisons between direct and indirect techniques), together with the most relevant subparameters identified within selected studies. The references strictly related to indirect ceramic and CAD-CAM/Cerec® (Sirona, Bensheim, Germany) restorations or restoration fit, as well as those dealing with restorations of deciduous teeth, were excluded from this review. In addition, wear tests and studies measuring restoration fracture resistance to monotonic stress/loading (in general, all

kinds of destructive tests) were not taken into consideration for this literature review.

Appraisal and Rating of Study Protocols and Results

The overall strength of evidence for clinical topics and reviews is usually defined by three factors: the quality, quantity, and consistency of the evidence. This approach, introduced in 1994,¹⁴ is now well established and is largely used to develop practice guidelines and other health-related policy advice.^{8,15-18} The "quality" refers to a study protocol that follows strict rules to limit selection, measurement, and confounding biases. The "quantity" refers mainly to the number of studies having evaluated the same topic and the overall sample size across all included studies. The "consistency" is defined by the extent to which similar findings are reported using similar or different study designs.⁸ This review tentatively applied this evidence "rating approach" whenever possible and when appropriate for an *in vitro* research field.

I. Photoelasticity—Photoelasticity aims to visualize stresses generated by different restorative techniques using composite¹⁹⁻²² or resin,^{23,24} placed in different substrates (such as transparent composite or resin, composite, and bovine teeth).^{21,25} After sectioning the samples, stress patterns and magnitude within the transparent material (restoration or cavity) are evaluated under a polarizing microscope. The photoelasticity studies that were reviewed are presented in Table 1.

The use of bovine teeth as a substrate proved inadequate for photoelasticity studies when a bulk technique was applied because of large gap formation, which lowered stresses.^{19,21} Self-curing and light-curing composites showed similar stress distribution patterns, while stress magnitude and development proved significantly different. Interestingly, maximal average stress in a self-curing material was only 12 MPa, vs 23 MPa in a light-curing material.¹⁹⁻²¹ Stress distribution and magnitude also proved to be influenced by cavity depth (less stress in a shallow cavity) and internal cavity design (less stress with internal bevel compared to box-shaped cavity).²² No differences in stress distribution or magnitude appeared between butt or round beveled margin designs.²² In two other studies,^{23,24} shrinkage stresses generated by a bulk technique proved surprisingly lower than those generated by different incremental techniques' but this later finding is in disagreement with those of several marginal adap-

Table 1: Selected Literature References for Photoelasticity
Kinomoto and Torii, 1998 ¹⁹
Kinomoto and others, 1999 ²⁰
Kinomoto and others, 2000 ²¹
Kinomoto and others, 2003 ²²
Jedrychowski and others, 1998 ²³
Jedrychowski and others, 2001 ²⁴
Wiegand and others, 2007 ²⁵

tation and bond-strength studies, as reviewed further in this article.

Conclusion: Photoelasticity

The main drawback of the photoelasticity approach is that the use of resin or composite replicas does not properly mimic the physical properties and behavior of natural teeth, as it produces a more perfect interface (composite-composite or composite-resin) than actually occurs in clinical conditions. The use of bovine teeth as a potential substrate also proved unsuccessful, with excessive gap formation, and, therefore irrelevant, low stress buildup within the restoration was observed. Furthermore, the photoelasticity approach is unable to mimic the effect of repeated functional or thermal stresses, which are responsible for restoration fatigue, the dominant pattern involved in clinical failures.

The protocol quality was considered “low,” as was the quantity of evidence. The consistency is also problematic for photoelasticity, making the overall strength of evidence insufficient. FEM is therefore more widely used to visualize and estimate the magnitude of polymerization contraction stresses in Class II restorations.

II. Finite Element Analysis—The FEM or analysis originated from the need to solve complex elasticity and structural analysis problems in civil and aeronautical engineering. Its development can be traced back to the work of Alexander Hrennikoff²⁶ and Richard Courant in 1943.²⁷ While the approaches used by these pioneers are dramatically different, they share one essential characteristic: the mesh discretization of a continuous domain into a set of discrete subdomains, usually called elements. This technique appeared in the study of composite polymerization stresses and restorative dentistry in the late 1980s^{28,29} and has since become a major tool for analyzing and understanding those phenomena. The FEM studies that were reviewed are presented in Table 2.

Model validation, natural tooth structure, and function

The micro-computed tomography scan was considered an effective method with which to develop 3D FEM models.^{30,31} Different studies also evaluated the development and distribution of stresses within normal posterior tooth structure to be used as references for FEM analysis. It was first shown that the behavior of enamel and dentin under different load axes was independent.³² The distribution and level of stresses also proved to be influenced by force direction (working or nonworking movements)³³ as well as by the elasticity modulus of the food morsel.³⁴ Maximal stresses were found in the occlusal enamel, the central groove of maxillary molars, and the lingual cusp of mandibular molars.^{33,34} Supporting cusps were generally well protected during both working and nonworking movements, while non-supporting cusps sustained mainly tensile stresses.³³ The chewing of nonhomogeneous morsels was also considered to produce the least favorable condition.³⁴

For restored teeth, the FEM approach was validated by comparing simulated stresses to those measured on natural teeth using different restorative solutions.^{30,35} It was then considered valid to use a linear elastic approach based on the post-gel shrinkage concept to calculate residual stresses in a tooth restored with composite.³⁵

Cavity design and dimensions

The relationship among cavity design, volume, and contraction stress was clearly established more than 20 years ago by the team of Davidson and Feilzer.^{28,36-38} However, at that time it proved impossible to visualize and precisely quantify stress distribution at interfaces or within the restored tooth structure. Since then, FEM studies have enabled a considerable progression of our understanding of stress development within complex material assemblages and restorative models.

Cast gold restorations, unbonded or bonded composite MOD restorations, and cavity size all proved influential factors for stresses.^{39,40} The unbonded condition was, however, less favorable and more prone to generate damaging stresses for the tooth. In cast gold restorations, depth was also the most critical factor governing stress elevation in enamel, while interaxial thickness (cavity floor width, in-between proximal preparations) was the most critical factor for dentin.³⁹ The influence of composite shrinkage stress in different Class I and II cavity geometries was evaluated in natural teeth and theoretical FEM models. The behavior of both

Table 2: *Selected References for Finite Element Analysis (FEM)*

Model validation, natural tooth structure and function
Verdonschot and others, 2001 ³⁰
Magne, 2007 ³¹
Goel and others, 1990 ³²
Magne and Belser, 2002 ³³
Dejak and others, 2003 ³⁴
Versluis and others, 2004 ³⁵
Cavity design and dimensions
Morin and others, 1988 ²⁸
Versluis and others, 2004 ³⁵
Davidson and others, 1984 ³⁶
Davidson and de Gee, 1984 ³⁵
Feilzer and others, 1987 ³⁶
Lin and others, 2009 ³⁷
Li and others, 2010 ³⁸
Lin and others, 2001a ³⁹
Lin and others, 2001b ⁴⁰
Fennis and others, 2003 ⁴¹
Fennis and others, 2005 ⁴²
Xu and others, 1999 ⁴³
Hubsch and others, 2002 ⁴⁴
Li and others, 2010 ⁴⁵
Lin and others, 2009 ⁴⁶
Influence of restorative technique, material properties, and/or material comparisons
Versluis and others, 1996 ⁴⁷
Spears, 1998 ⁴⁸
Kowalczyk, 2009 ⁴⁹
Kuijs and others, 2003 ⁵⁰
Ausiello and others, 2001 ⁵¹
Toparli and others, 1999 ⁵²
Arola and others, 2001 ⁵³
Interface and adhesive systems
Lin and others, 2001a ⁴⁰
Ensaff and others, 2001 ⁵⁴
Ausiello and others, 2002 ⁵⁵
Comparative behaviour of resin composite and ceramic restorations
Magne, 2007 ³¹
Magne and Belser, 2003 ⁵⁶
Ausiello and others, 2004 ⁵⁷
Belli and others, 2005 ⁵⁸
Yamamoto and others, 2007 ⁵⁹
Magne, 2010 ⁶⁰
Jiang and others, 2010 ⁶¹
Yamanel and others, 2009 ⁶²
Magne and Oganessian, 2009a ⁶³
Magne and Oganessian, 2009b ⁶⁴

Table 2: Continued.

Analyses and effect of stresses
Versluis and others, 2004 ³⁵
Lin and others, 2001a ³⁹
Ensaff and others, 2001 ⁵⁴
Versluis and others, 1998 ⁶⁵
Fenner and others, 1998 ⁶⁶
Li and others, 2008 ⁶⁷
Pantelic and others, 2007 ⁶⁸

experimental (same restorative configurations tested on natural teeth with stress gauge) and FEM models proved well correlated.³⁵ Shrinkage stresses appeared to be dependent on the configuration and size of restorations, with larger Class II restorations resulting in lower stress levels in the restoration and tooth-restoration interface as a result of the increased tooth deformation and stresses. Therefore, it can be concluded that shrinkage stress cannot be based on composite properties alone but depends also on the restoration configuration and dimensions as well as the restorative procedures. The FEM model of cusp replacing restorations on premolars has also shown the superior stress resistance of full occlusal coverage compared to single cusp coverage. Failures of analogous restorations made on natural teeth in such situations were mainly of an adhesive nature.^{41,42}

Cavity margins with 60° to 75° (compared to 90°) of inclination⁴³ and rounded or beveled margins (compared to unbeveled cavity margins)⁴⁴ proved, respectively, to offer the best resistance to vertical and lateral forces and a significant reduction of stresses along their adhesive interface. Li and coworkers⁴⁵ used a simplified tooth model with uniform E-modulus (6 GPa) in an attempt to optimize the restoration shape for stress management, using a load of 400 N. Using this model, a T-shaped cavity (larger occlusal opening and reduced bucco-lingual width of the cavity base) appeared to offer the most favorable design for MOD restorations on premolars. However, such a design is, unfortunately, clinically irrelevant on the basis of a geometric incompatibility with usual caries or restoration anatomy. Using an indirect composite inlay model on a premolar, Lin and coworkers⁴⁶ showed that the most influential factors for stress in indirect restorations were load (magnitude and direction) followed by cavity depth. Other factors, such as isthmus depth, interaxial thickness, and resin thickness, all had an insignificant impact on stress level. This study did also show that low elastic modulus resin cement contributed to

reducing the stresses that were transmitted to the tooth.

Influence of restorative technique, material properties, and/or material comparison

A first study⁴⁷ compared stress buildup and tooth deformation resulting from a MOD direct composite restoration using bulk placement or different incremental techniques and, surprisingly, showed an advantage of the bulk approach in contrast to the large majority of other *in vitro* studies (see “Microleakage” and “Marginal adaptation” sections) that have indicated the use of incremental techniques to minimize the negative consequences of polymerization shrinkage. Another FEM study⁴⁸ reached the opposing conclusion, indicating that the use of an incremental technique does help to control stresses in direct restorations. More recently, an interesting study⁴⁹ evaluated the impact of increment geometry in horizontal layering technique (perfectly horizontal or concave shape) as well the presence of a pre-layer (lining extending up to half-enamel thickness occlusally) in regard to the stresses developing in the adhesive interface and dental tissues. It was shown that concave layers associated with either regular (same thickness, up to half-enamel thickness) or edge shape (thinning of the lining toward half-enamel thickness) composite pre-layers were highly successful in reducing polymerization stresses. In larger composite buildups with cusp replacement, the bulk chemical curing technique induced less stress than did bulk or layered light-cured restorations. In this study, maximal stresses were observed at the restoration interface and at the cervical part of the remaining cusp.⁵⁰

The stiffness of composite resins also proved to be an influential factor governing stress development and tooth deformation as a result of composite shrinkage or functional loading. A stiff material induces more tooth deformation and increases preloading stress (stress state before simulated load) following polymerization shrinkage, while on the contrary, a low-elastic modulus composite induces less preloading stress but allows for more deformation under load.⁵¹ In addition to the aforementioned parameters, the position of load also influences stress development.⁴⁸ Interfacial problems are more likely with a low restoration modulus (10-20 GPa), while in high-modulus restorations, intercuspal stresses increase. The optimal E-modulus seemed, then, to be around 30 GPa.⁴⁸ This suggestion is, however, irrelevant to existing resin composite or ceramic systems used in restorative dentistry, which have, respectively, lower or higher elasticity modules.

The comparative behavior of sandwich restorations made of glass ionomer (GI) and amalgam or GI and composite showed that residual stresses were, respectively, of compressive or tensile nature.⁵² The maximum compressive stress occurred at the occlusal margin in the amalgam and decreased toward the cervical margin line. Conversely, in composite resin, the stress distribution was of a tensile nature and increased toward the cervical margin.⁵² Overall stress magnitude and location were related to the type of restoration, non-adhesive metal based (amalgam) or adhesive, composite restoration.⁵³ In both restoration types, maximal stresses were found at the interface but with lower magnitude in the adhesive restoration. Maximal stresses appeared in locations different from those identified in the previous study, with the highest stresses at the pulpal floor line angles for amalgam restorations and along occlusal lingual margins in composite restorations. Stress distribution was, however, only minimally influenced by occlusal load direction.⁵³

Interface and adhesive systems

The adhesive interface proved to play a major role in absorbing contraction stresses (and supposedly functional stresses as well) by elastic deformation.^{54,55} It was shown that stress magnitude and cusp deformation increased proportionally to adhesive layer stiffness, and, therefore, failures were more likely to develop at the interface, as it physically remains the weakest component of the system.⁵⁴ Moreover, in addition to a reduction of adhesive layer E-modulus, increasing the adhesive layer thickness would be an alternative way to reduce interfacial stresses. Similarly, cusp movement under load was inversely proportional to composite rigidity and proved again the significant impact of the elasticity of restorative components on stress development and potential incidence or type of failure.⁵⁵

Lin and coworkers⁴⁰ evaluated the impact of adhesive interface quality (bonded or “unbonded” interface) on the fracture potential of different cavity depths and loads. As expected, they observed that the more realistic “unbonded” configuration presented an increased risk for fracture.

Comparative behavior of resin composite and ceramic restorations

The type of restoration (inlay or onlay), the restoration size (large or small), and material type (composite or ceramic) largely influenced stress magnitude and direction as well as tooth deformation.^{31,56-59} Under load, interfacial stresses were mainly of a tensile nature in inlay restorations, while they were of a compressive nature in onlay

restorations.⁵⁶ Rigid porcelain restorations, compared to less rigid composite, featured more stress at the occlusal surface but reduced crown deformation and stress magnitude at the adhesive interface.⁵⁶ Using a model of a nonvital tooth with an overlay restoration, the material again proved to influence the stress magnitude in both force levels tested (200 or 700 N). Porcelain restorations showed a stress peak measuring 30%-50% higher than composite overlays, and differing maximal stress locations within the tooth were observed.⁶⁰ This study indicates that composite restorations with a much lower E-modulus have a better potential to reduce forces transmitted to the residual tooth structure.

In a report⁶¹ evaluating the stress distribution in molars restored with inlays and onlays made of gold, composite, or ceramic, both in vital and nonvital tooth configurations, much higher stresses were associated with the nonvital tooth configuration and inlay restoration. The stress differences in dentin at the preparation floor associated with the restorative material were extremely small, but lower absolute values were observed in composite restorations. However, another FEM study led to opposing conclusions. Using a vital tooth model and 200 N force applied on four different occlusal spots, materials with low elastic modulus values transferred more functional stress to the tooth structures, and the onlay design protected tooth structures more efficaciously than did the inlay design.⁶²

For indirect restorations, the hybrid layer and cement act as a stress dissipater, the efficacy of which is proportional to their elastic deformation potential.^{57,58} Interestingly, ceramic inlays luted with a high E-modulus cement failed to distribute stresses properly.⁵⁷ In general, porcelain restorations under load tended to collect stress inside their body, while composite restorations transferred more strains to the surrounding tissues.⁵⁸ The use of different composite liners also influenced the tensile interfacial stresses in composite or porcelain onlays. It was observed that stresses increased with a low-elasticity modulus base, and it therefore seems appropriate to use high-elasticity base materials.⁵⁹

Cusp deformation and recovery under load proved to be influenced by cavity extent and restorative material (composite or porcelain).³¹ Deformations ranged from 0.4 μm for an unrestored tooth up to 9-12 μm and 12-21 μm , respectively, for MOD or endo access cavities. Using a premolar model, the same author measured cusp widening induced by load in different cavity types (slots, MO, or MOD)⁶³ and

then for MOD composite and porcelain inlays, according to different contact zones.⁶⁴ It was then concluded that maintaining the residual tooth "bridge" in between slots or a proximal ridge has the potential to limit tooth deformation.⁶³ Moreover, the stiffness of the porcelain restoration resulted in a superior tooth stabilization effect, which was observed by reduced intercusp deformation.⁶⁴

Analyses and effects of stresses

The impact of curing light direction or curing mode on composite polymerization shrinkage proved less significant than expected, and, contrary to widespread belief, composite does not seem to shrink toward the light.⁶⁵ In fact, the factor that proved the most influential on shrinkage direction was the layer and cavity configuration factor.⁶⁵ Stresses induced by temperature changes (from ambient to the simulated contact with an imbibing liquid at 48°C) were found to be of a tensile nature, ranging between 7.4 and 8.6 MPa at two seconds and 9.2 and 11 MPa at eight seconds.⁶⁶

In an attempt to analyze apparent inconsistencies found in some FEM studies, Li and coworkers⁶⁷ approached the problem of composite polymerization stresses with an analytical solution using basic mathematical equations to describe the behavior of a simplified, cylindrical, Class I self-curing composite model. They pointed out again the influence of material shrinkage and Young's modulus to govern stress development. They also reported that stresses deep inside the restoration are higher than those at the restoration surface, which concentrate at the restoration margins. However, part of their protocol hypothesis included the existence of a perfect adhesive interface and linearly elastic tooth model. These factors represent a great divergence from clinical reality and may lead potentially to irrelevant study conclusions, such as the fact that the restoration volume has almost no influence on residual stresses. Pantelic and coworkers⁶⁸ measured tooth deformation in bulk Class I and II composite restorations by holographic interferometry and then evaluated related stresses in simplified FEM models. They observed that intercusp deformation was in the magnitude of 2 μm in Class I and up to 14 μm in Class II restorations, while stresses varied between 50 MPa in Class II and 100 MPa in Class I restorations. This has the obvious potential to damage the restoration interface or even the tooth structure itself, considering that average interfacial bond strength to dental tissues, such as enamel tensile strengths, lie within a range of 15 to 25 MPa. These values were of a relatively high magnitude

and close to those observed by Versluis and coworkers.³⁵ However, in other FEM studies,^{39,54} composite contraction stresses in similar conditions were in a lower range (20 to 40 MPa).

Conclusion: FEM studies

Within the limitations of this study protocol, the most relevant conclusions are the following:

- Results of 3D FEM models were validated by testing similar restorative configurations in natural teeth by strain gauge.
- Stress buildup in direct restorations is influenced by cavity design and dimensions as well as layering technique (geometry and configuration of layers) and material physical properties (mostly stiffness).
- A stiff direct material increased preloading stress after placement but reduced deformation under functional loading. In addition, lower E-modulus adhesives and cements reduce stress at the tooth-restoration interface.
- Restoration approach (adhesive vs nonadhesive) influences stress, with the highest stresses found at the pulpal floor line angles for amalgam and at the occlusal margins for composite restorations.
- A bevel or round chamfer reduces stress compared to a nonbeveled, butt preparation.
- Ceramic restorations reduce tooth deformation under load but show overall higher peak stresses. A “high” E-modulus composite (around 20 GPa) seems to have the best biomechanical behavior among all restorative materials in both vital and nonvital tooth configurations.

Conclusion: FEM methodology

FEM is a crucial model to study the localization and magnitude of stresses in unlimited restoration configurations and material combinations, with reproducible load conditions and tooth anatomy. This is considered an unparalleled advantage compared to any other experimental method using natural tooth substrate. However, one drawback observed in some FEM studies is the simulation of nonphysiological forces, which limits the possible impact of modeled stresses on interfaces or tooth substrate (adhesive or cohesive failure). Moreover, FEM models cannot perfectly replicate the biomechanical “complexity” of the tooth-restoration whole, such as the differential adhesion patterns and anisotropy of dental substrates. 2D FEM models also represent a simplification of *in situ* conditions. A final observation is that to date, and as is the case for photoelasticity, dental FEM studies generally do not replicate cycling stresses and the effect of moisture. This is significant, as both of these phenomena have

a major influence on restoration behavior and performance.

The absence of biological variability clearly supports the further use and development of this research model, although major limitations still exist in terms of possible clinical implications. The quality of evidence can consequently be considered satisfactory when using the latest 3D FEM models and taking into consideration the precise context of each study hypothesis. The quantity of evidence is, on the contrary, rather limited (as a result of the large number of study hypotheses), as is the consistency of the evidence (as a result of former primitive models or the 2D approach). This latter restriction should, however, recede with constant technology improvements.

III. Microleakage—The microleakage studies that were reviewed are presented in Table 3.

Comparison of restorative and layering techniques

Incremental and centripetal (layering from depth to surface) techniques showed a reduction in microleakage in cervical dentin compared to bulk-filling in numerous studies⁶⁹⁻⁷³; however, the use of various restorative techniques had no influence on microleakage at enamel margins.^{74,75} Overall, less microleakage was observed at enamel margins compared to cervical dentin.^{73,74,76-83} When comparing two existing curing modes of a comparable composite technology, the light-curing material produced less leakage than the self-curing one.⁸⁴

Other restorative variables (cervical margin position, cavity dimensions, matrix systems, etc)

The application of different matrix systems did not influence enamel microleakage, while the use of a “collimator or transmitting” cone reduced leakage at dentin margins, compared to an oblique layering technique using a translucent matrix.⁶⁹ In another trial,⁷³ the application of a centripetal technique and a clear matrix reduced dentinal leakage compared to metal matrices. In another study,⁷⁷ the use of “collimator or transmitting cone” applied with pressure against the composite surface reduced microleakage in enamel but not in dentin. Two other studies^{75,85} did not reveal any difference in dentin microleakage due to the matrix system.

With regard to the adhesive application, it was shown that the type of primer solvent was an influential factor for dentin microleakage but not for enamel. Similarly, an improper removal of water remnants following etching increased dentinal leakage.⁸³

Table 3: *Selected References for Microleakage*

Comparison of restorative and layering techniques
Neiva and others, 1998 ⁶⁹
Poskus and others, 2004 ⁷⁰
Federlin and others, 2002 ⁷¹
Idriss and others, 2007 ⁷²
Szep and others, 2001 ⁷³
Gallo and others, 2000 ⁷⁴
Ghavamnasiri and others, 2007 ⁷⁵
Hilton and others, 1997 ⁷⁶
Ziskind and others, 1999 ⁷⁷
Campos and others, 2005 ⁷⁸
Rodrigues and others, 2010 ⁷⁹
Uctasi and others, 2002 ⁸⁰
Tredwin and others, 2005 ⁸¹
Araujo and others, 2006 ⁸²
Carpena Lopes and Colle, 2009 ⁸³
Marotta Araujo and others, 1990 ⁸⁴
Others restorative variables (cervical margin position, cavity dimensions, matrix systems, etc)
Neiva and others, 1998 ⁶⁹
Szep and others, 2001 ⁷³
Ghavamnasiri and others, 2007 ⁷⁵
Ziskind and others, 1999 ⁷⁷
Campos and others, 2005 ⁷⁸
Araujo and others, 2006 ⁸²
Carpena Lopes and Colle Zanette, 2009 ⁸³
Marotta Araujo and others, 1990 ⁸⁴
Hilton and Ferracane, 1999 ⁸⁵
"Sandwich" techniques
Rodrigues and others, 2010 ⁷⁹
Tredwin and others, 2005 ⁸¹
Malmstrom and others, 2002 ⁸⁶
Tung and others, 2000 ⁸⁷
Frankenberger and others, 2003 ⁸⁸
Olmez and others, 2004 ⁸⁹
Wibowo and Stockton, 2001 ⁹⁰
Attar and others, 2004 ⁹¹
Civelek and others, 2003 ⁹²
Fabianelli and others, 2010 ⁹³
Ziskind and others, 2005 ⁹⁴
Sadegui Mostafa, 2009 ⁹⁵
Garberoglio and others, 1995 ⁹⁶
Aboushala and others, 1996 ⁹⁷
Besnault and Attal, 2003 ⁹⁸
Stockton and Tsang, 2007 ⁹⁹
Hagge and others, 2001 ¹⁰⁰
Koubi and others, 2009 ¹⁰¹
Payne, 1999 ¹⁰²
Loguercio and others, 2002a ¹⁰³
Loguercio and others, 2002b ¹⁰⁴

Table 3: Continued.

Polymerization protocol
Rodrigues and others, 2010 ⁷⁹
Uctasli and others, 2002 ⁸⁰
Malstrom and others, 2002 ⁸⁶
Sadeghi, 2009 ⁹⁵
Hardan and others, 2008 ¹⁰⁵
Fleming and others, 2007 ¹⁰⁶
Fleming and others, 2007 ¹⁰⁷
Atlas and others, 2009 ¹⁰⁸
Cenci and others, 2005 ¹⁰⁹
Different restorative materials and brands
Demarco and others, 2001 ¹³
Tredwin and others, 2005 ⁸¹
Civelek and others, 2003 ⁹²
Garberoglio and others, 1995 ⁹⁶
Belli and others, 2007 ¹¹⁰
El-Mowafy and others, 2007 ¹¹¹
Coli and others, 1997 ¹¹²
Aranha and Pimenta, 2004 ¹¹³
Majeed and others, 2009 ¹¹⁴
Fabianelli and others, 2003 ¹¹⁵
Yazici and others, 2002 ¹¹⁶
Besnault and Attal, 2002 ¹¹⁷
Mathew and others, 2001 ¹¹⁸
Bala and others, 2003 ¹¹⁹
Youngson and others, 1990 ¹²⁰
Loguercio and others, 2004 ¹²¹
Palin and others, 2005 ¹²²
Bagis and others, 2009 ¹²³
Comparison of direct and indirect techniques
Ziskind and others, 1998, part 2 ¹²⁴
Kenyon and others, 2007 ¹²⁵
Hasanreisoglu and others, 1996 ¹²⁶
De Andrade and others, 2007 ¹²⁷
Reich and others, 1990 ¹²⁸
Ziskind and others, 1998, part 1 ¹²⁹
Marginal leakage of restorations made in vivo
Abdalla and Davidson, 1993 ¹³⁰
Cenci and others, 2006 ¹³¹
Ferrari and Davidson, 1996 ¹³²

An adhesive cavity design (rounded internal geometry) was able to reduce marginal leakage compared to a box-shaped cavity.⁸⁴ Beveled margins also had the potential to reduce dentinal leakage, while a delayed finishing protocol (24 hours) had no influence.⁸⁵ As for marginal adaptation studies, occlusal loading increased microleakage in enamel.⁷⁸

The microleakage studies reviewed for the aforementioned variables were poorly conclusive.

Sandwich techniques

In enamel margins, a reduction in leakage was observed with increasing thickness of flowable resin composite (FRC), while in dentin, neither the thickness nor the presence of FRC as a gingival increment influenced microleakage.⁸⁶ Various adhesive systems (multicomponent, prime and bond, or simplified one component) were combined with FRC liners, but the adhesive type had no impact on dentin and enamel microleakage.⁸⁷ However, the presence of the FRC underneath “packable” composite restorations did reduce leakage.⁸⁷⁻⁸⁹ Conversely, in another trial,⁹⁰ the combination FRC/packable restoration showed more microleakage than did a resin-modified glass ionomer (rmGIC)/hybrid restoration. Several other studies⁹¹⁻⁹³ evaluating the influence of flowable liners observed a comparable, positive effect on microleakage, although, again, other authors^{81,94,95} presented conflicting conclusions. When using an autopolymerizing composite as a base underneath a direct light-cured composite restoration, marginal leakage was reduced after four months of humid storage and the consequent water uptake that occurred, compared to the initial status. In this study as well, the adhesive brand was shown to influence microleakage.⁹⁶

In some studies, the placement of a rmGIC liner in Class II open sandwich restorations helped to reduce cervical microleakage in comparison to full composite restorations⁹⁷⁻⁹⁹ and FRC or autopolymerizing composite liners,¹⁰⁰ while in other studies^{79,94,101} it did not have any influence. In one other study,¹⁰² the presence of a rmGIC liner produced more microleakage than was associated with a FRC liner. In a closed sandwich configuration, the rmGIC liner had no effect on microleakage⁹⁷ or reduced leakage.⁹⁹

The use of FRC as a liner or base was also evaluated against sandwich techniques using compomer and rmGIC. When comparing those various restorative systems, the sandwich restorations with FRC liner exhibited minimal leakage.⁹⁶ However, in similar tests, conflicting conclusions emerged, again with either comparable leakage⁹⁰ or increased leakage.^{103,104}

Polymerization protocol

The majority of studies comparing different curing protocols or modes (standard, soft-start, step, ramp, pulse, or turbo) did not demonstrate differences in microleakage.^{79,105,106} However, when comparing different curing modes, LED curing and Plasma arc curing induced more leakage than did conventional halogen polymerization,^{80,107} while with a FRC liner, curing modes (LED vs halogen) had no influence on

leakage.⁹⁵ Slow, gradual, or delayed light-curing modes reduced leakage compared to standard or modified pulsed and ramp curing.^{105,108} The light direction proved not to be an influential factor for microleakage.^{86,109}

Different restorative materials and brands

Amalgam used as a base was able to reduce cervical leakage compared to full composite restorations,¹³ although such a material combination is not popular anymore. Fiber inserts did reduce leakage at the enamel but not in cervical dentin,¹¹⁰ and glass fibers were better than polyethylene ones.¹¹¹ On the contrary, glass ceramic inserts did not reduce marginal leakage.¹¹² Finally, restorative hybrids showed less leakage than did packable resin composites, but without eliminating it completely.¹¹³ In fact, no material or brand is able to completely eliminate marginal or cervical leakage at the dentin level.¹¹⁴ At enamel margins, materials and brands did not have any influence on microleakage.^{81,114}

When comparing the performance of various adhesive systems, multicomponent systems (etch and rinse) presented less microleakage than did self-etch systems (one or two components).^{115,116} In another study,¹¹⁷ the comparison between self-etch and multicomponent etch and rinse systems in ambient and extreme temperature and humidity conditions proved to favor the self-etch brand. It was also shown¹¹⁸ that a double adhesive layer was an effective method to reduce leakage, compared to a single adhesive layer. When comparing restorative composite brands, differences in marginal leakage were observed despite a similar structure and composition.⁹⁶ Pursuing the same testing approach, more relevant information was provided when comparing different restorative brands used with the same adhesive.¹¹⁹ Actually, most of the studies that were reviewed compared different restorative systems (restorative material together with its specific adhesive), and while they observed various levels of leakage at the enamel or cervical dentin,^{96,120,121} it is difficult to ascertain whether the adhesive systems, restorative techniques, or materials accounted for the results.

One study⁹² compared a conventional hybrid to an ormocer system and observed less leakage with traditional composite technology. The silorane and oxirane restoratives were investigated in regard to their capacity to reduce microleakage. In one study,¹²² oxirane produced more leakage than silorane or conventional resin composite. When comparing silorane to a nanohybrid system with either vertical or oblique layering incremental

techniques, no leakage was observed with either technique in the silorane group. However, leakage was present in each hybrid composite group but to a reduced extent when using a vertical incremental method.¹²³

Comparison of direct and indirect techniques

A comparative leakage study evaluating the performance of direct and indirect composite restorations showed that less leakage occurred in the direct inlay group (one session, chair-side fabrication).¹²⁴ In another study, only outer sections showed more leakage in the direct group compared to the inlay technique.¹²⁵ A last study confirmed similar resistance to leakage between direct and indirect composite restorations,¹²⁶ demonstrating that microleakage studies rarely lead to “conclusive” findings.

Previous sealing of dentin surfaces, followed by a fresh layer of bonding resin application before cementation, was able to reduce leakage compared to a traditional cementation protocol (single application of the adhesive system prior to cementation).¹²⁷ When comparing direct techniques with indirect composite and ceramic inlays, the thickness of the cement gap and the divergence of cavity walls proved to be influential factors,^{128,129} and the direct technique induced more microleakage.

Marginal leakage of restorations made in vivo

An interesting protocol was applied to evaluate Class II restorations, combining *in vivo* placement and *in vitro* evaluation of microleakage following short-term clinical service and extraction.¹³⁰⁻¹³² It was shown that none of the techniques investigated was able to fully prevent microleakage *in vivo*¹³⁰ at either enamel or cervical dentin¹³² and that leakage scores using “classical,” mere *in vitro* methodology were poorly predictive of *in vivo* resistance to leakage.^{130,132} In one study,¹³⁰ the use of a rmGIC proved to have a beneficial effect on cervical microleakage performance. A better resistance to marginal leakage was also found for enamel compared to cervical dentin margins.^{131,132} Various matrix systems were tested in this configuration but without any significant influence on leakage.¹³¹

Conclusion: Microleakage studies

Within the limitations of this study protocol, the most relevant conclusions are that:

- Adhesive cavity design and beveling of margins reduced leakage.
- Halogen curing reduced leakage in comparison to LED and plasma light polymerization.

- Silorane technology induced less leakage than conventional hybrid resin composites.
- Otherwise, the results proved inconclusive in regard to
 - layering or restorative techniques,
 - influence of a low E-modulus liner underneath composite restorations,
 - curing protocol,
 - comparison among composite and adhesive systems and brands, and
 - comparison between direct and indirect techniques.

Conclusions: Marginal leakage methodology

The large majority of published reports did not test microleakage in association with mechanical loading and thermal cycling. It can therefore be considered that in the absence of functional stressing, this protocol mainly and only reveals the influence of the restorative technique (ie, polymerization stresses) and material physicochemical characteristics on the tooth-restoration interface resistance to leakage. In addition, the gap size allowing for die infiltration might be well below the dimension needed for bacterial penetration, which makes the possible clinical relevance of die leakage within ultrasmall margin imperfections unclear. Finally, the results of microleakage tests are only semiquantitative and are therefore less reliable (poor quality of the evidence). Then, regardless of its practical advantage, which in turn led to widespread use of this protocol, the microleakage literature is strongly characterized by limited coherence and conclusiveness (poor consistency of the evidence).

CONCLUSIONS

The first part of this article has reviewed selected literature dealing with the quality and *in vitro* behavior of adhesive Class II restorations using photoelasticity, FEM, and microleakage study protocols.

Photoelasticity has shown higher stresses in large cavities and with the use of light-curing composite, as compared to a chemically curing product. However, it led to conflicting results when comparing layering and bulk-fill techniques. Photoelasticity has several conceptual and methodological drawbacks and has therefore been advantageously replaced by FEM studies.

The validity and crucial role of the FEM protocol was validated by comparing stress levels in similar restorative configurations using natural teeth and strain gauges. This method confirmed the influence on stress of the cavity design and dimensions,

layering techniques, and material physical characteristics, such as stiffness. However, cyclic functional loading (fatigue) has not yet been replicated with FEM.

The use of the microleakage protocol allowed only a few hypotheses to be confirmed. Cavity and margin design, light-curing type, and composite structure and technology were the only variables that did have an influence on microleakage. However, when more studies were available, the conclusions regarding other variables proved highly inconsistent and do strongly indicate that the further use of this test method in the future should be strictly limited.

The second part of this review will cover the remaining non-destructive *in vitro* protocols, which include 1) the deformation resistance and fracture resistance to cyclic loading, 2) shrinkage stress and related tooth deformation, 3) bond strength (micro-tensile, tensile, and shear tests), and 4) marginal and internal adaptation. In addition, an “Evidence Index” will be proposed that aims to classify the different study protocols according to the coherence of their results and their potential clinical relevance, as estimated by their ability to simulate oral biomechanical strains.

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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***In Vitro* Performance of Class I and II Composite Restorations: A Literature review on Nondestructive Laboratory Trials—Part II**

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Clinical Relevance

In vitro research remains of primary importance to selecting and validating the techniques and products to be used *in vivo*. However, the clinical predictive value of such tests needs to be appraised and ranked to provide meaningful help toward the clinical decision-making process.

ABSTRACT

A literature review was conducted on adhesive Class I and II restorations and nondestructive *in vitro* tests using the PubMed/Medline database for the 1995-2010 period. The first part of

this review has presented and critically appraised selected literature dealing with the quality and *in vitro* behavior of adhesive Class II restorations using photoelasticity, finite element analysis, and microleakage study protocols. This second part reviews additional parameters, which are deformation and fracture resistance to cyclic loading, shrinkage stress and tooth deformation following restoration placement, bond strength (microtensile, tensile, and shear tests), and marginal and internal adaptation. In addition, a “relevance score” has been proposed that aims to classify the different study protocols according, firstly, to the resulting quality, quantity, and consistency of the evidence and then, secondly, to their potential clinical relevance, as estimated by their ability to simulate oral and biomechanical strains. The highest clinical relevance was attributed to marginal and internal adaptation studies, following cyclic

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loading in a moist environment. However, a combination of *in vitro* protocols will have an even greater predictive potential and has to be considered as a crucial preclinical research approach with which to investigate the numerous restorative configurations that cannot be efficiently and rapidly tested *in vivo*.

INTRODUCTION

Posterior adhesive restorations, as a substitute for metal-based restorations, have become the “standard of care” in an increasing number of dental offices and clinics.¹⁻³ However, the abundant number of available restorative options implies a limited standardization of these techniques, and this may lead to the possible application of improper clinical protocols. The time and effort demanded by *in vivo* trials does not permit all adhesive systems, base liners, and restorative products/techniques to be evaluated in prospective clinical studies and over a sufficient period of time. Therefore, the need for and the advantages of preclinical *in vitro* trials is undeniable. Unfortunately, the many laboratory evaluation protocols and their variability and complexity, coupled with an already-intricate study field, means that there is a clear need to organize *in vitro* research on Class II adhesive restorations. Furthermore, this organization should be based on the ability of the research protocol to reproduce the most important oral strains, to evaluate and tentatively appraise the potential clinical relevance, and to follow a thinking process successfully applied in clinical biomedical science.⁴⁻¹²

Part one of this review selected literature dealing with the quality and *in vitro* behavior of adhesive Class II restorations using photoelasticity, finite element analysis (FEM), and microleakage study protocols. Photoelasticity demonstrated that higher stresses could be observed in large cavities and those restored using a light-curing material compared to a chemically curing one.¹³⁻¹⁵ However, photoelasticity did show atypical results when comparing layering and bulk-filling techniques.^{16,17} Unfortunately, this method carries several conceptual and methodological limitations and therefore is characterized by improper quality and consistency of the evidence. It has been advantageously replaced by FEM.

The crucial role of the FEM protocol was validated by comparing stress levels in similar restorative configurations using natural teeth and strain gauges.^{18,19} This method then confirmed the influence of cavity design and dimensions,²⁰⁻²³ layering techniques,^{24,25} and the physical characteristics of the

materials, such as stiffness,²⁶⁻³³ with a good consistency of the evidence. Despite the fact that FEM neither emulates the effect of moisture nor that of cyclic masticatory function (fatigue), the recent three-dimensional modeling approach shows a good quality of the evidence for stress distribution within the tooth-restoration as a whole.

The use of the microleakage protocol only allowed a few hypotheses to be confirmed with a good consistency of results. Only cavity and margin design,^{34,35} light-curing type,^{36,37} and composite structure and technology³⁸⁻⁴¹ had an influence on microleakage. However, there are a lot of studies utilizing this protocol, possibly because of its simplicity. When more of these studies were reviewed, the conclusions proved highly inconsistent. This strongly indicates that further use of the microleakage protocol should be limited as a result of the overall poor quality and consistency of the evidence associated with this protocol.

The second part of this review will cover the remaining nondestructive *in vitro* protocols, which are 1) deformation resistance and fracture resistance to cyclic loading, 2) shrinkage stress and related tooth deformation, 3) bond strength (microtensile, tensile, and shear tests), and 4) marginal and internal adaptation. In addition, a “relevance score” will be proposed based on the aforementioned criteria (quality, quantity, and consistency of the evidence), taking into consideration the ability of the protocol to simulate oral biomechanical strains.

MATERIALS AND METHODS

The search strategy, detailed in Part I of this review, included an appraisal of the PubMed/Medline database using the following primary key words: *in vitro*, Class II, posterior composites, inlays and onlays, tooth colored, and composite. For this second part, additional key words related to study hypothesis, such as cavity configuration, polymerization, or light-curing, or to study methodology, such as resistance to fracture and deformation, shrinkage stress, tooth deformation, bond strength and microtensile bond strength, and marginal and internal adaptation, were used to identify all existing references. The search was conducted with the limit “Dental Journal” and from 1995 to 2010. Perusal of the references of relevant articles allowed completion of the review (references of the references). A few older “major” references were cited, when appropriate. Articles were first classified according to the experimental protocol, each one corresponding to a specific review table, and were then subclassi-

fied according to the parameters/hypothesis investigated. For microleakage, bond strength, and marginal adaptation protocol, the type of restoration (direct and indirect) was also considered, and then the references were analyzed according to the subparameters previously described in part one of this review). The overall strength of evidence was appraised according to the three factors of quality, quantity, and consistency. Whenever possible and appropriate, the approach applied was the same as introduced in 1994 by Gyorkos and Abrahamowicz.⁷ This process is now well established and largely used to develop practice guidelines and other health-related policy advice.⁸⁻¹²

References related exclusively to indirect ceramic and CAD-CAM/Cerec® restorations (Sirona, Bensheim, Germany) or restoration fit, as well as those dealing with restoration of deciduous teeth, were excluded from this review. In addition, wear tests and studies measuring restoration fracture resistance to monotonic stress/loading (in general, all kinds of destructive tests) were not taken into consideration for this literature review.

I. Deformation and Resistance to Cyclic Loading

The studies that were reviewed are presented in Table 1. When comparing the deformation of intact and restored teeth using composite or ceramic in MOD cavities, the mean tooth compliance (relative deformation) after preparation was about 2.0, and mean tooth compliance was back to 1.1 in composite and 1.0 in the ceramic group. This demonstrated the ability of both restorative materials to reinstall tooth resistance under a load of 11.17 Kg.⁴² However, after cyclic loading, more samples fractured in the composite group than in the ceramic group, although this was not significant in terms of mean cycles to failure.

The resistance to fracture following cyclic loading and increasing force (200 to 1000 N) for composite MOD onlays (buccal cusp replacement) with or without additional palatal partial coverage demonstrated an increasing resistance to fracture with full occlusal coverage. However, at the same time, more dramatic failure patterns were observed.⁴³ Therefore, clinical recommendations could not be drawn, as lowering the remaining cusp could eventually lead to untreatable failures. The aforementioned results were submitted to additional FEM analysis, and this substantiated the superior resistance to fracture of the overlay configuration and also provided a more detailed picture of the various

Table 1: <i>Selected references for deformation and resistance to cyclic loading</i>
Shor and others, 2003 ⁴²
Fennis and others, 2004 ⁴³
Fennis and others, 2005 ²¹
Kuijs and others, 2006 ⁴⁴
Magne and Oganessian 2009a ⁴⁵
Magne and Knezevic, 2009a ⁴⁶
Magne and Oganessian 2009b ⁴⁷
Magne and Knezevic, 2009b ⁴⁸
Magne and Knezevic 2009c ⁴⁹

stresses (tensile, shear, and compressive) that account for adhesive interface or restoration failure.²¹ It was also concluded that adhesive failures are more likely to occur with a high E-modulus composite and that lowering the E-modulus might trigger cohesive restoration fractures. Another study⁴⁴ from the same authors included ceramic overlays, which were compared to direct and indirect composite restorations. In this study, no significant difference was observed with regard to overall fatigue resistance among the three restorative options, while a combination of adhesive and cohesive failures was predominantly observed in the indirect groups.⁴⁴ These latter results might be attributed to a lower mechanical resistance of the adhesive interface and cement layer underneath indirect restorations and, in particular, to the lower stiffness of the cement, compared to a highly filled composite (82 vol% and 92 wt%) or ceramic restoration. The aforementioned studies thus concluded that in a vital tooth configuration, with cyclic loading ranging from normal function (200 N) to parafunctional forces (1000 N), the choice of material might not be a crucial factor for overall mechanical resistance and clinical success. However, it must be pointed out that the tested composites (direct and indirect) were conventional, highly filled hybrids, with high E-modulus (19.6 GPa and 23.0 GPa), and these are markedly higher than the current nano-hybrid materials with moduli around 10 GPa or lower.

Magne and coworkers⁴⁵⁻⁴⁸ interestingly applied a similar protocol to a nonvital tooth configuration with forces ranging from 200 N to 1000 or 1400 N. In their first article, the influence of restoration thickness (1.5 to 3.5 mm) using a composite system developed for CAD-CAM technology (Paradigm MZ100®, 3M, St Paul, MN, USA) was tested. They observed that increasing the thickness of the restoration improved the resistance to fatigue and

also reduced the occurrence of subgingival fractures. This demonstrated the protective effect of thick composite overlays made of high mechanical strength and E-modulus composite.⁴⁶ When comparing 3-mm-thick ceramic (Vita MKII CEREC, VITA Zahnfabrik, Bad Säckingen, Germany) and composite (Paradigm MZ100) overlays, the fatigue resistance of the composite material was significantly superior, and the efficiency of immediate dentin sealing (to establish adhesion prior to impression) was also effective, as demonstrated by an absence of adhesive failures.⁴⁹ The same protocol was repeated with a restorative nano-hybrid composite, and these composite overlays showed a better resistance to fatigue than did the ceramic restorations.⁴⁸ When comparing both composites, Paradigm MZ100 exhibited a higher survival rate (73%) compared to the nano-hybrid brand (50%), even though this was not statistically significant. In the same test, none of the ceramic restorations survived the last test phase at 1400 N. Moreover, ceramic restorations showed a much higher proportion of subgingival, nonrepairable fractures.^{46,48,49} These two series of studies dealing with either a vital or nonvital tooth configuration evaluated the behavior of restorations under physiological and nonphysiological parafunctional forces. The protocol included a FEM to tentatively explain the findings with a natural substrate. In the vital tooth configuration, the choice of material appeared less influential than the restoration configuration with regard to fracture resistance and failure pattern. Conversely, in a nonvital tooth situation, the choice of material and the restoration thickness markedly influenced the stress distribution, fracture resistance, and fracture pattern.

Conclusion: Deformation and Resistance to Fatigue Loading—The aforementioned findings might have a crucial impact on our understanding of restoration reaction and resistance to cyclic forces. Specifically, the potential impact of the material's physical characteristics (ie, E-modulus and flexural strength) on medium- and long-term restoration behavior might largely depend on the extent of the preparation and the intrinsic capacity of the remaining tooth structure to resist functional stresses. In a vital tooth, it can be logically assumed that the restoration plays a less important protective role than it does in a nonvital configuration. In addition, a less rigid (significantly less than dentin; ie, nano-hybrid composite) or stiff and brittle material (ie, feldspathic porcelain) would likely increase the risk of restoration/tooth failure when treating fragile teeth (nonvital) in high stress-bearing areas. The quality and consistency of the evidence here are satisfactory.

However, the quantity of the evidence is rather limited, although such criteria seem less crucial as a result of the protocol applied (same tooth/teeth used for testing different cavity configurations or FEM stress simulation).

Only nondestructive tests or those involving cyclic loading were taken into consideration for this review because of the fact that mere resistance to fracture ("classical" fracture-resistance protocol) mimics the reaction of the system to extreme monotonic, linearly increasing stresses, and these are considered as poorly relevant as simulations for *in vivo* failures. Such tests neither reproduce accidental fracture (totally different stress kinetics) nor simulate other restoration failure patterns such as marginal leakage, tissue demineralization, pulpal complication, or fractures triggered by repeated stresses (fatigue). Likewise, the fracture patterns observed in such tests (which include axial or severe cusp and restoration fractures of vital tooth configurations) are practically nonexistent *in vivo*, with the exception of rather rare traumatic tooth fractures.⁵⁰ One can therefore assume that the quality of evidence would be insufficient, and this justifies the exclusion of such research in the present review.

II. Deformation of Teeth and Shrinkage Stress During and After Restoration Placement

The studies that were reviewed are presented in Table 2.

Layering Techniques—When comparing different composite filling techniques (bulk, bulk + re-restoration and incremental) to amalgam restoration in Class II MOD cavities of different widths (1, 2.5, and 5 mm), more deformation resulted from adhesive techniques, with the highest deformation being measured in 5-mm bulk composite restorations.⁵¹ The concept of re-restoring a tooth involves the placement of a bulk-fill composite restoration that is fully polymerized, and then a new slot is subsequently cut into the composite after polymerization. This slot is subsequently restored with more composite, and this technique has been proposed as a means to dissipate stress in the final restored tooth. In this study, it was observed that re-restoration did reduce stress compared to initial values.

In Class I cavities, tooth deformation proved to be minimal in comparison to Class II MO (medium or large) or MOD cavities. The size and cavity design or configuration factor proved to be influential factors for tooth deformation⁵² and also for stress development. This occurred in an inverse relationship at the

Table 2: Selected references for deformation of teeth and stress during and after restoration placement
Layering techniques
Versluis and others, 2004 ¹⁹
Shor and others 2003 ⁴²
Kamel and others 1995 ⁵¹
Tantbijorin and others 2004 ⁵²
Gonzalez Lopez and others 2007 ⁵³
Park and others 2008 ⁵⁴
Curing protocols
Versluis and others, 2004 ¹⁹
Fleming and others 2007 ³⁷
Comparaison of materials and brands:
Fleming and others 2007 ³⁷
Palin and others 2005 ⁴¹
Fleming and others 2007 ⁵⁵
Bouillaguet and others 2006 ⁵⁶
Fleming and others 2007 ⁵⁷

restorative interface, as measured directly on teeth and by FEM study.¹⁹ More recent studies have confirmed the increased deformation observed in Class II MOD restorations when compared to two-surface MO design⁵³ as well as the reduction of tooth deformation that is observed with layering techniques.⁵⁴ However, in this later study, no significant difference was observed between the horizontal and oblique layering techniques.

The deformation of intact and restored teeth using composite or ceramic in MOD cavities was also reviewed. The studies showed a mean tooth “compliance” of 2.0 (relative deformation) following preparation, and then the “compliance” reverted to 1.1 in the composite group and 1.0 in the ceramic group. This demonstrated the ability of both restorative materials to return the tooth’s resistance to flexure under a load of 11.17 Kg.⁴²

Curing Protocols—Versluis and coworkers¹⁹ studied the effect of the curing protocol by using various combinations of light intensity and exposure time (but corresponding to similar curing energy) and observed large variations in shrinkage strain, as measured by both FEM and experimental methods. Their results actually revealed the positive impact of extending curing time with a reduced light intensity.¹⁹ Various curing light units and polymerization protocols were compared with regard to cuspal deflection of MOD restorations made of various materials (resin composites and an ormocer). The curing light type proved influential (LED induced less deformation), as did the restorative materials. The curing protocol of using a

halogen curing unit (standard vs soft-start) had no influence on cuspal deformation³⁷; however, microleakage was observed to be inversely proportional to cuspal deformation, even though the authors could not explain the possible link between lower deformation and higher leakage.

Comparison of Materials and Brands—The influence of the composition of the matrix resin was also evaluated to assess cuspal flexure following the placement of each composite layer as well as after treatment completion. It was shown that the classical bisphenol A diglycidyl ether dimethacrylate and triethylene glycol dimethacrylate (TEGMA) resin blend augmented cuspal flexure compared to ethoxylated bisphenol A glycol dimethacrylate (Bis-EMA) and urethane dimethacrylate (UDMA) compositions.⁵⁵ However, the authors did not comment on the material E-modulus, which largely differed among the tested materials and which is also likely to have influenced tooth deformation.

Electronic speckle pattern interferometry (ESPI) proved to be a viable method with which to monitor tooth dimensional changes during composite placement as the device doesn’t contact the tooth.⁵⁶ The same authors also measured the influence of various composite systems on cuspal deflection following a single increment placement in 2 × 2.5 × 11-mm MOD cavities. The least amount of deformation was recorded with the experimental silorane system, while the flowable composite did not induce more deformation than a conventional hybrid. Among the nano-hybrid materials, variable, cumulative cusp displacement was also recorded, though it was significantly less than that associated with the conventional hybrid. The stiffness of the material proved once again to influence the reaction to composite polymerization shrinkage.

Fleming and coworkers^{55,57} compared previous data obtained with a halogen light-curing unit (LCU) to new data generated with LED technology. Despite large numerical differences in favor of the ormocer material compared to the Z100 system, no statistical significance was revealed between both of these light-curing technologies.³⁷ The same authors investigated the cuspal deformation of experimental oxirane and silorane materials and compared it to that of monomodal composite systems (Z100 and Z250, 3M).⁴¹ They observed a significant reduction in cuspal deflection with the oxirane and then the silorane but with, respectively, an increase or no difference in microleakage values. The authors then put the relative “impact” of cuspal deformation on cavity seal into perspective.

Conclusion: Tooth Deformation and Shrinkage Stress—The cavity size and design (configuration factor) as well as material physico-chemical composition (filler and matrix and consequently the material's stiffness) proved to influence tooth deformation and stress development within the tooth structure or the restorative interface. When considering the design of the studies under review, the quality of the evidence has to be considered to be high, with good consistency. The light curing type (LED vs halogen) only proved to influence cuspal deformation (less deformation for LED curing) in some studies but had no influence on microleakage. The curing mode (soft-start vs conventional curing mode with halogen LCU) had no influence on either of these parameters. Therefore, the ability of a hypothetically "improved" curing approach, such as soft-start curing, appeared to be ineffective in reducing tooth deformation, while an extended curing time with continuous, lower irradiance did demonstrate reduced tooth deformation, even though it was tested in a different experimental setup. With regard to these hypotheses about curing modality, the quantity and consistency of the evidence were rather limited.

Conclusion: Tooth Deformation and Shrinkage Stress Methodology—The tooth deformation observed following the placement and polymerization of various composite materials and curing protocols validates the results obtained by FEM studies. Therefore, when measurements produced on natural teeth are compared to FEM, it confers on these tests a high quality of evidence. The ESPI approach without direct interference with the restored tooth appears to be a promising alternative to conventional strain gauges.

III. Microtensile and Shear Tests

The adhesion studies that were reviewed are presented in Table 3.

Comparison of Restorative and Layering Techniques—Several studies compared the influence of layering vs bulk-fill approaches on dentin bond-strength (BS). They all concluded that a bulk-fill technique did lead to lower bond strength compared to restorations placed incrementally.⁵⁸⁻⁶¹ The results regarding the influence of different layering approaches proved rather controversial, with some studies⁵⁹ showing higher bond strength values for the horizontal technique, while two other studies^{58,60} concluded that there was no difference between horizontal and oblique or vertical layering techniques. When combining three to four horizontal and

oblique layers in different geometries, the highest microtensile bond strength (MTBS) values were observed with the four increments. All other combinations of three horizontal and oblique layers exhibited similar MTBS values, and all were lower than that observed for four increments.⁶²

Other Restorative Variables (Cervical Margin Position, Cavity Dimensions, and C-Factor)—Cavity depth proved influential for bond strength, with lower values in deep dentin and the highest values observed on a flat preparation with low C-factor (CF=1). When a higher C-factor (CF=3) was used, all values fell, which demonstrated the impact of restricted free-surface and composite flow.⁶³ Consequently, the C-factor, and therefore bond strength, also proved to influence failure modes at the adhesive interface.⁶³ The cavity size was also shown to be an influential factor for dentin adhesion, and with an appropriate layering technique the negative impact of larger cavity dimensions could be counteracted.⁶¹ When attempts were made to evaluate the impact of preparation wall location (gingival, pulpal, and axial) on MTBS, no trend was found. The results actually demonstrated that adhesion was influenced by the adhesive system rather than by the preparation surface or location.⁶⁴

Sandwich Techniques—In one study,⁵⁸ the presence of a flowable resin composite (FRC) liner did not improve MTBS in Class II cavities restored incrementally using either a horizontal or oblique layering technique. In another study,⁶⁵ the differences in MTBS were specific to the product rather than influenced by the presence of a flowable composite liner underneath bulk or incrementally filled restorations. It was observed that a lining of FRC improved adhesion when vertical or oblique layering techniques were applied but had no apparent effect underneath horizontal increments. Once again, these findings were product specific.⁵⁹ Other authors concluded again that the use of a FRC liner alone did not improve MTBS underneath bulk-filled restorations with a high C-factor, while the presence of fibers or a combination of FRC together with fibers did increase MTBS.⁶⁶ Incorporation of glass fibers also showed stable BS values regardless of the C-factor.⁶⁶

Polymerization Protocol—Incremental techniques provided better MTBS than did bulk filling for the two different irradiation modes tested (continuous and stepped). MTBS values on flat dentin specimens were also higher than in a Class I cavity configuration, with the exception of the combination of incremental technique and stepped curing mode.⁶⁰

Table 3: *Selected References for Microtensile and Shear Bond Strength*

Comparison of restorative and layering techniques
Figueiredo Reis and others, 2003 ⁵⁸
Nikolaenko and others, 2004 ⁵⁹
dos Santos and others, 2004 ⁶⁰
He and others, 2007 ⁶¹
Niu and others, 2009 ⁶²
Other restorative variables (Cervical margin position, cavity dimensions, and C-factor)
Hez and others, 2007 ⁶¹
Yoshikawa and others, 1999 ⁶³
Cavalcanti and others, 2010 ⁶⁴
Sandwich techniques
Figueiredo Reis and others, 2003 ⁵⁸
Nikolaenko and others, 2004 ⁵⁹
Cavalcanti and others, 2008 ⁶⁵
Belli and others, 2006 ⁶⁶
Polymerization protocol
dos Santos and others, 2004 ⁶⁰
D'Alpino and others, 2006 ⁶⁷
Ilie and others, 2006 ⁷¹
Comparison of materials
Cavalcanti and others, 2008 ⁶⁵
Nikaido and others, 2002 ⁶⁸
Purk and others, 2004 ⁶⁹
Purk and others, 2006 ⁷⁰
Ilie and others, 2006 ⁷¹
Indirect restorations
Coelho Santos and others, 2005 ⁷²
Paul and Schaerer 1997 ⁷³
Magne and others, 2005 ⁷⁴
Frankenberger and others, 2007 ⁷⁵
Comparison of direct and indirect techniques
Aggarwal and others, 2008 ⁷⁶
Frankenberger and others, 1999 ⁷⁷
de Andrade and others, 2007 ⁷⁸
Purk and others, 2004 ⁷⁹

Different combinations of light sources (plasma, halogen and LED) were used to cure the dentin bonding agent (DBA) and composite in Class I cavities, and this revealed the significant influence of irradiation conditions. Overall, bond strength was more dependent on the light source used for curing the DBA rather than that used for curing the composite. In this study, the LED curing of the DBA together with halogen curing of the restorative composite produced the lowest MTBS values.⁶⁷

Comparison of Materials—Two adhesive systems (self-etch one and two step) were tested after

mechanical and thermal fatigue. The one-step system presented lower MTBS values and more than 50% of sample debonding during the testing, which was presumably due to an overwet phenomenon. In this study,⁶⁸ the short period of mechanical loading (50,000 cycles) did not influence the results. In an attempt to evaluate the impact of contact time of the primer on the tooth substrate, additional priming times of 30, 60, and 120 seconds were added after normal application duration, but these did not influence MTBS, as measured on the gingival wall of Class II cavities.⁶⁹ In another study⁷⁰ from the same authors, it was concluded that MTBS values were not influenced by location (pulpal or gingival wall) for the various adhesives tested. However, the three-step total-etch, water-based adhesive and the two-step acetone-based prime and bond systems produced lower values than the two-step water-based self-etch and two-step total-etch ethanol-based systems.⁷⁰

Several composite types and brands were tested for polymerization shrinkage and their interface quality, microhardness profile, flexural strength, and elasticity-modulus following a bulk application in a Class I configuration. It was found that MTBS was correlated to elasticity modulus and the velocity of contraction stress development within restrictive cavity configuration.⁷¹ Therefore, one cannot predict that a high MTBS will be based only on a low E-modulus since the polymerization kinetics play an important role in the development of interfacial stresses and adhesion.⁷¹

Indirect Restorations—Various adhesives (one-step, two-step, and three-step systems) were compared following two modes (pre-cured or non-pre-cured) before the placement of indirect composite inlays. The effect of pre-curing appeared to be material and location specific, and the thickness of the adhesive layer appeared to be increased in the case of pre-curing.⁷² However, the relevance of the aforementioned results in relation to pre-curing the adhesive system for the cementation of indirect restorations would seem to be dubious since the concept of “dual bonding”⁷³ was not fully implemented in this study (adhesive layer thinned and light-cured just prior to adhesive cementation). This latter concept is also supported by more recent results^{65,74} obtained on flat dentin or overlay-like preparations demonstrating that light-activation of the adhesive layer before indirect cementation, renamed “immediate dentin sealing,” is crucial to obtaining high MTBS.

The presence of temporary cement used for the interim restoration reduced MTBS values in Class I

inlays, and to overcome this effect, cleaning of the cavity or immediate dentin sealing was needed.⁷⁵ The removal of cement excesses with a scaler or air polishing with a soft glass were effective treatments, while another air-polishing paste with round particles was unable to restore good MTBS values.⁷⁵

Comparison of Direct and Indirect Techniques—The effect of cyclic loading was evaluated on direct and indirect Class II composite restorations. It was shown⁷⁶ that next to marginal adaptation, MTBS values were superior in the indirect group. When evaluating the influence of different generations of adhesives (third self-etch, fourth total etch, and fifth one bottle) in combination with direct composite and indirect ceramic restorations, the former multistep adhesive generations produced higher bond strengths, while the pre-curing of the adhesive before cementation of indirect restorations also increased the bond strength.⁷⁷ In a similar study configuration,⁷⁸ with simplified cavity design, the dual bonding concept once again noticeably increased the bond strength at buccal walls while reducing MTBS at pulpal walls. When interposing a layer of low-viscosity resin composite, the bond strength measurements were significantly lowered as a result of cohesive fractures in the low-filled liner. Interestingly, a comparison⁷⁹ between *in vivo* and *in vitro* MTBS bond strength on axial and gingival walls demonstrated lower values *in vivo*, which were particularly pronounced at the gingival walls, most likely as a result of higher substrate wetness.

Conclusion: Microtensile and Shear Tests—Within the limitations of this study protocol, the most relevant conclusions, based on a satisfactory quantity and consistency of the evidence, are that

- higher bond strengths were obtained with layering techniques (vs bulk);
- for indirect restorations, “dual bonding” or “immediate dentin sealing,” as opposed to an application and curing of the DBA just before placing the restoration, increased bond strength; and
- the cavity C-factor is an influential factor for bond strength (high CF reduces MTBS).

All other study variables, including curing protocols, cavity depth, the presence of flowable composite liner, light source, and various adhesive systems, did not have a clear impact on MTBS, and, therefore, no recommendations can be drawn as a result of the limited evidence related to quantity and consistency.

Conclusion: Microtensile and Shear Test Methodology—Bond strength and, in particular, microtensile

bond strength tests measure the capacity of an adhesive interface to resist stresses induced by polymerization and occlusal function. They actually represent the first attempt to evaluate the potential of a specific restorative system or technique to establish the biomechanical balance needed to maintain sealed margins and reinforce the remaining tooth structure. Such features are crucial in Class I and II adhesive restorations in order to obtain satisfactory medium- and long-term clinical behavior. When combined with mechanical and thermal stressing (oral environment simulation), MTBS tests most likely increase their potential clinical relevance and adequately complement marginal adaptation studies. MTBS also have the potential to measure regional variations of bond strength, something that was not possible with conventional tensile or shear bond strength tests. However, this latter potential ability requires more investigation. The MTBS methodology does potentially suffer from tissue inhomogeneity, but on the other hand, it provides a precise, quantitative evaluation method, which confers an acceptable quality of evidence.

IV. Marginal Adaptation

The marginal adaptation studies that were reviewed are presented in Table 4.

Comparison of Restorative and Layering Techniques—In the absence of mechanical loading, two studies^{80,81} did not find any significant difference in marginal adaptation between bulk-fill and layering techniques, while a third report⁸² presented opposing findings of significantly more cervical defects in the bulk-fill technique group. In proximal microcavities, more sophisticated filling techniques, such as the three-site layering concept and ceramic inserts, did not show any advantage over a simple two-layer technique using either a restorative or flowable composite.⁸³ Accordingly, “overengineering” the restorative technique appeared useless for small volumes.

In an attempt to evaluate the benefit of additional retentions in small box preparations simulating restoration repair, the smallest box-only composite additions (without undercuts or occlusal retentions) provided the best resistance to cyclic loading.⁸⁴

Other Restorative Variables (Cervical Margin Position, Cavity Dimensions, Matrix Systems, etc)—The beveling of margins proved beneficial to marginal adaptation,^{83,85,86} but mainly when enough tissue remained above the cemento-enamel junction.^{87,88} When less than 1 mm of enamel height remained,

the bevel no longer had a positive influence, and in such situations, an indirect technique provided better adaptation.⁸⁷ The instruments used for finishing and beveling margins proved to be influential with regard to marginal adaptation. Specifically, ultrasonic-driven instruments induced more marginal defects compared to sonic instruments^{83,85} or a fine diamond round bur.⁸³ The vibration induced by ultrasonic energy during composite placement also proved to be beneficial for Class II adaptation of nonbeveled cavities.⁸⁵

Sandwich Techniques—Sandwich techniques with conventional glass ionomer cement as a lining downgraded the adaptation to dentin when compared to full composite restorations^{87,88} or sandwich restorations using resin modified glass ionomer cement (rmGIC) liner or full composite restoration.⁸⁹ A rmGIC liner or base did show⁹⁰ the potential to improve marginal adaptation *in vitro*. The same potential was also demonstrated by a compomer; however, the adaption was only improved in a closed sandwich configuration.^{86,91,92} But the rationale for using a fluoride-releasing material in an open sandwich configuration was finally questioned, as literature reviews^{93,94} have not confirmed the protective role of GICs against recurrent caries. Other materials, such as chemically curing or flowable composites, were considered to facilitate restoration placement and/or reduce the negative impact of polymerization shrinkage. This literature review found that the presence of either a flowable liner or chemically curing composite base actually improved marginal adaption, but without totally suppressing marginal defects.^{77,84,95,96} The aforementioned findings were confirmed recently another study,⁹⁷ which showed a significant reduction of imperfect margins after loading when applying rmGIC or flowable composite liners with lower E-modulus. In another study,⁹⁸ a positive effect was only observed when a thin, pre-cured flowable composite lining was applied. The cervical gap size in lined composite restorations was linearly correlated to the strain absorption capacity (negative correlation) and shrinkage (positive correlation).

Influence of Polymerization Protocol—It was first suggested by Goracci and de Martinis⁹⁹ that a slow polymerization mode could reduce marginal defects in Class II restorations. Since then, only a few reports have evaluated and confirmed the impact of curing protocol on the quality of adaptation in the Class II restoration. The adaptation to enamel of Class II MOD restorations was not influenced by the curing light energy (medium intensity conventional

halogen or high-intensity plasma), while the step-curing protocol produced better occlusal and cervical adaption than did pulse-delay or ramp-curing protocols.¹⁰⁰ This partially supports other *in vitro* studies in which the authors studied the effect of various polymerization protocols on contraction force¹⁰¹ or distribution.¹⁹ In an attempt to confirm the advantage of the three-sided light-curing protocol over a conventional occlusal curing, it was shown that a reduced light intensity is likely to be the influential factor that improves restoration adaptation.¹⁰² In a recent study,¹⁰³ the impact of curing time and energy density on contraction stress and marginal adaptation was evaluated. It was shown that a minimal radiant exposure was needed to reach a satisfactory adaption and that a further increase in light density did not significantly affect contraction stress or adaptation. Nevertheless, relevant and conclusive studies clarifying the role and potential impact of curing protocols and light intensity on marginal adaptation are still needed.

Comparison Between Adhesive and Composite Types or Systems—Marginal adaptation to enamel was not affected by gingival fluid contamination when this happened just after acid etching. However, gingival fluid did adversely affect adaption when the contamination happened after adhesive placement.¹⁰⁴ These results should not necessarily be considered valid for blood or saliva contamination.

The use of a filled adhesive system improved the marginal and internal adaptation of mixed Class II cavities when compared to a nonfilled, thinner “prime and bond” adhesive system. The thicker and consequently elastic bonding resin was considered to act as a stress-breaking layer.⁹¹ The performance of simplified adhesive systems used with their respective composite also proved inferior to the multicomponent system that served as the control.¹⁰⁵

The comparison between ormocers and a traditional hybrid composite used in Class II cavities was clearly in favor of the hybrid composite, which presented very high percentages of perfect adaptation both in occlusal and cervical enamel. The adhesive used for the ormocer tested in this study was believed to be responsible for the unsatisfactory adaptation observed with the ormocer.¹⁰⁶ The influence of ceramic inserts on proximal adaptation of Class II restorations was dependant on the level of the cervical margin and the type of insert used.¹⁰⁷ Anatomically shaped inserts improved adaptation to enamel only, while round-shaped, beta-quartz inserts had no influence at all on adaptation when compared to full composite restorations. In dentin,

Table 4: *Selected References for Marginal and Internal Adaptation*

Comparison of restorative and layering techniques
Tjan and others, 1992 ⁸⁰
Idriss and others, 2003 ⁸¹
Stoll and others, 2007 ⁸²
Hugo and others, 2001 ⁸³
Frankenberger and others, 2003 ⁸⁴
Other restorative variables (Cervical margin position, cavity dimensions, matrix system, etc)
Hugo and others, 2001 ⁸³
Schmidlin and others, 2007 ⁸⁵
Dietschi and others, 2002 ⁸⁶
Dietschi and others, 1995a ⁸⁷
Dietschi and others, 1995b ⁸⁸
Sandwich techniques
Belli and others, 2001 ³¹
Frankenberger and others, 1999 ⁷⁷
Frankenberger and others, 2003 ⁸⁴
Dietschi and others, 1995a ⁸⁷
Dietschi and others, 1995b ⁸⁸
Dietrich and others, 1999 ⁸⁹
Dietrich and others, 2000 ⁹⁰
Dietschi and others, 2002a ⁸⁶
Dietschi and others, 2002b ⁹¹
Dietschi and others, 2003 ⁹²
Randall and Wilson, 1999 ⁹³
Wiegand and others, 2007 ⁹⁴
Garberoglio and others, 1995 ⁹⁵
Belli and others, 2001 ⁹⁶
Kwon and others, 2010 ⁹⁷
Chuang and others, 2004 ⁹⁸
Influence of polymerization protocol
Versluis and others, 2004 ¹⁹
Goracci and Martinis, 1996 ⁹⁹
Hofmann and Hunecke, 2006 ¹⁰⁰
Sakaguchi and others, 2004 ¹⁰¹
Losche, 1999 ¹⁰²
Prado and others, 2010 ¹⁰³
Comparison between adhesive and composite types or systems
Dietschi and others, 2002 ⁹¹
Spahr and others, 2000 ¹⁰⁴
Göhring and others, 2003 ¹⁰⁵
Kournetas and others, 2004 ¹⁰⁶
Strobel and others, 2005 ¹⁰⁷
Indirect composite restorations
Dietschi and others, 2003 ⁹²
Comparison between direct and indirect class II restorations
Manhart and others, 2001 ¹
Manhart, 2004 ³
Paul and Sharer, 1997 ⁷³

Table 4: Continued.

Aggarwal and others, 2008 ⁷⁶
Frankenberger and others, 1999 ⁷⁷
Dietrich and others, 1999 ⁸⁹
Dietschi and others 2002 ⁹¹
Bertschinger and others, 1996 ¹⁰⁸
Dietschi and Herzfeld, 1998 ¹⁰⁹
Papathanasiou and Bardwell, 2001 ¹¹⁰
Iida and others, 2003 ¹¹¹
Evaluation of marginal and internal adaptation of class II restorations following short-term clinical function
van Dijken and others, 1998 ¹¹²
Lindberg and others, 2000 ¹¹³
Andersson-Wenckert and others, 2002 ¹¹⁴
Andersson-Wenckert and others, 2004 ¹¹⁵
Opdam and others, 2007 ¹¹⁶
Lindberg and Van Dijken, 2005 ¹¹⁷

the inserts had no positive impact on restoration quality.

Indirect Composite Restorations—The influence of resinous bases with increasing E-modulus underneath Class II MOD composite inlays was evaluated after mechanical loading. The best results were obtained with a “highly filled” flowable material, while the restorations having no base, a compomer, or a “low-filled” flowable or a restorative material lining showed more marginal defects.⁹² These results indicated that material mechanical properties such as rigidity/elasticity and viscosity have the potential to influence restoration adaptation after loading. It is interesting to mention that these differences appeared only after loading, which supports the use of cyclic loading to evaluate the impact of different materials or treatment protocols on Class II restoration adaptation and quality.

Comparison Between Direct and Indirect Class II Restorations—In the presence of thin cervical enamel (0.5-mm thickness and 1-mm height) the indirect composite restorations had a better adaptation compared to a direct, multilayered composite filling.⁸⁸ The presence of a bevel also improved the cervical adaptation in both direct and indirect restorations, but only when there was “thick” (>1 mm) enamel remaining. With a butt margin design, thick enamel was beneficial to indirect restorations only.⁸⁸ In a study⁸⁸ evaluating the influence of restorative technique (direct vs indirect composites) and liners (GIC or rmGIC), the inlay technique proved overall to be superior to the direct composite option. In this study, the presence of GIC or rmGIC liners lowered the excellent adaption percentages in

both direct and indirect restorations. Once again, the benefit of glass ionomers used as liners was not substantiated by *in vitro* studies when evaluated in a protocol that was more clinically relevant.

The combination of the dual bonding technique (applying the adhesive system before impression or further restorative procedures)^{73,108} together with an inlay or insert technique yielded better adaptation than did direct or indirect techniques using a conventional adhesive cementation technique (applying the adhesive at the time of cementation).¹⁰⁹ In addition, when comparing a direct technique to ceramic inlays using the dual bonding technique, better results were obtained with this latter approach.⁷⁷ Moreover, in this same study, third- and fourth-generation adhesives showed better performance than did those of the fifth generation. In another test,⁷⁶ in which the test samples underwent cyclic loading, the performance of composite inlays was observed to be superior to the direct technique. When comparing a direct technique to direct chair-side inlays or laboratory indirect inlays, the lowest amount of gaps was observed in the indirect group. A reduction in gaps was also observed in the direct inlay group compared to the group in which the direct technique was utilized, but this finding was not significant.¹¹⁰

Comparing different inlay materials in mixed Class II cavities (composite, low-fusing ceramic, Spinell and aluminous porcelains) did not show any significant difference in either marginal or cervical adaptation between these three ceramic materials, which had differing structure and stiffness.¹⁰⁹ The composite inlay, however, showed a better marginal adaptation in cervical dentin. In a similar study, the cement type appeared to be the influential factor for cervical adaptation to dentin. Better cervical adaptation to dentin was also observed with ceramic inlays compared to a direct technique, although once again, this was dependant on the luting material.^{1,110}

Finally, it was observed that the proportion of gap-free resin-dentin interface was not influenced by the restorative technique (direct or CEREC inlay) but instead by the presence of a low-elasticity flowable composite liner, which significantly decreased the amount of defects at the same interface.¹¹¹

Evaluation of Marginal and Internal Adaptation of Class II Restorations Following Short-term Clinical Function—An interesting approach to testing the marginal and internal adaptation of Class II adhesive restorations was developed by van Dijken and coworkers.¹¹² They sought to integrate the clinical

environment and strains, and their concept was to restore premolars scheduled to be extracted (one month after restoration placement) for orthodontic reasons and then to apply the same evaluation protocol as was used for *in vitro* investigations.¹¹² This approach confirmed the advantage of using a multicomponent adhesive system over a simplified one, and it also verified that the directed shrinkage technique (placing a base of self-curing composite underneath a light-curing restorative material) produced a dentin adaptation that was comparable to that obtained using a horizontal multilayering technique.¹¹² The adaptation for sandwich restorations using a compomer or rmGIC base was superior to full composite restorations after this short period of clinical service^{113,114} and confirmed the findings of many *in vitro* investigations.⁸⁹⁻⁹¹ However, it has to be considered that these findings were not confirmed after longer *in vivo* observation periods.^{115,116} Using the same protocol, the one-month adaption of Class II restorations with a FRC was observed to be equivalent to a full composite filling. Using this same test model and time frame, no influence on restoration adaptation was reported¹¹⁷ between a soft-start curing and continuous irradiation curing technique.

Conclusion: Marginal Adaptation—Within the limitations of this study protocol, the most relevant conclusions based on a satisfactory quantity and consistency of the evidence are that

- the position of restorative margins influenced the marginal adaptation (less defects observed at enamel margins);
- a bevel improved cervical adaptation in both direct and indirect restorations when enough enamel was present (>1 mm);
- the dual bonding technique (application of the adhesive system before impression and cementation) improved restoration adaptation;
- multicomponent adhesive systems showed better margins than did simplified ones;
- the use of a FRC with low E-modulus or a chemically curing composite base showed a potential for better marginal adaption underneath both direct and indirect restorations; and
- a better overall adaptation was obtained with indirect techniques.

The influence on marginal adaptation of other variables, such as the filling technique, the curing protocol and light intensity, the presence of a GIC or rmGIC liner, or the composite type used for direct restorations or material type (composites or ceram-

ics) for indirect restorations, could not be ascertained as a result of the insufficient quantity or consistency of the available evidence.

Conclusion: Marginal Adaptation Methodology—Phenomena such as nano-leakage, leakage, pulpal complications, and secondary caries, which are induced by interface breakdown, represent the majority of clinical failures observed in all types of direct restorations.^{3,118} Therefore, evaluating the behavior of adhesive restorations and interfaces with natural tissues under simulated function, pulpal pressure, and a moist environment helps to identify weak points and allows a better understanding of how to reduce the incidence of defects around or underneath a restoration.^{92,119-121} This undoubtedly confers upon such a research approach the highest quality among all protocols used to test Class II restorations.

In fact, observing the restoration marginal adaptation without mechanical loading will only reflect the behavior of the system used to fabricate the restoration or placement/insertion stresses and will not provide information about the reaction of the overall system to function. Studies^{86,92,109,122} using multiple loading cycle steps have actually shown the impact of mechanical load magnitude and stress duration on the quality of marginal and internal adaptation of the restoration. For instance, a restorative system that exhibited a good immediate adaptation due to the increased flexibility of the liner later showed an unsuccessful behavior due to increased deformation under load and adverse behavior to fatigue once it was mechanically stressed. In other words, satisfactory initial adaptation of a restorative system can neither predict an optimal clinical behavior nor inform us about the reaction to long-term functional stresses or the oral cavity environment. The effect of long-term exposure to moisture is also an important test condition in order to reveal phenomena such as hydrolytic degradation and expansion of the restorative system due to water sorption.^{115,116,123} The limited duration of *in vitro* investigations therefore still represents a weak aspect of such testing protocols and further justifies the need for *in vivo* trials, despite their numerous aforementioned practical limitations.

The sensitivity threshold and overall “quality” of evidence for marginal adaptation protocols should also be addressed, as procedural confounders exist for the laboratory stages (ie, control of sample moisture, polishing technique, experience of the operator, real load applied, etc), all of which can affect the significance of some studies and explain

the conclusions of a recent and controversial review¹²⁴ questioning the relevance of marginal-internal adaptation tests of Class V restorations. As a result, the “apparent” absence of a correlation between clinical and *in vitro* studies regarding the performance of Class V restorations was erroneously interpreted as a possible irrelevance of marginal leakage tests instead of as an indication that confounders and sensitivity issues exist, which affect both the *in vitro* and clinical studies under review. This underlines once again the importance of extremely well-standardized study protocols and proper simulation of the oral environment (ie, functional loading) for *in vitro* trials.

V. Comparison of Methods and Evidence Hierarchy for In Vitro Trials

Clinically, restorations can potentially fail because of restoration/tooth fracture, loss of anatomy and function (chemical and mechanical wear), or interface degradation, leading to marginal leakage, pulpal pathology, and recurrent decay. Such failures are therefore of three types: structural breakdown, surface degradation, or loss of cohesiveness between the restoration and tooth structure. Oral cavity strains responsible for those failures are of a mechanical, chemical, thermal, and bacteriological nature. In addition, the repetitive occurrence of those stresses, known as “fatigue,” is of particular importance for both *in vivo* and *in vitro* research.¹²⁵ Therefore, the best approach to evaluate the ability of a restorative system to resist such strains and degradation patterns is a clinical trial, and scientists and clinicians thus continue to call for medium- to long-term studies to discriminately appraise the various operative protocols and material choices. Unfortunately, clinical evaluation times shorter than three to five years^{126,127} seem insufficient, and this strengthens the need for preclinical, *in vitro* evaluation protocols.¹²⁶⁻¹²⁸

In a similar fashion to the accepted hierarchy of evidence in clinical research, there is also an obvious and increasing need to assess the relevance of laboratory protocols. Therefore, a first important consideration is to evaluate the capacity of *in vitro* tests for adhesive posterior restorations to replicate major oral strains, such as functional forces, thermal changes, and moist environment. This represents the initial rationale and assessment model for developing a hierarchy of the predictive value or evidence level of *in vitro* trials, such as we have proposed in Table 5.

Table 5: Proposed Hierarchy of Evidence for Class II In Vitro Trials, Based on the Capacity of the Laboratory Protocol to Simulate Oral Cavity Strains. Relevance or Hierarchy Degree Is Ranked on a 1-5 Scale, 5 Being the Highest Score

In Vitro Protocol	Stress Conditions ^a		Relevance Score
	Monotonic Mechanical Loading	Cyclic	
Resistance to fracture	+	–	1
Photoelasticity	+	–	2
Marginal leakage	–	–	1
		+T&ML	2
Bond strength	+	–	2
		+T&ML	3
Resistance to deformation	+	–	2
		+ML ^b	3
Finite element analysis			
Two dimensional	+	–	2
Three dimensional			3
Resistance to fracture	–	+ML ^b	3
Polymerization-induced tooth deformation	+	–T&ML	3
Wear resistance	–	+T&ML	4
Marginal adaptation	–	–	3
		+ T&ML	4
Marginal and internal adaptation	–	–	4
		+T&ML	5
Abbreviations: ML, cyclic mechanical loading; T, thermal cycling; –, without; +, with.			
^a Most frequent study design.			
^b Cyclic strains may be applied prior to testing.			

For instance, resistance to fracture tests without cyclic stressing induce fracture patterns that are irrelevant to the failures observed clinically and were therefore attributed the minimal score (1). As well, microleakage tests, which show poorly consistent results and use a semiquantitative evaluation scale, were also considered poorly relevant to clinical conditions and were thus given scores of 1 or 2 when thermal cyclic or mechanical loading was used. Photoelasticity also suffers from main technological limitations, as previously described, and it was thus also attributed a low relevance score (2). Despite the fact that the evaluation of wear in contact areas following cyclic loading was not reported in this review (as the related references were not in the selected review period), this methodology was attributed a high score of relevance (4), even though wear resistance tests appear nowadays to be less crucial as a result of the considerable improvements in the physical properties of composites.

The reaction of posterior adhesive restorations to intraoral strains is the result of complex interactions among the filling material, the tooth substrate, and their environment. To date, there is no single *in vitro* test able to simulate all of the aforementioned strains and degradation patterns and then able to

reliably predict the clinical performance of a restorative system. Therefore, considering a combination of protocols would appear to be the safest approach at the present time. For instance, information collected from computer simulation (FEM) or tooth deformation (score of 2 to 3 for each) can contribute to a better understanding of stress development and management in adhesive restorations. Bond strength tests (score of 2 to 3) would complete this first level of evaluation by enabling an understanding of how well the adhesive interface reacts to the placement of the restoration and the subsequent functional load.

The second evaluation level would be provided by adaptation studies (score of 3) and, in particular, those studies that submit samples to cyclic loading (scores of 4 to 5). Such protocols appear more discriminative in terms of predicting clinical behavior since they mimic a global interaction of the restorative system with the tooth in a simulated oral environment. They also provide meaningful information about the quality of interfaces following fatigue.^{88,91,92,120,129-131} However, it may be necessary to perform these studies with an increase of load and number of cycles in order to simulate parafunctional forces and long-term behavior. A

force feedback through stress sensors could also improve loading control and should be considered as part of a desired implementation for most of the existing “mastication simulators,” which presently lack such a feedback system.

In clinical studies potential confounders exist. Some of these are sample size, patient selection (ie, age and gender, social background, hygiene, existence of parafunctions, etc), observation period, patient drop-out, clinician skill, and clinical evaluation thresholds, to cite only the most important ones. This logically explains why only multicenter and multioperator, randomized controlled studies with medium- to long-term observation periods are truly conclusive.⁴⁻⁶ The unfortunate reality is that such studies are either totally missing or cannot investigate detailed parameters, such that preclinical, *in vitro* studies remain a valid and decisive evaluation approach.

In order to improve the quality of the evidence in *in vitro* trials, hidden or confounding variables thus have to be identified and tentatively eliminated or controlled. Depending on the protocol, those procedural confounds that have to be considered are

- origin and condition of teeth (human or animal origin, type of teeth, age, presence of decay, storage conditions, etc),
- control of sample moisture,
- finishing of the restorations (thermal and mechanical stresses), and
- control of forces (ie, magnitude, stress profile, frequency).

Therefore, it seems advisable to avoid drawing clinical conclusions from *in vitro* protocols showing relevance scores that are below 3, unless these are combined with other evaluation methods. Following such a thinking process in dentistry would seem advantageous for editors, reviewers, and readers and would limit the risk of misinterpretation of *in vitro* research and the subsequent dissemination of insufficiently founded clinical guidelines.

GENERAL CONCLUSIONS

An abundant number of study hypotheses corresponding to almost unlimited combinations of preparation techniques, adhesive procedures, restorative options, and materials were submitted to various *in vitro* protocols. Some of these hypotheses were repeatedly tested and some consensus arose in regard to the quantity and consistency of the evidence. However, many other combinations re-

main yet to be validated by either additional *in vitro* research or clinical trials as a result of the insufficient quantity, quality, or consistency of the available evidence.

The following conclusions can therefore be made based on the systematic conclusiveness of various *in vitro* studies, and some recommendations can conceptually be made to guide clinicians toward their operative choices, even though some caution might still apply in the absence of absolute confirmation through clinical research.

- 1) Stress management remains an issue with modern composite technology because of the substantial volumetric polymerization shrinkage that occurs as a byproduct of this chemistry. As yet, there is no new composite formulation in existence that can significantly limit or totally eliminate shrinkage and still maintain all of the proven performance of hybrid composites, even in *in vitro* testing situations.
- 2) The stresses occurring during restoration placement (direct techniques) or function can be controlled by a number of methods.
- 3) The control of curing light energy (low irradiance with extended polymerization time) helps reduce stresses transmitted to the restoration, adhesive interface, and tooth structure. However, the advantages of modified light-curing protocols such as ramp curing, soft-start curing, and step curing were not fully verified.
- 4) Multilayering is mandatory for direct restorations. No protocol seems especially superior; however, cavity size and configuration are influential factors.
- 5) Dual bonding (IDS) improves the adhesion and adaptation to dentin for indirect techniques.
- 6) The “elastic” base lining concept (placement of a stress-breaking layer) proved efficient and superior to “traditional” full composite restoration techniques; however, the thickness and E-modulus of such liners are influential factors.
- 7) Indirect restorations proved better than direct ones in most *in vitro* conditions, when used in large cavities.
- 8) The material’s stiffness, restoration thickness, and configuration (no coverage, partial coverage, or full occlusal coverage) play a crucial role in treating large cavities or nonvital teeth as a result of the imperative need for tooth stabilization and reinforcement. It seems advisable to use “stiffer” composites or ceramics for restoring weakened posterior teeth, such as those that have been endodontically treated.

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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