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Potassium Iodide Reversal of Silver Diamine Fluoride Staining: A Case Report

S Garg • A Sadr • DCN Chan

Clinical Relevance

The major drawback with silver diamine fluoride (SDF) application is the dark staining of teeth and restorative materials. Therefore, SDF use on adult dentition is limited. Improving the esthetic outcome by stain reduction would greatly enhance the opportunity for its universal use.

SUMMARY

This article describes the clinical protocol of using potassium iodide (KI) to reverse staining caused by silver diamine fluoride (SDF). SDF contains silver, fluoride, and ammonia. It has been used to arrest dental caries mainly in pediatric applications. The major drawback of SDF application is the dark staining of both teeth and restorative materials. Hence, its use on adult dentition is limited. Improving the esthetic outcome by stain reduction would greatly enhance the opportunity for SDF's universal use. This case demonstrates how KI can effectively reverse the staining.

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INTRODUCTION

Silver diamine fluoride (SDF) has been used to reduce the incidence and progression of caries in primary dentition and the results have been well documented.[1-3] SDF was first developed in Japan.[4] Other countries, such as Brazil, England, and Hong Kong, have also been using it to arrest caries in children. Initially, SDF was not approved in the United States partly due to the dark staining of carious teeth. The US Food and Drug Administration, however, approved SDF in August 2014 to reduce tooth sensitivity for those who are 21 years of age or older, and SDF became available in the US market one year later.[5] It is used off-label for the arrest of dental caries.

Despite its great potential for arresting caries, the SDF concept is not taught extensively in the standard restorative dentistry curriculum at US dental schools.[6] At the University of Washington School of Dentistry's predoctoral program, our involvement with SDF started as student-initiated requests after their rotation in pediatric dentistry, where the subject of SDF was introduced. The students questioned why the Department of Restorative Dentistry did not use SDF to control decay in our adult patient population. In response to the students' queries, we began a series of research projects and clinical protocols trying to embrace the use of SDF for our adult population.[7-9] We are confident at this time that the esthetic outcome of SDF application through stain reduction would greatly enhance the opportunity for its universal use.

Clinical Case Report

Medical and Dental Background—The patient in this case was a 32-year-old healthy male who suffered from severe decay of the maxillary anterior teeth. His chief complaint was "chipped and broken teeth." The patient's medical history was noncontributory. His dental history included no regular visits to the dentist for more than a decade. The patient also admitted he was a heavy smoker, having smoked a pack of cigarettes per day for the past 15 years but quitting two years ago. He had recently gotten a new job and subsequently dental insurance. Hence, he presented to our dental clinic for a comprehensive dental examination.

The extraoral exam revealed asymptomatic clicking of the left temporomandibular joint during jaw opening. The intraoral examination found generalized gingivitis with severe calculus deposition. There were retained root tips of #1 and #16; #32 was partially erupted, and #17 was impacted. The examination further revealed advanced occlusal carious lesions on teeth #15 and #18.

The most striking finding was the grossly decayed maxillary anterior teeth (Figure 1a,b). We conducted detailed interviews to find out the possible etiology. The patient had normal saliva flow, and no relevant medical information was found to be the possible cause for his dental condition. We ascribed the gross decay to his excessive sugar consumption, lack of dental hygiene, and avoiding care due to dental and medical anxiety. The caries risk assessment indicated that the caries risk was high because of the multiple advanced caries lesions.

All the carious maxillary anterior teeth tested vital to pulp testing, except for #7. Radiographic examination revealed a 3 × 4-mm periapical radiolucency on #7, although the patient was asymptomatic (Figure 2).

For #7, an initial differential diagnosis of necrotic pulp, asymptomatic apical periodontitis was made, and the patient was referred for root canal treatment, followed by scaling and root planing. Another referral was presented to the Department of Oral Surgery for third-molar extractions.

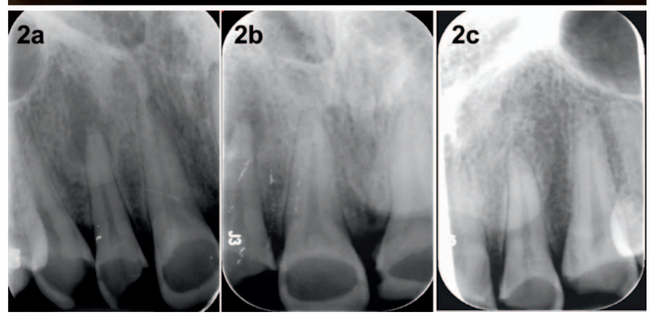
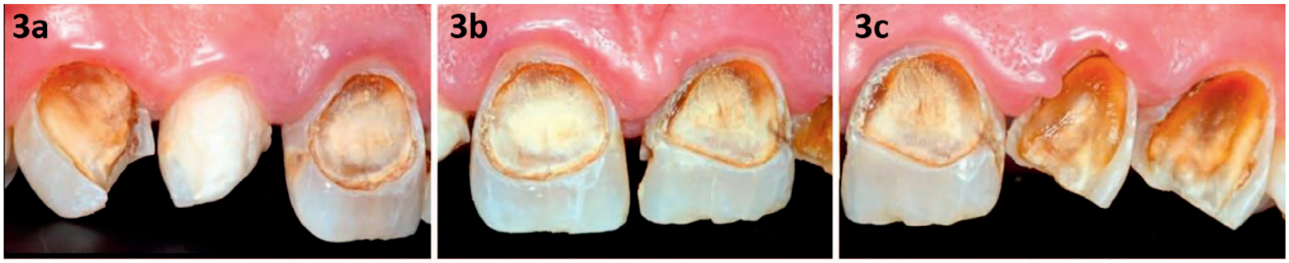


Figure 1. *(a): Preoperative picture of the maxillary teeth before #7 root canal treatment. (b): Preoperative picture of the maxillary teeth after #7 root canal treatment and resin-modified glass ionomer interim restoration.*

Figure 2. *(a), (b), and (c): Preoperative radiographs of the maxillary front teeth.*

Interim Restorations for Maxillary Anterior Teeth With SDF and Potassium Iodide Application—After discussing the findings with the patient, he was aware of the condition of his maxillary anterior teeth and was motivated to improve his dental health. Since caries risk was high, our immediate treatment phase was to control the caries progression after scaling and root planing. Dietary counseling was done with complete oral hygiene instructions. SDF with potassium iodide (KI) treatment protocols were explained to the patient along with the advantages and disadvantages of such treatments. Decay was removed mainly from the cavity margins using large round burs with a slow-speed hand piece (Figure 3). The removal of soft and infected dentin is crucial to adequate bonding for subsequent restoration. It would also improve the penetration of SDF into the remaining carious dentin and provide a better substrate for application of the glass ionomer restorative material. Additionally, the demineralized enamel would pick up a significant amount of SDF staining at the margins of the restoration and look stained.

The preparations were cleaned and dried, and SDF was applied followed by KI. SDF treatment can



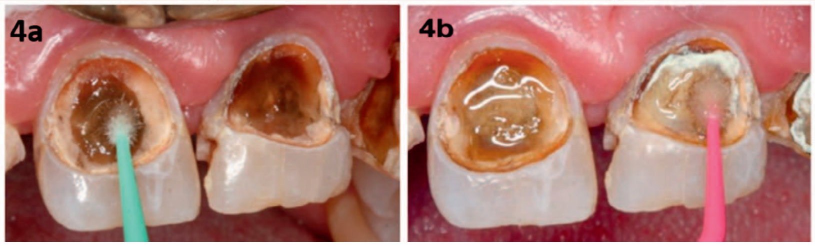


Figure 3. *(a), (b), and (c): Finished cavity preparations.*

Figure 4. *(a): Application of silver diamine fluoride (SDF) with black stain already appearing. SDF treatment can increase the microhardness of carious lesions in dentine and the mineral density of carious lesions in enamel. (b): Application of potassium iodide (KI) showing immediate formation of tripotassium phosphate, K_3PO_4, a white delinquent powder, and silver iodide, also a white powder.*

increase the microhardness of carious lesions in dentin and the mineral density of carious lesions in enamel. Figure 4a,b shows the staining caused by SDF before and after KI application.

Since five of the six anterior teeth tested vital, we prescribed interim glass ionomer restorations for the anterior teeth after SDF and KI treatment (Figure 5a,b). Application of KI returns the SDF-treated dentin to a lighter substrate more amenable to esthetic restorations. This step was deemed important since the interim glass ionomer restorations were to be in place for a few months and patient acceptance and confidence was ensured. Later, these glass ionomer restorations were also to serve as buildups for permanent crowns or veneers. Resin-modified glass ionomer (RMGI) is a highly translucent restorative material because of its high glass filler content. Application of RMGI over SDF-treated dark dentin would unlikely be able to cover the color completely. Final restorations were to be done three to six months later, after all the symptoms, including gingivitis, subsided. The patient was informed to follow all the oral hygiene instructions and improve his gingival health to receive final restorations. Further, at the six-month follow-up appointment, all the restorations were evaluated, touched up with flowable composite, and polished (Figure 6). This helped smoothen the rough surfaces caused by long-term RMGI exposure to oral cavity. The treatment protocol is detailed in Table 1.

Figure 5. *(a): Interim resin-modified glass ionomer restorations. (b): Formation of yellowish margin on the incisal of the central incisors believed to be a precipitate of silver iodide. Silver iodide is highly photosensitive and can turn dark with exposure to light.*

Figure 6. *(a) and (b): Finished and polished restorations with flowable composite touch-up at six-month follow-up. Note the improved gingival health and slight dark staining of teeth.*

Table 1: Recommended Protocol for Potassium Iodide (KI) Staining Reversal
• Dispense appropriate amount of silver diamine fluoride (SDF) into disposable medicine cup (one drop can be applied to at least five teeth with moderate-size cavities).
• Apply petroleum jelly or use rubber dam to protect soft tissue near affected areas.
• Dry affected tooth surfaces as much as possible with air syringe or with cotton pellets.
• Use a microbrush saturated with SDF to paint directly onto the tooth surface.
• Avoid cavity margins or soft tissues.
• Allow to absorb for one minute, then remove excess with cotton pellets.
• Dispense appropriate amount of KI into disposable medicine cup.
• Use a microbrush saturated with KI to paint directly onto the tooth surface, like SDF application. Reaction products form immediately.
• Restore areas with resin-modified glass ionomer or composite restoration as indicated.

DISCUSSION

SDF is available in an 8-mL bottle (Advantage Arrest Silver Diamine Fluoride 38%, Elevate Oral Care, West Palm Beach, FL, USA) and indicated primarily for the treatment of dentinal hypersensitivity. Each bottle can treat up to 125 sites, with a site defined as up to five teeth.

Medically, KI is known as an expectorant and is prescribed to loosen and break up mucus in the airways. The loosened mucus can then be coughed up, so one can breathe more easily if one has long-term lung problems (eg, asthma, chronic bronchitis, emphysema). KI is also used along with antithyroid medicines and in radiation emergency.

SSKI (potassium iodide oral solution, USP) is a saturated solution of potassium iodide containing 1 g of potassium iodide per milliliter. The SSKI used in this case was manufactured by Upsher-Smith Laboratories, Inc (Maple Grove, MN, USA). The normal dosage for adults is about 0.3 mL (300 mg) or 0.6 mL (600 mg) diluted in one glassful of water, fruit juice, or milk three or four times daily. For stain reversal purpose, the KI dosage used is comparable to 0.3 mL of the saturated KI (1 g/mL) solution. However, the amount applied immediately reacts to form other reaction products. A small, safe amount of KI may reach the saliva.

The combination effect of a SDF and KI treatment on the permeability of demineralized dentin to *Streptococcus mutans* was investigated more than a decade ago;[10] however, only recently was KI suggested to manage the staining problem.[5,7,9,11] It was suggested that discoloration of the carious lesion can be avoided without affecting the caries-arresting effect of SDF. The suggested explanation is that the silver ions from the SDF solution will react with the iodide ions from the KI solution to form silver iodide. We further elucidate the proposed chemical reactions between silver compounds and the major tooth components, hydroxyapatite, as follows:

$$Ca_{10}(PO_4)_6(OH)_2 + Ag(NH_3)_2F \rightarrow CaF_2 + Ag_3PO_4 + NH_4OH$$

The formation of CaF_2 and Ag_3PO_4 was confirmed by *in vitro* studies, and they are considered the major products of the reaction of SDF with tooth tissue.

For the stain reduction, we are proposing that the following reaction occurred where tripotassium phosphate, a white delinquent powder, is formed.[9] The white powder is the main reason for the stain reduction. Another double-reaction product, silver iodide, is a yellowish-white powder but considered to be photosensitive and can turn dark with exposure to light:

$$Ag_3PO_4 + 3KI \rightarrow 3AgI + K_3PO_4$$

Our case report confirms laboratory findings that the restoration margin may still be at risk of discoloration. Yet overall staining compared to that of SDF alone was greatly reduced. It was reported that SDF + KI treatment inhibited development of secondary caries on GIC restorations but was not as effective as SDF treatment alone. Therefore, it seems that the use of KI should be justified for cases where esthetics are important, such as the case presented in the current report.

Potential Risk Associated With SDF and KI

There have been no adverse reports of SDF after around 50 years of use in Japan.[4] Silver allergy would be a contraindication. If soft tissue is not protected with petroleum or rubber dam, desquamate processes, such as ulcerative gingivitis (Figure 7b) can occur. The symptom will go away in 48 hours, but the patient needs to be informed if that happens. Use of KI solution should be avoided in pregnant and lactating women. Potassium iodide can cause fetal harm, abnormal thyroid function, and goiter when administered to a pregnant woman. The patient ought to be informed of the potential hazard. KI can also cause the desquamate process if in contact with soft tissue (Figure 7d) unless the soft tissue has been protected before SDF application, in which case the desquamate process will not occur. SDF has been

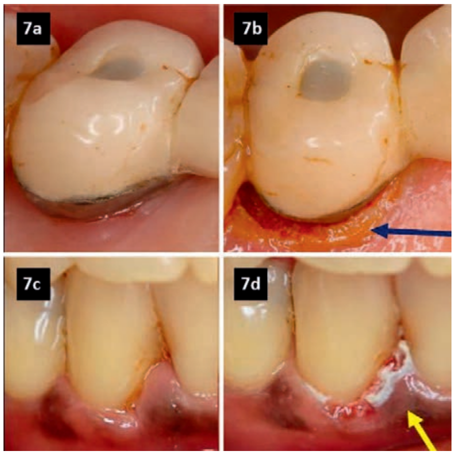


Figure 7. *Application of silver diamine fluoride (SDF) to arrest caries at a defective crown margin (a) resulted in soft tissue reaction (b). Gingival tissue before (c) and after (d) application of potassium iodide (KI). Minor reactions can occur even after protection of soft tissue by petroleum jelly.*

approved as a desensitizer, and it has been reported in the literature that SDF causes minimal adverse effects; however, further data on the effects of SDF and KI on pulpal complex are needed.

Restoration Following Treatment of Dentin

While it was reported that the application of SDF did not affect the bond strength of RMGI to dentin, others reported that the application of SDF may significantly decrease the bond strength of composite to dentin, depending on the protocol and adhesive system used.[10] Rinsing with water spray for 15 seconds improved bond strength, but superficial refreshing of SDF treated dentin prior to bonding showed the highest bond strength. In the previously mentioned report, a two-step self-etch adhesive and a universal adhesive used after phosphoric acid etching showed better performance than universal adhesive alone on SDF treated dentin. It was also reported that the application of SDF + KI to dentin surfaces before the placement of GIC restorations did not affect the bond strength of GIC to dentin and did not adversely interfere with the fluoride uptake into the adjacent demineralized dentin. In this case, a resin-modified glass ionomer was used as the restorative material, which has the advantages of GIC with improved mechanical properties and esthetics.

Clinical Aspects and Benefits

Rampant caries control treatments, such as the case reported here on anterior teeth, have been suggested to quickly increase patients' self-esteem and motivate them to improve their oral health.[12] Since these procedures typically involve minimal tooth structure removal (drilling), they cause little discomfort and anxiety for the patients avoiding dental care. These treatments also bear the advantage of quickly providing access to much-needed care and reducing caries progression.

The SDF has multiple aspects that make it a unique choice for such a case; it is a bactericidal agent and reduces the growth of cariogenic bacteria.[10,11,13] SDF not only inhibits demineralization and promotes the remineralization of demineralized enamel and dentin but also hampers degradation of the dentin collagen in caries-affected dentin.[13-15] In experimental animal model studies, pulp histology was not significantly altered in the molar cavities exposed to SDF, concluding that SDF caused minimal adverse effects.[16] Further, SDF has a strong preventive effect that is comparable to or stronger than fluoride varnish. Studies show that a single application of SDF can significantly increase the resistance of dentin against demineralization.

SDF + KI has both the antibacterial and caries-arresting properties, and its remineralization potential is expected to improve in combination with the RMGI. The suggested treatment also benefits the long-term treatment planning goals by providing a basis for treatment prognosis in each individual patient. A current dental terminology code was approved in 2016 for such caries arresting treatments (code D1354), allowing reimbursement for off-label use of SDF. We anticipate that dentists will be using more of such treatments as SDF + KI for caries in the adult population following the approach presented in this report.

Alternate Treatment

As an alternate treatment to control decay, the American Dental Association recommends application of fluoride varnish every six months as an effective measure in the primary and permanent dentition of children and adolescents.[17] As a precaution, fluoride varnish may decrease the bond strength of composite restorations to dentin.[18] The atraumatic restorative technique is another viable alternative; however, it does not involve the use of SDF, while SDF has shown strong caries-arresting, collagen-preserving, and antibacterial effects that might not be achieved by RMGI alone. In this case, arresting active dentin caries was a primary goal; therefore, this technique was selected. Further clinical studies should compare the results of both techniques.

CONCLUSIONS

Our case report confirms that the application of KI helps reverse staining caused by SDF to a large extent. Restoration margins may still be at risk of discoloration. KI can help enhance the esthetic outcome by stain reduction, thus making SDF a mainstream choice for preventing caries. With the approval of a current dental terminology code in 2016 for caries-arresting treatments, we anticipate that dentists will be using more of SDF to help prevent caries in the adult population. We encourage that SDF be taught in the standard restorative dentistry curriculum of dental schools as a viable caries control tool. Dentists should also be acquainted with the products and clinical protocols to be able to help their high-caries-risk patients.

Disclaimer

The clinical pictures were digitally cropped and oriented for comparison.

Regulatory Statement

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

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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Clinical Research

Clinical Evaluation of Nd:YAG Laser With and Without Dentin Bonding Agent for the Treatment of Occlusal Hypersensitivity

L Guo • PK Kayastha • L Chen • M Shakya • X Chen

Clinical Relevance

The use of a Nd:YAG laser (1064-nm wavelength, 30 mJ of energy, 10 pulse/s, 60 seconds, two times) with a self-etch dentin bonding agent could significantly reduce occlusal dentinal hypersensitivity over a longer period of time.

SUMMARY

Purpose: The aim of the present study was to evaluate and compare both the immediate and delayed desensitizing effects of the Nd:YAG (neodymium-doped:yttrium aluminum garnet; Nd^{3+}:$Y_3Al_5O_{12}$) laser with and without dentin bonding agent (DBA) on occlusal dentinal hypersensitivity (DH).

Methods and Materials: Twenty-one patients with a total of 117 chronic occlusal hypersensitive teeth were selected. Each subject had at least three hypersensitive teeth. These teeth were randomly allocated into three groups: group 1, DBA on the occlusal surface; group 2, Nd:YAG laser (1064-nm wavelength, 30 mJ of energy, 10 pulse/s, 60 seconds, two times); and group 3, Nd:YAG laser (1064-nm wavelength, 30 mJ of energy, 10 pulse/s, 60 seconds, two times) with DBA. Pain was assessed using a visual analog scale after stimulation of the sensitive teeth by using the sharp tip of an explorer and an air blast prior to treatment and immediately, one week, one month, and three months after treatment by one blinded examiner.

Results: A significant reduction in occlusal DH occurred at all time points in all of the experimental groups. The three groups showed significant improvements in discomfort immediately after treatment and after one week

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†Lan Guo and Pujan Kranti Kayastha contributed equally to this work.

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($p<0.001$), but the Nd:YAG laser with DBA group had greater efficacy when compared with the other groups. The Nd:YAG laser group and Nd:YAG laser with DBA group had no significant differences at one month and three months after treatment ($p>0.05$); however, their desensitizing efficacy was superior to the DBA group.

Conclusions: The Nd:YAG laser with DBA may be most effective in the long-term treatment of occlusal DH, although other measures also reduce DH.

INTRODUCTION

Dentinal hypersensitivity (DH), one of the most common dental clinical conditions, is characterized by short, sharp pain arising from exposed dentin in response to thermal, evaporative, tactile, osmotic, or chemical stimuli that cannot be ascribed to any other form of dental defect or pathology.[1,2] It is reported that the prevalence of DH varies from 3% to 98% in the population. The age range of DH is wide, having peak prevalence between 40 and 50 years of age, with females having a slightly higher predilection than males. Maxillary teeth are more commonly affected than mandibular teeth, with a greater occurrence on the buccal/lingual surface than on the occlusal surface.[3] Hypersensitivity in younger patients is often caused by dentin exposure due to erosion, while gingival recession often causes hypersensitivity in older patients due to the exposure of the dentinal tubules in the cervical areas because of periodontal disease and intensified brushing activity.[3]

However, DH on the occlusal/incisal tooth surfaces has also been frequently reported. Occlusal surfaces are more prone to all forms of tooth wear, such as attrition (especially associated with bad habits such as bruxism, biting objects, etc) abrasion, and erosion, all of which cause increased DH when compared with cervical tooth surfaces.[4]

DH has been widely described using the hydrodynamic theory, the most suitable and acceptable theory proposed by Braennstrom and Astroem in 1964.[5] Most pain-producing stimuli, such as thermal, chemical, and mechanical stimuli, disrupt the inward and outward flow of dentinal fluid that activates intradental nerve fibers, via a mechanoreceptor response, resulting in pain. The common stimuli include hot, cold, sweet, and sour foods and drinks as well as cold air.[6,7] DH is due to a combination of any of the previous conditions that exposes the dentinal tubules, such as periodontal pathogens, trauma, dental bleaching, removal of orthodontic fixed appliances, professional oral hygiene, acidic foods and beverages, bad oral hygiene habits, or incorrect oral hygiene causing gingival recession.[8] The exposure of occlusal dentin could occur as a result of attrition from occlusal wear, trauma, dental bleaching, professional oral hygiene, parafunctional habits (such as bruxism), occlusal adjustment, inappropriate tooth brushing, erosion from an acidic diet, or other factors.[9] Desiccation and frictional heat generated during cavity preparation also increase the likelihood of hypersensitivity.[10]

For the treatment of DH, occluding the dentinal tubules is the primary and the most important procedure. Studies have shown that sensitive dentin contains eight times more tubules than nonsensitive dentin, and these tubules are twice as wide.[11,12] Desensitizing agents have been used to occlude the dentinal tubules as a professional measure to treat DH. These agents should be nonirritating to the pulp, relatively painless on application, easily carried out, rapid in action, consistently effective for a long period, and without staining effects, as proposed by Grossman in 1935.[13,14] Many desensitizing agents have been tried with varying degrees of success,[15,16] but most of the therapies have failed to satisfy one or more of these criteria.

Desensitizing agents are applied as a long-term treatment option for a preservative method of management of sensitive teeth.[17] Most of the commonly used desensitizing agents in the treatment of DH include anti-inflammatory agents (corticosteroids), protein precipitates (formaldehyde, silver nitrate, strontium chloride hexahydrate), tubule-occluding agents (calcium hydroxide, sodium fluoride, potassium nitrate), and tubule sealants (resins and adhesives) that work by forming a physical barrier in the dentinal tubules to prevent the flow of dentinal fluid and thus block the activation of the mechanoreceptors in the dentinal tubules by forming a protein precipitate, hydroxyapatite crystal deposits, or resin or hybrid tags.[11,12,14,18-20]

The use of lasers in the dental field mostly fulfills the characteristics required by Grossman for the treatment of DH. The use of the neodymium-doped: yttrium aluminum garnet, $Nd^{3+}:Y_3Al_5O_{12}$ (Nd:YAG) laser was found to be more effective when compared with other low- and high-power laser therapy, including CO_2 (10,600), Er:YAG (2940), Er,Cr:YSGG (2780), GaAlAs, and 810-nm diode laser.[8,10,18,21,22] Low-power lasers were found to act only on the nerve level, whereas middle-power lasers such as Nd:YAG produce desensitization by either acting on the internal tubular nerve or obliterating the dentinal tubules. The effect of the Nd:YAG laser on hypersensitive teeth may be due to occlusion of tubules, which may be either through coagulation of proteins inside the dentinal tubules formed due to a photobiomodulating effect on the odontoblasts or melting and recrystallization of hydroxyapatite crystals of the dentinal tubules, preventing the fluid flow inside the dentinal tubules or by acting directly at the nerve level by blocking C and A"β nerve fibers. The Nd:YAG laser produces direct nerve analgesia via destruction of the internal tubular nerve, thus preventing hypersensitivity.[8,14,16,18,21,23-34] Desensitization caused by different lasers depends on multiple factors, such as the type of laser device and various irradiation parameters (eg, power density wavelength, wave mode, pulse frequency, number of repeated applications, and distance from the surface).[30,34-36]

Lasers have been used for the treatment of DH, and some authors report that laser combined with drugs may be a preferable treatment for DH.[24,30,33,36] Treatment with low- and high-power lasers has been shown to display the characteristics proposed by Grossman.[10]

Occlusal hypersensitivity is a serious condition that troubles the dental practitioner. There are few studies on the treatment of occlusal hypersensitivity using an Nd:YAG laser. The purpose of this study was to evaluate and compare the immediate, one-week, one-month, and three-month posttreatment desensitizing efficacy of Nd:YAG laser with and without a dentin bonding agent (DBA) on occlusal DH.

METHODS AND MATERIALS

Study Design

This study was designed as a randomized controlled trial comparing the therapeutic efficacy of the Nd:YAG laser with and without DBA on occlusal DH. A Nd:YAG laser (HSM-III, HTSD, Chengdu, China) and Adper self-etch adhesive liquid (3M ESPE, Seefeld, Germany) as the DBA were used. Subjects who were able to complete the entire therapy and follow-up procedures were selected. Appropriate, approved informed consent was signed from each subject after the nature of the study and the possible discomfort and risks had been fully explained.

Subject Selection

Twenty-one patients (8 men and 13 women; aged 23-69 years, mean age 49.95 ± 13.67 years) with a total of 117 hypersensitive teeth were examined for the presence of occlusal DH at the Characteristic Specialist Clinic on Tooth Sensitivity in the West China College of Stomatology Sichuan University (Table 1). Each patient contributed at least three hypersensitive occlusal surfaces and presented stage 4-7 of occlusal surface wear according to the criteria of Smith and Knight.[37] The degree of occlusal DH was determined qualitatively using a disposable sharp dental explorer stimulus and a three-second cold-air blast from a three-way dental syringe at a distance of 2 mm from each site to be tested. Meanwhile, adjacent teeth were isolated from the air using gauze squares and cotton rolls. All stimuli were performed by one examiner (operator 1) using the same equipment, yielding a similar air pressure each time.

The patients were required to have had more than one month of DH and to have not used other desensitizing methods, such as fluoridated toothpastes or tubule sealers, to decrease the degree of DH. Meanwhile, we excluded pregnant and lactating women and those with chronic or debilitating diseases to avoid probable side effects of laser treatment. Teeth that were nonvital, cracked, carious, or had deep restorations, crowns and abutments, pulpitis, periapical periodontitis, or active periodontal disease were also excluded.

In addition, subjects were asked to use a standardized toothbrush and toothpaste without any desensitizing agent for the three-month trial period. All participants completed the study and reported 100% compliance.

Treatments

After a baseline pain assessment, the teeth were randomly assigned to group 1 (DBA treatment), group 2 (Nd:YAG laser treatment), or group 3 (Nd:YAG laser with DBA treatment).

Prior to therapy, all hypersensitive teeth received cleaning and disinfection with 75% alcohol. A few patients experienced pain for a short time period but were able to endure the procedure. Since pumice residues may remain in the dentinal tubules, which may affect laser treatment, we used alcohol, which is easy to apply, volatile, and leaves no residue in the dentinal tubules.[30] The region being treated was isolated using gauze squares and cotton rolls, and the occlusal surface was dried with gauze before each treatment session. The vitality of all experimental teeth was checked with an electric pulp tester before and after each treatment session. The

Table 1: *Age, Gender, Stage of Wear, and Tooth Type in the Patient Population*

Variable	n	Group1 n	Group2 n	Group3 n
Age, y				
11-30	3	1	1	1
31-50	7	2	3	2
51-70	11	4	3	4
Gender				
Female	13	4	5	4
Male	8	3	2	3
Stage of wear				
4	21	6	8	7
5	46	18	14	14
6	37	11	12	14
7	13	4	5	4
Tooth type				
First molar	66	24	22	20
Second molar	40	12	13	15
Third molar	11	3	4	4

patients were blinded as to what type of therapy each tooth was receiving.

Group 1 was treated with DBA, which was applied at the sensitive site on the occlusal surface and allowed to sit for 15 seconds. The DBA was then reapplied, allowed to sit for 15 seconds, and light cured for 20 seconds.

Group 2 was subjected to treatment with Nd:YAG laser (1064 nm) set at 30 mJ and 10 pps for 60 seconds, using a sweeping motion and without coolant (the duration was changed because of the size of tooth wear) after black ink was applied. The laser beam was applied using a 320-mm optical fiber. The distance between the end of the optical fiber and the occlusal surface was maintained at 2 mm with the help of an orthodontic wire. Protective eyewear was worn by both the investigator and the patient while using the laser.

Group 3 was treated with a combination of the Nd:YAG laser with DBA. The therapy methods and clinical parameters were the same as in groups 1 and 2. The therapy was performed by the same investigator (operator 1).

Pain Assessment

A visual analog scale (VAS) was used to document occlusal hypersensitivity caused by a disposable sharp dental probe and a three-second air blast from each site to be tested. The VAS was administered in a standard manner, with the initial explanation given by the same clinician to all participants. All patients were asked to define their level of hypersensitivity on a VAS scale ranging from 0 to 10 (a 10-cm line). On this scale, 0 and 10 represented *no pain/no discomfort* and *worst pain/severe discomfort*, respectively. All pain assessments were performed in the morning in the same clinic, in an area free of noise, music, or conversation. All stimuli were applied by a single investigator in the same dental chair with the same equipment. Evaluation of pain was scheduled before treatment, immediately after treatment, and at one week, one month, and three months posttreatment. The treatments were performed by operator 1, and the pain was assessed by the other examiner (operator 2).

Statistical Analysis

Statistical analysis was performed using SPSS 16.0 software for Windows (Statistical Program for Social Sciences Inc, Chicago, IL, USA). The statistical significance of data for all clinical and VAS scores within and between groups was determined by using one-way analysis of variance. Least significant difference post hoc test for multiple comparisons was used to determine the differences in the VAS scores within groups at different times. Changes with p values <0.05 were considered statistically significant.

RESULTS

All 21 patients completed the three-month study period. Each tooth was tested for pulp vitality before treatment, immediately after treatment, and one week, one month, and three months after treatment. There were no adverse reactions reported nor any clinically detectable complications, and all experimental teeth responded normally to the vitality test. Because of the randomization procedures, the three groups were well matched in demographics, including age, sex, stage of wear, and tooth type (Table 1). The response of the patients to the probing or air blast throughout the study and the mean VAS values at the different time points are presented in Table 2. The results of the probing and air blast were similar. The initial mean hypersensitivity scores were well matched in the three groups ($p>0.05$), although the treatment in the three groups resulted in significant improvements in discomfort immediately after treatment and after one week ($p<0.001$). Group 3 had a higher degree of desensitization when compared with the other groups. At the one- and three-month evaluations, there was a statistically significant difference between groups 1 and 2 and between

Table 2: *Comparison of the Mean ± Standard Deviation VAS Scores of Patients' Perceptions in the Three Treatment Groups*

	Group 1	Group 2	Group 3	p^a
Hypersensitivity after provoking with probe				
Before the treatment	7.03 ± 1.15	7.06 ± 1.20	7.01 ± 1.08	0.981
After the treatment				
Immediate	2.56 ± 1.02	1.63 ± 0.97	1.20 ± 0.78	<0.001*
One week	2.58 ± 0.97	1.56 ± 0.94	1.16 ± 0.69	<0.001*
One month	2.93 ± 1.06	1.45 ± 0.78[b]	1.41 ± 0.84[b]	<0.001
Three months	3.71 ± 1.16	1.51 ± 0.76[c]	1.47 ± 0.87[c]	<0.001
Hypersensitivity after provoking with air blast				
Before the treatment	6.41 ± 0.96	6.43 ± 0.79	6.40 ± 0.69	0.987
After the treatment				
Immediate	2.41 ± 0.92	2.03 ± 0.85	1.02 ± 0.68	<0.001*
1 week	2.40 ± 0.98	2.01 ± 0.97	1.16 ± 0.69	<0.001*
1 month	2.71 ± 0.93	1.23 ± 0.79[d]	1.30 ± 0.72[d]	<0.001
3 months	3.35 ± 0.98	1.31 ± 0.76[e]	1.24 ± 0.72[e]	<0.001

[a] *The differences between groups immediately posttreatment and at one week, one month,, and three months after treatment were tested by one-way analysis of variance.*
[b] *Significant difference after one month by provoking with probe in group 2 and group 3.*
[c] *Significant difference after three months by provoking with probe in group 2 and group 3.*
[d] *Significant difference after one month by provoking with air blast in group 2 and group 3.*
[e] *Significant difference after three months by provoking with air blast in group 2 and group 3.*
* *Statistically significant differences in the multiple comparison using least significant difference method.*

groups 1 and 3 ($p<0.001$). There was no statistically significant difference between groups 2 and 3 ($p>0.05$). However, the desensitizing efficacies of groups 2 and 3 were superior than group 1.

DISCUSSION

DH is one of the most difficult and frequent conditions in the dental clinic for both patients and dental practitioners. DH causes sharp pain that disturbs patients' normal dental activity, and because long-term relief by preservative professional treatment is difficult to achieve, DH presents a great challenge for dental practitioners. The required treatment depends on the etiology, degree of discomfort, and extension and depth of the lesions.[10]

According to the hydrodynamic theory for DH, exposed dentinal tubules cause inward and outward flow of dentinal fluids under the given stimuli, activating intradental nerve fibers and causing sharp pain on the teeth. Occlusion of the exposed dentinal tubules and/or blockage of nerve activity are the treatment choices for DH. Freshly exposed coronal dentin is more sensitive than cervical dentin. This may be due to the higher conduction velocity or structural differences in dentinal innervations and in the dentin structure itself.[34]

Preservative treatment of occlusal DH is difficult because the occluded layer formed by desensitizing agents is typically very thin and can be worn out by physical forces such as brushing, occlusion, and acidic food.[18,19] The combined effects of laser and drug therapy have been found to provide improved desensitization and long-term efficacy.[10,12,19,30,33,36] Therefore, in this experiment, the long-term desensitizing effect of the combination of an Nd:YAG laser and DBA was compared with that of DBA and laser alone. The Nd:YAG laser can be used to reduce hypersensitivity without detrimental thermal effects on the pulp.[29,30,32] Nd:YAG laser is a near infrared laser with a primary wavelength of 1064 nm. It is nonionizing in character and is therefore nonmutagenic.[18] However, exposure to Nd:YAG laser energy leads to morphological changes of the dentin surface, characterized by a glazed, melted resolidified surface with the occasional formation of globules and cracks.[38]

DH is a pain sensation that is difficult to quantify. However, a VAS is widely used to assess DH, as it is easily understood by patients, sensitive in discriminating among the effects of various types of treatment and change in pain, and has advantages of being a continuous scale. Thus, the VAS scale was found to be suitable for evaluating the pain response in DH studies.[10,21,26,30,35]

The present study provides information about the clinical effectiveness of the Nd:YAG laser with and without DBA in the treatment of occlusal hypersensitivity. It showed that the mean hypersensitivity score was well matched in the three groups. However, immediately after treatment and at one week, one month, and three months posttreatment, the adhesive group and the other two groups were significantly different ($p<0.001$). It is possible that using adhesive alone was unable to occlude the dentinal tubules and that problems arise when the adhesive breaks away, resulting in exposure of the tubules.[15] Since the purpose of applying resin is to occlude dentin orifices, the loss of occluded resin due to physical forces such as mastication and brushing would result in reduced effectiveness.[33] In addition, there are greater chances of dislodging or breaking the adhesives on the occlusal surface due to occlusal forces.

However, there was no significant difference between groups 2 and 3 immediately posttreatment or at one week and three weeks after treatment ($p>0.05$). Some scholars have found microcracks, carbonization of tooth surfaces or open tubules, and a consequent increase in intrapulpal temperature with some teeth when using Nd:YAG laser irradiation.[10,21,28] In this study, no microcracking, carbonization, or pulpal damage was detected, which may be due to the management of the parameters and continuous motion of the laser over the treatment surface during the procedure.

It is possible that the two treatments tested in this study may reduce DH by different mechanisms. DBA reduces DH by the formation of protein precipitates traversing the septa in the deeper part of the tubules and formation of resin tags near the surface, thereby blocking fluid flow across dentin.[18,20,33] Whereas the mechanism of Nd:YAG may affect the occluding or narrowing of the dentinal tubules by melting and recrystallization of dentin, evaporation of the dentinal fluid, or direct nerve analgesia.[8,14,16,18,21,23-34] The use of an Nd:YAG laser before the application of a desensitizing agent modifies the dentin surface, increasing the adhesion property of the desensitizing agent while occluding the open dentinal tubules, which are not affected by laser therapy. The effectiveness of laser therapy before or after the use of a desensitizing agent shows no statistical significance. After application of a desensitizing agent, the Nd:YAG laser incorporates the desensitizing agent within the dentin during melting or recrystallization.[19,24] The most important issue in laser therapy is to determine the right parameters to use in order to achieve optimal results, without inducing detrimental pulpal effects or causing fractures or carbonization.[28,38]

Some scholars have shown that Nd:YAG laser irradiation (30 mJ, 10 pps, two minutes) can be used to seal exposed dentinal tubules without the dentin surface cracking and detrimental pulpal effects.[31,39,40] That study found that laser use with 1-mm dentinal thickness causes pulpal disruption while a dentin thickness of greater than 1 mm provides no such effect. Dentin without ink negligibly absorbs or scatters the laser. The use of black ink enhances the amount of melting and recrystallization of the stained dentin, which results in the closure of dentinal tubules.[28] Black ink also prevents the laser beam from penetrating excessively into the tooth structure and therefore protects the pulp from excessive effects.[32] In the present study, the laser was applied for two minutes, and the remaining ink layer from the tooth surface was wiped out with warm water.

The current results indicate that the application of laser with or without dentin bonding agent is better than the single use of a DBA. As DH is due to multifactorial causes, it cannot be concluded that blockage of exposed dentinal tubules is the only option for successful long-term treatment. Other predisposing factors, such as parafunctional habits, must be treated simultaneously to decrease the relapse rate. We suggest using laser with DBA for a synergistic effect as well as proper sealing of opened tubular dentin. The operation is simple, does not require special equipment, is suitable for patients with occlusal dentin sensitivity, and can be popularized in clinical application.

CONCLUSIONS

Because of the short duration of the present experiment and difficulty in monitoring the personal habits of the subjects, such as brushing technique or type of food intake, it is difficult to conclude how long the effects of the Nd:YAG laser will be effective. We cannot determine whether the dislodgement of resin tags formed with DBA or the fracture of recrystallized tubules causes relapse. Further microscopic studies are necessary to determine the cause of relapse of occlusal DH.

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Regulatory Statement

This study was conducted in accordance with all the provisions of the local human subjects oversight committee guidelines and policies of approval of the Department of Operative Dentistry and Endodontics, West China School of Stomatology, Sichuan University, Chengdu, China.

Conflict of Interest

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

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Controlling *In Vivo*, Human Pulp Temperature Rise Caused by LED Curing Light Exposure

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Clinical Relevance

In vivo pulp temperature rise during exposure of intact premolars to a high-powered LED light-curing unit can be prevented by applying air flow simultaneously with the exposure.

SUMMARY

Objective: The objective of this study was to evaluate the *in vivo* effectiveness of air spray to reduce pulp temperature rise during exposure of intact premolars to light emitted by a high-power LED light-curing unit (LCU).

Methods and Materials: After local Ethics Committee approval (#255945), intact, upper first premolars requiring extraction for orthodontic reasons from five volunteers received infiltrative and intraligamental anesthesia. The teeth (n=9) were isolated using rubber dam, and a minute pulp exposure was attained. The sterile probe from a wireless, NIST-traceable, temperature acquisition system was inserted directly into the coronal pulp chamber. Real-time pulp temperature (PT) (°C) was continuously monitored, while the buccal surface was exposed to a polywave LED LCU (Bluephase 20i, Ivoclar Vivadent) for 30 seconds with simultaneous application of a lingually directed air spray (30s-H/AIR) or without (30s-H), with a seven-minute span between each exposure. Peak PT values were subjected to one-way, repeated-measures analysis of variance, and PT change from baseline (ΔT) during exposure was subjected to paired Student's *t*-test (α=0.05).

Results: Peak PT values of the 30s-H group were significantly higher than those of 30s-H/AIR group and those from baseline temperature ($p<0.001$), whereas peak PT values in the 30s-H/AIR group were significantly lower than the baseline temperature ($p=0.003$). The 30s-H/

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AIR group showed significantly lower ΔT values than did the 30s-H group ($p<0.001$).

Conclusion: Applying air flow simultaneously with LED exposure prevents *in vivo* pulp temperature rise.

INTRODUCTION

Light-emitting diode (LED) light-curing units (LCUs) have become part of everyday clinical dentistry. The success of these devices is due to their efficiency and design, as they are battery driven and often do not require cooling fans. In addition, these LCUs are able to emit light with considerably higher radiant emittance values and have higher source longevity than do conventional quartz-tungsten-halogen lights (QTH).

Over the last decade, powerful LED LCUs have become commercially available to promote better polymerization of resin-based materials using shorter exposure durations. These devices are capable of emitting light with irradiance over 2000 mW/cm^2, and exposure times of no longer than five seconds are recommended by some manufacturers. As a consequence, these high-power LED LCUs generate heat in the target object.[1] In this regard, several *in vitro* studies report a significant temperature increase within the pulp chamber of extracted teeth, ranging from 1.5°C to 23.2°C.[2-8] Although this temperature range depends on LCU type, radiant emittance, and tooth characteristics,[3-12] there is a consensus that the use of some LED LCUs can result in a pulp temperature (PT) rise to values close to, or even higher than, the threshold temperature increase of 5.5°C, a value considered harmful to the pulp.[13] Most recently, a new *in vivo* methodology comprising the placement of a temperature probe within the pulp in human premolars has been developed.[14,15] Using this method, higher PT rise than 5.5 °C in intact premolars was observed as radiant exposure value increased.[15]

Heat control during restorative procedures to assure pulp integrity has been a great concern among clinicians and researchers.[13,16,17] For instance, several studies evaluated the effectiveness of alternative methods to reduce the heat caused during tooth preparation when using slow- and high-speed hand pieces and have shown it to be an effective method in reducing heat generated during that restorative step.[17-22] Other studies evaluated the use of different lasers instead of burs,[23-27] as well as the use of different cooling system protocols, including air and water spray from the triple syringe.[18,28-30] In addition, some cooling strategies have proven to be effective in reducing temperature rise within the pulp chamber during the debonding of orthodontic brackets[31] or during the fabrication of provisional restorations comprising the use of self-polymerized acrylic resins.[32] In this regard, different approaches have been suggested to reduce heat during the polymerization of resin composites, such as the use of reduced irradiance,[30,33] or discontinuous curing modes.[34] However, such procedures may compromise monomer conversion and impair the mechanical properties of the resulting resin composites.[35] To date, only one *in vitro* study demonstrated that cooling strategies comprising the use of air or the combination of air/water can reduce temperature rise during exposure of indirect restorations to curing light.[36] Another study showed that a cooling system installed in a LED LCU was effective in reducing the maximum temperature rise within the pulp chamber and speeding up the cooling process of the tooth after light shut off.[4] Based on these findings, it is reasonable to assume that the use of air spray would prevent PT rise *in vivo*, in human premolars, during exposure to the light emitted from a polywave LED LCU (Bluephase 20i, Ivoclar Vivadent, Schann, Linchestein Principality). However, no *in vivo* study has evaluated the effectiveness of such procedures during exposure to a curing light.

Thus, the purpose of this *in vivo* study was to measure and evaluate PT changes when intact human premolars were exposed to a high-intensity LED LCU, while either simultaneously applying an air spray from the opposite side of the exposure or not. The research hypotheses were that 1) the application of air spray during LCU exposure will significantly reduce PT rise in comparison to when no air spray is used, and 2) PT values following light exposure with air spray will result in PT values significantly lower than pre-exposure, baseline values.

METHODS AND MATERIALS

Irradiance Measurement of the Polywave LED LCU

The spectral power of the polywave LED light was recorded five times in High mode, using a laboratory grade spectroradiometer (USB 2000, Ocean Optics, Dunedin, FL, USA) and a 6-in integrating sphere (Labsphere, North Sutton, NH, USA), previously calibrated using a National Institute of Standards and Technology (NIST)-traceable light source. The LCU tip end was positioned at the entrance of the integrating sphere, so all light emitted from the unit was captured. Spectral power was measured between 350 and 550 nm, using software (SpectraSuite v2.0.146, Ocean Optics), which also provided a total value within that range. The optical emitting area of the distal end of the light guide was calculated, and this value was divided into the integrated spectral power value to derive the total radiant exitance from the curing light.

In Vivo Measurement of Intrapulpal Temperature

The study was previously approved by the local Ethics Committee (protocol #255945). Five patients requiring extraction of first premolars for orthodontic reasons (n=9) were recruited from the orthodontic specialization programs in Ponta Grossa, State University of Ponta Grossa and the Brazilian Association of Dentistry, Parana section. The subjects, four females and one male, ranging from 12 to 30 years old, passed through an initial consultation phase, in which the volunteers were informed about the study aims and all methodology involved in the research. Patient inclusion criteria included 1) treatment plans indicating premolar extractions for orthodontic reasons, 2) the presence of healthy, intact, noncarious, and nonrestored, fully erupted treatment teeth, and 3) patients with well-controlled health conditions that allowed all procedures involved in the research to be performed with minimal risk. Exclusion criteria included those patients who were currently under medication. After having the benefits and risks for participating in the study explained, the volunteer subjects, or the subject's legally authorized representative (for subjects under the age of 18 years), signed the informed consent document. The subject's medical history was obtained and reviewed by at least one clinician participating in the study, prior to any treatment being performed.

All teeth tested were anesthetized using a local anesthetic (2% mepivacaine hydrochloride with epinephrine, Mepiadre, DFL Industria e Comercio, Rio de Janeiro, RJ, Brazil). Only intact, upper first premolars were evaluated. The teeth received both infiltrative as well as intraligamental injections. The premolar received isolation with rubber dam. A deep class I preparation was then made on the occlusal surface, using a round diamond bur (#1013, KG Sorensen, Cotia, SP, Brazil), under constant irrigation, until the preparation floor was near the roof of the pulp chamber. The pulp exposure was carefully obtained with the aid of a root canal explorer, so the exposure diameter was as small as possible. After pulp exposure was obtained, a sterile thermocouple probe from a wireless temperature acquisition system (Temperature Data Acquisition-Thermes Wfi, Physitemp, Clifton, NJ, USA) was inserted directly into the pulp chamber. The thermocouple probe was connected to an isolated, battery-driven data acquisition device that wirelessly sent temperature values to a computer, where temperature was displayed and recorded in real time. With the probe remaining in place, the occlusal preparation was then filled using a provisional restorative material (Cavitec, CaiTHEC Ltda, São José dos Pinhais, PR, Brazil), to minimize heat loss from the tooth through the cavity walls and pulp access. The baseline pulpal temperature value was established after approximately 15 to 22 minutes. The emitting end of a high power, polywave LED curing unit (Bluephase 20i, Ivoclar Vivadent), used in its high-power mode (1244 mW/cm^2), was placed directly against the facial enamel surface, in the cervical region. The following exposure conditions were then applied, during which data were recorded at every 0.2 seconds: three seconds prior to light exposure, an air spray from a triple syringe was held 1-mm from the lingual enamel surface, opposite of where the LCU tip was placed (air pressure set to 28 psi). A 30-second exposure in high-intensity mode (radiant exposure of 37.3 J/cm^2) was applied to the facial surface, and the air stream was terminated at the same moment the LCU turned off (30s-H/AIR). A seven-minute time span then passed, to allow baseline pulpal temperatures to return to the pre-exposure values. Another exposure was then given as stated before, but without application of the air spray (30s-H). At the end of temperature acquisition, the probe was carefully removed from the tooth. After testing was completed, the teeth were atraumatically extracted, as planned for the patient's orthodontic treatment. Following extraction, the probe was reinserted into the pulp chamber of some extracted teeth, and X-rays were taken from the proximal surface, with the probe in position as it was intraorally, to verify probe position during testing (Figure 1).

Statistical Analyses

Peak PT during exposure and PT increase during exposure relative to the pre-exposure baseline value (ΔT) were determined. Peak PT data were evaluated using a one-way, repeated-measures analysis of variance, whereas ΔT was compared using a paired Student's *t*-test. All statistical testing was made using a preset α of 0.05. *Post hoc* power analysis was performed for statistical analyses of peak PT and ΔT

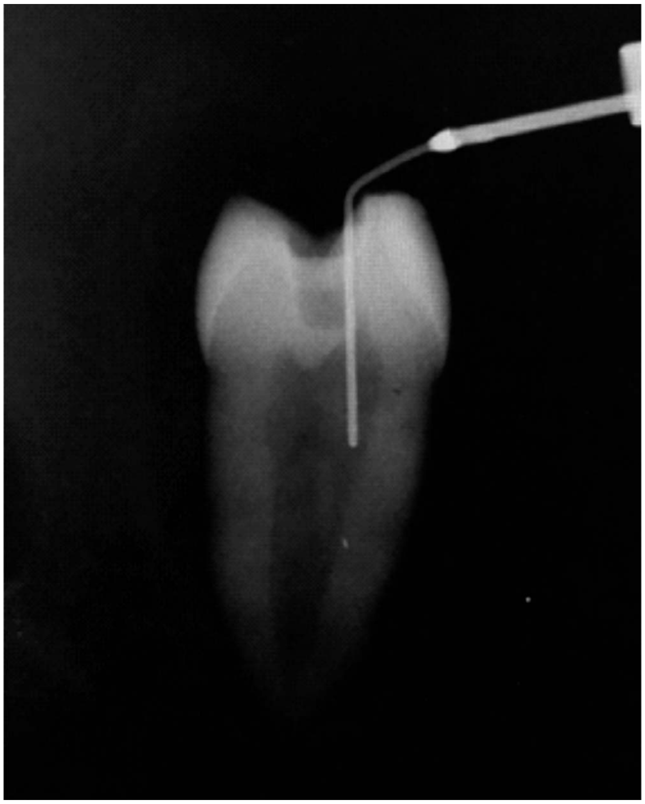

Figure 1. *X-ray analysis after tooth extraction to confirm if the probe was properly positioned into the pulp chamber during data acquisition.*

values. All analyses were performed using commercial statistical software (Statistics 19, SPSS Inc, IBM Company, Armonk, NY, USA).

RESULTS

In Vivo Measurement of Intrapulpal Temperature

For the number of evaluated teeth (n=9), the *in vivo* study was adequately powered for both peak PT and ΔT values (>99.0%; α=0.05). The results of peak PT and ΔT are shown in Table 1. The PT from exposure to the 30s-H condition (37.5±0.5°C) was significantly greater than that of the baseline PT (35.4±0.6°C). On the other hand, the use of the 30s-H/AIR condition resulted in significantly lower PT values (34.0±1.0°C) than the baseline (35.4±0.6°C) (p=0.003). As a result, the ΔT values observed when teeth were exposed to a 30s-H mode were significantly higher (p<0.001) than those observed using the 30s-H/AIR condition.

Table 1: *Means (SD) of Peak Temperature Values (°C) and ΔT (°C) for Each Experimental Condition*[a]

Test Parameter	Baseline	30-sH	30s-H/AIR
Peak temperature	35.4 ± 0.6 B	37.5 ± 0.5 A	34.0 ± 1.0 C
ΔT		2.3 ± 0.5 a	−1.3 ± 0.5 b

[a] *Within a test parameter (row), values identified using similar letters (uppercase: peak temperature; lower case, temperature difference from baseline (ΔT) are not significantly different.*

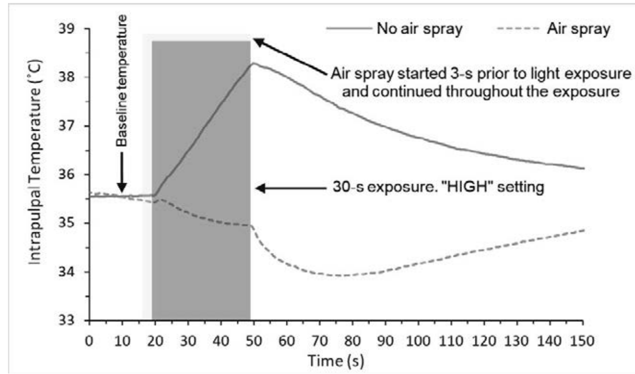

Figure 2. *Representative,* in vivo*, real-time PT profiles during a 30-s exposure on high output mode (30s-H) without (blue line) or with (30s-H/AIR) (orange line) simultaneous application of air spray from the opposite tooth side. Duration of air-spray depicted by the light yellow rectangle, and duration of light exposure represented by the blue box.*

Figure 2 shows representative real-time profiles of PT change during exposure to 30s-H and 30s-H/AIR conditions. Exposure to the 30s-H mode resulted in an immediate PT increase, characterized by an ascending straight line, which was followed by a slow temperature drop, following light termination. On the other hand, exposure to the 30s-H/AIR condition caused a slow PT decrease while the buccal surface was exposed to curing light. When the light terminated and the air spray stopped, PT dropped more quickly, for approximately 30 seconds, before it started to rise again.

DISCUSSION

The data clearly indicate that air spray application during light exposure was able to prevent PT to rise. Therefore, the first research hypothesis was not rejected. These results are in agreement with those from a previous *in vitro* study,[36] which attributed the ability of air flow to remove the hot air around an exposed tooth. According to the authors, the hot air around the exposed tooth would be partly responsible for the temperature increase within the tooth. Moreover, the current results can also be attributed to the thermal behavior of enamel and dentin. In this regard, when an intact tooth is exposed to a curing light, the thermal energy from enamel dissipates inward, toward the dentin and pulp chamber, as well as outward to the ambient environment.[37] Because dentin has a low thermal diffusivity, the thermal energy is not only transferred to the pulp but is also stored within it.[37] This thermal behavior is responsible for gradual dissipation of heat energy toward the pulp, sustaining higher temperature values within the pulp, even after the curing light has shut off, as previously shown.[15] Conversely, when an air flow was started three seconds before the light was turned on and was maintained during light exposure, the temperature of enamel and dentin dropped. Thus, higher thermal energy was required to heat these substrates. Therefore, when air flow and exposure to light occurred simultaneously, the heat generated during the 30-second exposure to the curing light emitting 1244 mW/cm^2 (approximately 37.3 J/cm^2) was not capable of increasing the temperature of enamel and dentin to values that could cause a PT rise. Indeed, based on the real-time analysis of temperature change during a 30-second exposure to light with air flow, a slow PT decrease was noted during exposure to curing light (Figure 2). This finding infers that the use of air flow during exposure to a curing light was more effective in decreasing PT than was light in transferring heat to the pulp. For this reason, it is reasonable to assume that longer exposures to a curing light emitting 1244 mW/cm^2, which is an irradiance value commonly found in commercially available LED LCUs, would not be harmful for the pulp when air flow is applied simultaneously.

Interestingly, the temperature drop in dentin due to air flow not only avoided PT rise during exposure to the LED light but also decreased PT to lower values than that of the baseline PT (Table 1). As a matter of fact, PT values showed a continuing fast decrease for approximately 30 seconds after air flow stopped (Figure 2). Therefore, the second hypothesis was not rejected. This finding confirms the presence of a gradient temperature created between the pulp and the cooled pulp chamber walls, due to the decrease in dentin temperature during air flow. In other words, the lower temperature of dentin chamber walls, in comparison to that of the pulp, causes the heat from the pulp to flow toward the dentin chamber walls by thermal conduction, to reach thermodynamic equilibrium, resulting in the continuous post-air flow PT drop. In a restorative procedure with photo-activated resin-based composites, when sequential tooth exposures to the LED light are required to ensure optimal polymerization of resin composite layers, a prepared tooth having PT lower than the baseline temperature would provide further protection against pulp damage. In that clinical condition, higher radiant exposure values would be required to increase PT to the threshold values considered harmful for the pulp (approximately 42.5°C)[13] than when such restorative procedures are performed on teeth having PT at the baseline values. Further investigation is required to confirm such assumptions.

The current results demonstrate that air flow was very effective in preventing PT rise during exposure to an LED light using its "high" mode in intact premolars *in vivo*. In this context, it is worth noticing that PT rise may be influenced by the translucency and thermal diffusivity of the substrate interposed between the heat source and the pulp.[15,38] Because resin composites may show a wide range in translucency[39] and lower thermal diffusivity depending on the amount and type of filler content,[40] PT rise may be higher during the exposure of a class V preparation to curing light when the prepared cavity is filled with more translucent resin composites having low filler content in comparison to that observed on intact teeth. For instance, previous *in vitro* findings have shown that exposing teeth with a class V preparation either empty or filled with resin composite to a curing light caused higher PT rise than did exposure of an intact tooth to a curing light.[41] As a consequence, one could state that air flow may not be as effective in these clinical scenarios as it was in intact teeth. For this reason, in an attempt to overcome this study limitation, the intact teeth were exposed to LED light for 30 seconds, which is longer than 10- or 20-second exposure usually recommended by the manufacturers of most recently commercially available resin composites. In other words, because of the direct positive relationship between exposure interval and PT rise,[15] the 30-second exposure to light may cause higher PT rise than that expected even when a class V preparation filled with translucent resin composites with high thermal diffusivity is exposed to shorter exposure intervals, such as 10- or 20-second exposure to LED light. For this reason, it is reasonable to assume that applying air flow along with the curing light exposure in these restorative procedures may be as effective as the air flow applied in the condition evaluated in the current study. In addition, because intact teeth were evaluated, similar results could also be expected in procedures involving the delivery of curing light to intact teeth, such as in-office bleaching, when cementing ceramic laminates, or when placing composite resin veneers.[1,42]

Based on these findings, exposure of intact premolars to a curing light along with simultaneous application of an air flow is shown to be an effective method to prevent temperature rise within the pulp during exposure to high irradiance levels. However, because of differences in morphology and dentin thickness among teeth, care should be taken when assuming that similar results should be expected on other teeth, such as anterior incisors. Despite this limitation, such an easy and time-efficient approach should be added to the clinician's routine, because it can reduce the risk of pulp thermal damage when powerful LED devices are used.

CONCLUSION

Within the limitations imposed by this *in vivo* study, it is possible to conclude that 1) air flow applied simultaneously with exposure to LED light is capable of preventing a temperature increase within the pulp during curing light exposure. In addition, 2) this procedure causes a further temperature drop in the pulp after exposure to a curing light.

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Regulatory Statement

This study was conducted in accordance with all the provisions of the local human subjects oversight committee guidelines and policies of approval of the State University of Ponta Grossa. The approval code for this study is #255945.

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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Is Optical Coherence Tomography a Potential Tool to Evaluate Marginal Adaptation of Class III/IV Composite Restorations *In Vivo*?

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Clinical Relevance

Both optical coherence tomography and scanning electron microscopy revealed partially poor marginal qualities in clinically successful composite restorations. Clinical performance cannot be successfully predicted by the extent of perfect margins.

SUMMARY

Objective: Margin analysis of Class III and IV composite restorations *in vitro* and *in vivo* occurred by scanning electron microscopy (SEM) and optical coherence tomography (OCT). The results were compared and related to clinical evaluation.

Methods and Materials: Eight Class III composite restorations were imaged *in vitro* using OCT and SEM. The margins were analyzed quantitatively. OCT signals were verified by assignment to the criteria perfect margin, gap, and positive/negative ledge. *In vivo* quantitative margin analysis of Class III/IV composite restorations made of the micro-hybrid composite Venus combined with the self-etch adhesive iBond Gluma inside (1-SE) or etch-and-rinse adhesive Gluma Comfort Bond (2-ER) (all Heraeus Kulzer) was carried out using OCT and SEM after 90 months of clinical function. The results were compared with clinical evaluation (US Public Health Service criteria; marginal integrity, marginal discoloration).

Results: *In vitro*, the correlation between OCT and SEM was high for all four margin criteria (Kendall tau b [τ_b] correlation: 0.64-0.92, $p_i \leq 0.026$), with no significant differences be-

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tween OCT and SEM ($p_i \geq 0.63$). *In vivo*, a moderate correlation was observed (τ_b: 0.38-0.45, $p_i < 0.016$). Clinically, the cumulative failure rate in the criterion marginal integrity was higher for the 1-SE group (baseline 90 M, $p = 0.011$). Similarly, OCT and SEM detected higher percentages of the criterion gap in the 1-SE group (p: 0.027/0.002), in contrast to perfect margin. Both, gap and perfect margin ranged widely between 0.0% and 88.7% (OCT) and between 0.0% and 89.0% (SEM).

Conclusion: Despite the positive selection bias after 90 months with only a few patients left, quantitative margin analysis allows for differentiation between the two adhesives at this specific date. OCT in particular offers the possibility to evaluate marginal integrity directly *in vivo*.

INTRODUCTION

The integrity of the tooth-composite interface is regarded as the most important factor determining the clinical success of composite restorations.[1–3] Thus, marginal integrity is among the most important elements when evaluating composite restorations and adhesive systems in laboratory testing and clinical trials as well as in daily clinical practice.[4–6] In order to avoid complications such as postoperative sensitivity, marginal discoloration, caries adjacent to the restoration margin, and pulpal disease, restorations should be placed with excellent marginal qualities.[3]

Numerous methods are available for laboratory testing of adhesive systems. These include bond strength testing,[3] morphologic assessments of the tooth-composite interface,[7] evaluation of marginal integrity,[4–6,8–10] evaluation of internal tooth-restoration adaptation,[4,9–11] dye penetration,[7,12] and bacterial leakage or three-dimensional (3D) assessment of restorations by micro-computed tomography.[3,13,14] Apart from marginal adaptation, these techniques are not applicable to *in vivo* conditions because of their destructive and/or invasive character. [9,11,15–17] Evaluation of marginal integrity *in vivo* can only be carried out by a few methods, such as visual examination and probing according to US Public Health Service (USPHS) criteria[18] and quantitative margin analysis using replica techniques.[6,19] Some clinical trials have combined these two methods with the detailed recording of gap formation offered by scanning electron microscopy (SEM) analysis to supplement the rather approximate clinical estimation.[4,20]

SEM analysis is widely accepted as the gold standard,[10,17,21] and is applied in numerous *in vitro* and *in vivo* studies even though it is a very technique-sensitive and time-consuming method.[9,10,20,22–24] This includes complex intermediate and partially destructive preparation steps such as producing impressions and replicas, mounting the replicas, as well as gold coating and imaging procedures under vacuum using high-energy electrons.

Besides the need for long-term clinical trials,[6,25,26] further methods for nondestructively evaluating the integrity of restoration margins and the tooth-composite interface must first be developed *in vitro*.[5,14] In addition, *in vivo* evaluation represents a particular challenge.

Optical coherence tomography (OCT) allows for depth resolved visualization of surface structures and could therefore make an important contribution to assessing restoration margins. The basic principle of the digital imaging method is that light is backscattered from areas that include structures of different refractive index, such as tooth-composite interfaces or gaps. OCT has been an established diagnostic tool in ophthalmology for years and has been implemented in other fields of medicine, such as dermatology and cardiology, over the past decade, with a first experimental application in dentistry in 1998.[27-29] OCT is based on the principle of low-coherence interferometry, which has already been described in various publications.[15,16,30–33] The method provides two-dimensional (2D) cross-sectional and 3D volumetric images, is nondestructive and noninvasive, and allows real-time imaging with high spatial resolution in the micron range. *In vitro* studies have already demonstrated the ability of OCT to provide usable images of composite restorations.[5,13,15,34,35] Structures can be imaged up to a depth of 2 to 2.5 mm due to the individual refractive indices of dental hard tissues and restoration materials. The characteristics and ability of this technique to generate high-resolution images with a handheld device make the OCT system a potential tool for assessing marginal qualities of composite restorations *in vivo*. That sparked our interest to evaluate restorations in service for a longer time period as part of a clinical study.

With regard to high esthetic demands, the reliability of the micro-hybrid composite Venus in the anterior region was evaluated in a four-year prospective clinical trial.[11] Class III/IV lesions were restored using the composite in combination with the one-step self-etch adhesive iBond Gluma inside or with the two-step etch-and-rinse adhesive Gluma Comfort Bond. After 48 months, the one-step self-etch adhesive showed inferior clinical results (USPHS criteria), since decreased marginal integrity and an increased number of dark marginal color lines (undermining marginal discoloration) were found.[11] It remained unclear as to whether the cumulative failure rates of both groups (one-step self-etch adhesive and two-step etch-and-rinse adhesive) converged or diverged. The restorations were to be reassessed after 90 months of clinical function, both clinically and using quantitative margin analysis.

The aims of the present study were as follows:

1. *In vitro* evaluation of marginal qualities of Class III and IV composite restorations using OCT compared with the established replica technique (SEM).
2. *In vivo* evaluation of Class III and IV composite restorations after 90 months of clinical function in terms of clinical failure rates and quantitative margin criteria (OCT, SEM).
   The difference between the adhesive systems was to be determined. The hypothesis was that increased numbers of clinical failures and margin gaps would occur in the group using the one-step self-etch adhesive compared with the restorations using the two-step etch-and-rinse adhesive.
3. Exploratory evaluation of the relationship between clinical outcome parameters and quantitative margin analysis.

METHODS AND MATERIALS

In Vitro

As the first part of this study, an *in vitro* investigation was performed to validate the OCT. Four unrestored, caries-free human anterior teeth extracted for periodontal reasons were included with patients' approval (local Ethics Committee protocol no. 299-10-04102010). The specimens were cleaned and stored in distilled water. Each tooth received two Class III cavity preparations (mesiobuccal, distobuccal, size $3 \times 3 \times 2$ mm each) using diamond burs (107 μm, 46 μm; Busch & Co GmbH & Co KG, Engelskirchen, Germany) under sufficient water cooling. Cavity margins were located in enamel and not beveled.

The prepared cavities (n=8) were randomly divided into two groups. The purpose was to provoke different marginal qualities, for example, marginal gaps, composite overhangs, underfilled, and perfect margins in order to evaluate them using SEM and OCT.

The first four cavities were treated with the one-step self-etch adhesive Adper Prompt L-Pop (3M Deutschland GmbH, Seefeld, Germany) according to the manufacturer's instructions, while the other four cavities were etched with 35% phosphoric acid etching gel (Vococid, Voco GmbH, Cuxhaven, Germany) to remove any smear layer. However, no adhesive was applied to encourage marginal and interfacial gaps. The nano-hybrid composite Tetric EvoCeram (Ivoclar Vivadent AG, Schaan, Liechtenstein) was used as the restoration material. Each cavity was restored using the incremental layering technique (layer thickness up to 2 mm). Each layer was light cured for 20 seconds (Bluephase, Ivoclar Vivadent AG; 1200 mW/cm^2, output determined with curing radiometer Demetron Model 100, Danbury, CT, USA). The restorations were carefully finished (finishing burs 46 μm/26 μm; Busch & Co GmbH & Co KG) and polished (CompoMaster silicone points; Shofu Dental GmbH, Ratingen, Germany) to preserve different marginal qualities.

To identify identical parts of the margins in both the SEM and OCT images, regions of interest (ROI) were defined by drilled holes along the restoration margins. Markings of a flowable composite (GrandioSO Flow, Voco GmbH) served as an additional orientation help (Figure 1). Subsequently, silicone impressions of the restored teeth were taken (polyvinylsiloxane Coltene President putty soft, President plus light body; Coltene/Whaledent AG, Altstätten, Switzerland) for fabricating epoxy replicas (Stycast 1266; Emerson & Cuming, Waterloo, Belgium). Replicas were mounted, sputter-coated with gold (20 nm, Edwards Sputter Coater S 150B; Edwards Ltd, Irvine, United Kingdom), blinded, and imaged using SEM in topography contrast at 250× magnification (20 kV, CamScan CS24; Cambridge-Scanning Com. Ltd, Cambridge, United Kingdom). The length of the criteria—perfect margin (PM), gap (G) positive ledge (PL), and negative ledge (NL) (Table 1) —was determined and expressed as a percentage of the total length of the examined restoration margin.

In addition, the restored teeth were imaged nondestructively with spectral-domain OCT (SD-OCT, 3D-volume scans, TELESTO SP 5, 1310 nm; Thorlabs GmbH, Dachau, Germany).

With this technique, the light of the SD-OCT broadband source was separated into a sample and a reference arm (Michelson interferometer configuration). The light of the sample arm was backscattered at phase boundaries between zones of different refractive index and was brought to interference

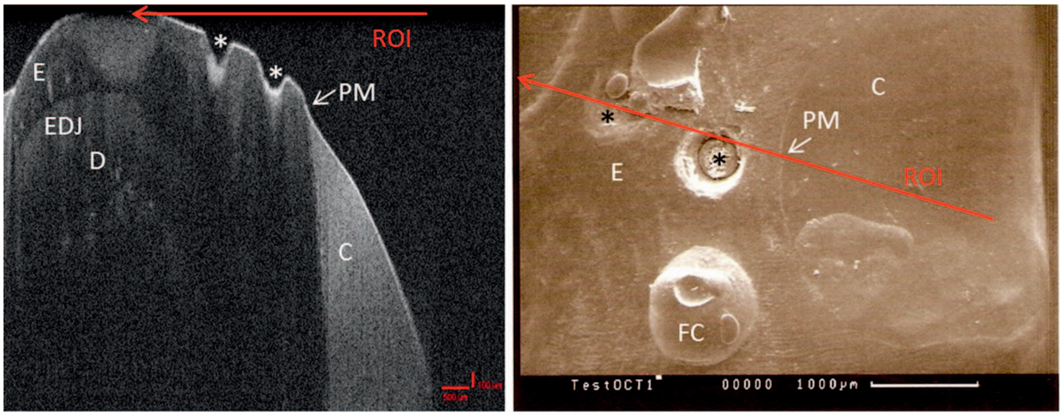

Figure 1. *Verification of OCT with SEM. Within the ROI, the OCT cross-sectional image and the SEM image can be compared. The holes (asterisks) define the ROI, the marking of flowable composite (FC) supports the orientation. C, composite restoration; D, dentin; E, enamel; EDJ, enamel-dentin junction; PM, perfect margin.*

with the unaffected light of the reference arm. The frequency of the resulting interferogram was measured, which was directly related to the depth of the scattering structure within the object. After Fourier Transform, a depth profile of the backscattering was generated (A scan). The point-by-point scanning of the OCT beam across the sample produced 2D cross-sectional images (B scans), and the line-by-line scanning produced a series of 2D images from which 3D image stacks were created.

The process of OCT imaging was as follows: the scanning probe fixed to create the right angle of light incidence, the sample tooth mounted, ROI set, focused on specimen, the surface dried using a cotton pellet to leave the surface moist with no visible water droplets (controlled hydrated condition), 2D cross-sectional imaging of ROI performed, and 3D image stack created (center wavelength 1310 ± 107 nm, sensitivity ≤106 dB, axial/lateral resolution <7.5 [air]/15 μm, field of view maximum 9 mm $\times$ 9 mm $\times$ 2.58 mm [pixel size $700 \times 700 \times 512$], imaging speed 91 kHz, A-scan average 1).

The OCT signals within the predefined ROI were verified by comparison with the corresponding SEM images (Figure 1). Thereafter, the OCT margin analysis was performed.

For each criterion, the number of B-scans was counted and expressed as a percentage of all available images depicting the examined restoration margin (Table 1). SEM and OCT examinations were performed by a single blinded and calibrated operator (A. S. S.-O.).

In Vivo

Materials, Selection Criteria, and Clinical Procedure—All test subjects included in the present study were participants in a long-term prospective clinical trial that started in October 2003 (local Ethics Committee, protocol no. 087/2003).[11] This trial compared the clinical performance of the one-step self-etch adhesive iBond Gluma inside (1-SE) with the two-step etch-and-rinse adhesive Gluma Comfort Bond (2-ER) in combination with the micro-hybrid composite Venus (all products by Heraeus Kulzer GmbH, Hanau, Germany).[11] At baseline (BL) of the

Table 1: *Margin Analysis Criteria (Optical Coherence Tomography and Scanning Electron Microscopy)*

Evaluation Criteria	Characterization
Perfect margin (PM)	No interruption of continuity, margin barely visible, no irregularities, no gaps or marginal openings, no marginal deficiencies
Gap (G)	Marginal opening, crevice between tooth structure and composite material
Positive ledge (PL)	Composite restoration situated on a higher level than adjacent tooth structure (eg, due to overfilling, composite excess), including overhangs
Negative ledge (NL)	Composite restoration situated on a lower level than adjacent tooth structure (eg, due to underfilling, increased wear of composite material), including chipping fractures of excess composite material if not associated with gap

prospective study, 35 patients were enrolled, age 18 to 65 years, and in need of 90 Class III (n=51) or Class IV (n=39) restorations. Fillings were placed in pairs (1-SE/2-ER) per test person and randomly assigned, in accordance with American Dental Association Guidelines (USPHS criteria).[18] Cavity preparation was defect-oriented, and enamel margins were slightly beveled. Restorations were placed under rubber dam isolation, and all products were used strictly following manufacturers' instructions. The restorations were finished and shaped with fine-grained diamond burs (15-25 μm, Intensive SA, Grancia, Switzerland) and polished with flexible silicone rubber polishing points and polishing brushes (Ivoclar Vivadent AG).

Clinical Evaluation—19 patients were included in the 90-month clinical reassessment. Each restoration was clinically scored by the principal investigator (M.H.) according to USPHS criteria,[11] focusing on marginal discoloration (MD) and marginal integrity (MI, single-blind rating alpha to delta).

To compare the results of quantitative margin analysis (SEM, OCT) and clinical evaluation, marginal integrity and marginal discoloration were selected from the USPHS criteria. The restoration-related cumulative failure rates were calculated at each recall interval for each criterion.[11]

Quantitative Margin Analysis (SEM/OCT)—Nine of the 19 patients with one restoration with each adhesive were randomly allocated to OCT and SEM analysis (approval of the local Ethics Committee, protocol no. 131-11-18042011). OCT imaging and impression taking (polyvinylsiloxane Coltene President putty soft, President plus light body) took place at the same appointment of the 90-month clinical reassessment. Epoxy resin replicas were produced (Stycast 1266), mounted and sputter coated with gold for SEM quantitative margin analysis as described in the *in vitro* part of this study (Table 1). Margin analysis by OCT and SEM used the same evaluation criteria (Table 1). Non-accessible parts of the restoration margins resulting from artifacts or a lack of clinical access were excluded, for example, when restoration margins were covered by gingiva.

All 18 restorations of the nine patients were subjected to image analysis with Fourier domain Swept-Source-OCT (SS-OCT, OCS 1300SS; Thorlabs Inc, Newton, NJ, US). The parameters of the OCT equipment were: center wavelength 1325 ± 100 nm, sensitivity 100 dB, axial/lateral resolution 12 (air)/25 μm, field of view ≤10 mm × 10 mm × 3 mm (pixel size 512 × 512 × 512), and imaging speed 16 kHz. After cleaning the restorations and tooth surfaces and drying by air syringe, the handheld and mechanically stabilized scanning probe was positioned at a distance of approximately 3 cm at a right angle to the restoration surface. The restoration area was brought into focus, and 2D cross-sectional images and 3D image stacks were generated within approximately six seconds. The data were saved, and the margin analysis was performed as described previously.

For testing intrapersonal reproducibility, four of the *in vivo* composite restorations (two per adhesive system) were randomly selected for three blinded reassessments of SEM and OCT images by one operator at one-week intervals. The mean percentages of marginal criteria and standard deviations were determined.

Statistical Analysis

Quantitative Margin Analysis—The parameters PM, G, PL, and NL were determined. Wilcoxon test and Kendall tau b (τ_b) were used for nonparametric comparison and measuring correlation between OCT and SEM analyses.

Clinical Evaluation—For clinical assessment of all 19 patients, the failure rates of the criteria MD (code C), MI (codes C and D), and cumulative failure rates (CFR) (BL - 90 M) were determined. Groups were compared using the McNemar test (one-sided because of a significant decrease of margin quality up to 48 months). The clinical results of the nine patients subjected to additional OCT imaging were descriptively evaluated (percentages).

Comparison of Clinical Assessment and Margin Analysis—Eighteen restorations of the nine patients were simultaneously subjected to clinical evaluation and margin analysis. The percentages of marginal criteria PM, G, PL, and NL (OCT and SEM) were listed according to the clinical ratings A, B, and C (MI and MD). The percentages of PM, G, PL, and NL of the restorations with clinical scores A, B, and C were statistically compared (Kruskal-Wallis test and Mann-Whitney U test, not normally distributed data). Accordingly, correlations between the percentage of PM, G, PL, and NL of restorations and ratings A through C of clinical outcomes MI and MD were determined (Kendall τ_b).

For a comparison between both adhesives, on the basis of the percentages of PM, G, PL, and NL (OCT, SEM), the nonparametric Wilcoxon test was made (one-sided, see previous description).

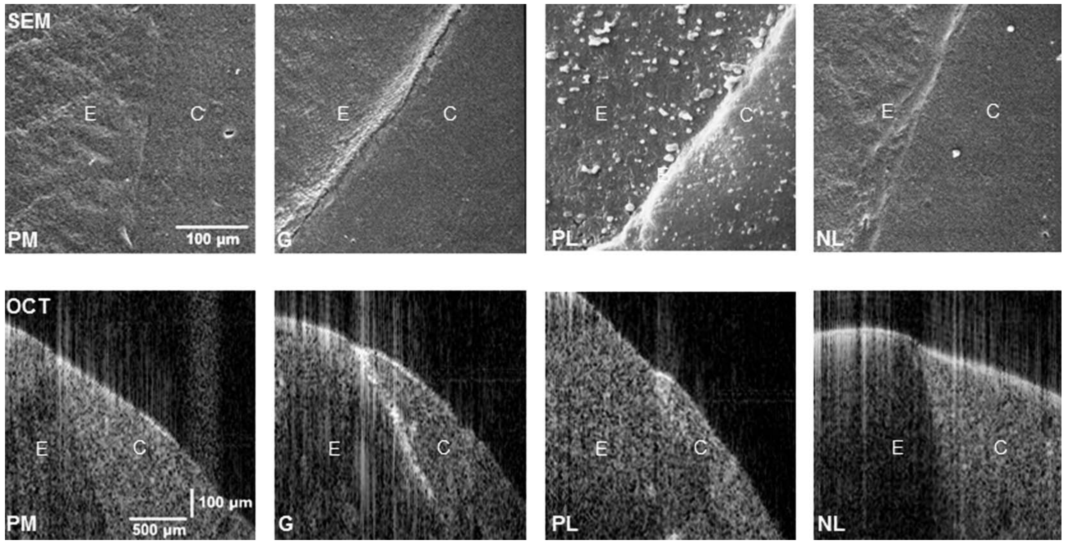

Figure 2. *Representative SEM and OCT images of a region of interest, each showing the marginal critera perfect margin (PM), gap (G), positive ledge (PL) and negative ledge (NL). C, composite; E, enamel.*

Statistical analysis was performed using SPSS 15.0 for Windows (SPSS Inc, Chicago, IL, USA) at the significance level of 0.05. Due to the exploratory nature of this research, raw *p*-values are reported, and we refrained from correction for multiple testing.

Friedman and Wilcoxon tests were used to assess the intrapersonal reproducibility of OCT and SEM margin analysis in terms of marginal criteria PM, G, PL, and NL. Means and standard deviations were calculated. Intrapersonal standard errors were 7.2% and 7.0% (OCT) or 18.4% and 4.8% (SEM) for small and large extension of the marginal criteria PM, G, PL. and NL. No significant differences between the individual reassessments were observed (p_i: 0.13-1.0).

Based on the margin analysis at 90 months, a *post hoc* calculation was carried out to estimate the power of the quantitative margin analysis by OCT and SEM with respect to parameter gap (PS-Power and Sample Size Calculation, version 3.0.43, free trial, Vanderbilt University, Nashville, TN).

RESULTS

In Vitro

It was possible to assess identical parts of the restoration margins in both the OCT B-scans and SEM images. Each of the four criteria for quantitative margin analysis could be displayed by OCT (Figure 2). The Gs between tooth hard tissue and composite restoration were shown as bright lines due to increased signal intensity in these areas. PLs and NLs were identifiable by contour changes, while PMs showed a consistent junction between tooth and restoration, distinguishable by different material brightness without additional signals at the interface (greyscale).

A strong significant correlation could be found between OCT and SEM quantitative margin analysis (τ_b PM/G/PL/NL: 0.79/0.86/0.92/0.64; p_i: 0.003-0.026, Table 2) without significant differences between both methods in all assessed criteria (p_i: 0.63-1.0).

In Vivo

Clinical Evaluation—Table 3 summarizes recall rates, reassessment rates, and cumulative failure rates with regard to the clinical criteria MD and MI from baseline to 90 months. At 90 months, 62.9% (1-SE) and 61.5% (2-ER) of the composite restorations could be reassessed. Compared with group 2-ER, in group 1-SE, the cumulative failure rate regarding to marginal integrity (restoration loss over time) was significantly enhanced (p=0.011, Table 3).

The nine subjects who received quantitative margin analysis showed the following clinical results (Table 2). In the 1-SE group, two restorations failed with MI of code C or D. One of the remaining seven restorations showed MD of code C. Thus, three of the restorations (33.3%) failed in both criteria. In the 2-ER group, no restoration failed in the criterion MI, 11.1% of restorations failed in both criteria with one of nine restorations showing MD of code C. The

Table 2: *Evaluation of Marginal Qualities of Class III and IV Composite Restorations Using SEM and OCT* In Vitro *or* In Vivo *at 90 Months Recall (Nine Restoration Pairs): Explorative Clinical Evaluation of Nine Restoration Pairs*

Margin analysis	PM	G	PL	NL
Correlation OCT – SEM, $\tau_b/(p_i)$				
In vitro	0.79 (0.006)	0.86 (0.003)	0.92 (0.003)	0.64 (0.026)
In vivo	0.38 (0.016)	0.45 (0.004)	0.44 (0.006)	0.43 (0.009)
OCT vs SEM, p_i				
In vitro	0.844	1.00	0.625	0.844
In vivo	0.812	0.516	0.018	0.980
1-SE vs 2-ER[a]; 9 pairs of restorations *in vivo*				
1-SE				
OCT	42.63	36.75[b]	10.55	8.17
SEM	38.79	38.73[c]	14.57	7.63
2-ER				
OCT	53.21	15.71	13.15	15.52
SEM	56.05	10.34	22.02	11.59
p_i				
OCT_{SEvsER}	0.190	0.027	0.348	0.064
SEM_{SEvsER}	0.080	0.002	0.065	0.064
Clinical evaluation		**Failure MI + MD, %**		
1-SE vs 2- ER; 9 pairs of restorations				
1-SE		33.3		
2-ER		11.1		
p		0.625		

Abbreviations: 1-SE, one-step self-etch adhesive iBond Gluma inside; 2-ER, two-step etch-and-rinse adhesive Gluma Comfort Bond; G, gap; MD, marginal discoloration; MI, marginal integrity; OCT, optical coherence tomography; NL, negative ledge; PL, positive ledge; PM, perfect margin; SEM, scanning electron microscopy; $\tau_b/(p)$: Kendall tau b/(p_i).
[a] *Mean values (%).*
[b] *Increase of 134% related to 15.71 (2-ER).*
[c] *Increase of 274.6% related to 10.34 (2-ER).*

displayed differences between the two groups were not statistically significant (MD: p=1.0, MI: p=0.5, sum of both criteria: p=0.625).

Quantitative margin analysis, OCT vs SEM—OCT enabled detailed imaging of restoration margins under *in vivo* conditions. Statistical analysis revealed a moderate significant correlation between OCT and SEM (τ_b PM/G/PL/NL: 0.38/0.45/0.44/0.43; p_i<0.016, Table 2). No significant differences could be found between both methods with regard to the criteria PM, G, and NL (p_i: 0.516-0.98, Table 2), while for PL a statistically significant difference was observed (p=0.018).

Clinical Evaluation and Quantitative Margin Analyses, Marginal Integrity—A statistically proven relationship arose from MI (clinical evaluation) and PM based on SEM (quantitative margin analysis) with a moderate significant correlation (τ_b=–0.4, p=0.034, statistical analysis). Therefore, in Table 4, merely for MI (ratings A, B, and C), the percentages of G and PM along restorations were represented. Using SEM, the B-rated restorations in Table 4 showed a significantly 39% lower mean value for PM compared with A-rated restorations (37.12% vs 61.04%, p-value of the SEM-investigation p_{SEM}: 0.016), with OCT there was a nonsignificant 19% decrease (44.22% vs 54.59%, p-value of the OCT-investigation p_{OCT}: 0.272). A stronger but nonsignificant effect resulted for G; 73% more Gs were observed by SEM analysis at B-rated restorations compared with A-rated restorations (28.92% vs 16.74%, p=0.171). OCT revealed 60% more Gs at restorations rated as B (32.00% vs 20.01%, p=0.272, Table 4). For margin criteria PL and NL, neither OCT nor SEM analysis showed a statistically proven relationship with MI (τ_b: –0.240 ... +0.160; all p-values p_i: 0.203-0.764). This was true for ratings A and B (p_i: 0.350-0.791).

Marginal Discoloration—All ratings A through C of MD showed no significant differences for PM, G, PL, NL (p_i: 0.25-1.0). In addition, no statistically significant correlations could be proven (τ_b: –0.170 ... +0.237, p: 0.201-0.881, statistical analysis).

Table 3: *Clinical Performance of iBond Gluma Inside/Venus vs Gluma Comfort Bond/Venus in the Period Baseline – 90 Months*

	iBond Gluma inside/Venus						Gluma Comfort Bond/Venus					
	Baseline	**6 Months**	**12 Months**	**24 Months**	**48 Months**	**90 Months**	**Baseline**	**6 Months**	**12 Months**	**24 Months**	**48 Months**	**90 Months**
Patients seen/ recalled, n	35	32/35	33/35	31/33	24/30	16/28	35	32/35	33/34	31/33	23/32	17/29
Recall response, %	100	91.4	94.3	93.9	80.0	57.1	100	91.4	97.1	93.9	71.9	58.6
Trials failed/ dropped out before, n				4	7/1	9/1			1	1/1	1/2	4/2
Trials reassessed/ recalled, n	45	41/45	42/45	39/41	30/37	22/35	45	41/45	42/44	41/43	35/42	24/39
Reassessment rate, %	100	91.1	93.3	95.1	81.1	62.9	100	91.1	95.5	95.3	83.3	61.5
Control period, months[a]		6.1 (0.89)	13.0 (1.23)	24.0 (0.72)	47.9 (0.66)	89.5 (1.41)		6.1 (1.00)	13.2 (1.38)	23.8 (0.78)	47.9 (0.82)	89.4 (1.65)
Cumulative failure rate, %, marginal discoloration	0	0	2.4	2.7	6.9	12.5	0	0	0	0	3.0	16.0
Cumulative failure rate, %, marginal integrity	0	0	7.1	14.3	20.0	41.8**	0	0	0	0	5.9	7.7**

[a] *Mean (standard deviation).*
*** Significantly different (p=0.011).*

1-SE vs 2-ER

The results of the quantitative margin analyses of 1-SE vs 2-ER are shown in Table 2.

In the 1-SE group, significantly higher percentages of Gs were detected by OCT (134.0%) and SEM (274.6%) compared with the 2-ER group (OCT: 36.75 vs 15.71, p=0.027; SEM: 38.73 vs 10.34, p=0.002). There was no statistically significant difference between the adhesive systems regarding PM, PL, and NL (p_{iOCT}/p_{iSEM}:>0.064/>0.064). In both groups, the percentages of G and PM varied considerably. Considering the values of all evaluated nine restorations in each group, G ranged between 1.3% and 88.7% with OCT and between 0.0% and 86.9% with SEM analysis, while ranges for perfect margin were between 0.0% and 88.6% (OCT) or 4.7% and 89.0% (SEM), respectively.

Test Power

Based on this margin analysis of nine pairs of restorations at 90 months and the measured group differences for G of 28.4% (SEM) or 21.0% (OCT), a *post hoc* test power of 76.60% (SEM) or 59.40% (OCT) was estimated (α=0.05). Thus, under the conditions of the actual study, a target test power of 80% would require 10 (SEM) or 13 (OCT) pairs of restorations, respectively.

Supplemental Information by OCT

OCT images provided supplemental information about inner structures of dental hard tissues and composite material (eg, enamel cracks, interfaces between composite increments, and porosities within the composite material) that remained undetected by

Table 4: *Percentages of Gaps and Perfect Margins Detected in Quantitative Margin Analysis with OCT and SEM in Comparison to Clinical Assessment Criterion Marginal Integrity (1-SE and 2-ER)*

Margin Criterion	**Mean Clinical Score of Marginal Integrity**		
	A	**B**	**C[a]**
Gap (G)			
OCT [%]	20.01	32.00[b]	55.71
SEM [%]	16.74	28.92[c]	41.45
Perfect margin (PM)			
OCT [%]	54.59	44.22[d]	35.24
SEM [%]	61.04**	37.12**[e]	51.87

Abbreviations: 1-SE, one-step self-etch adhesive iBond Gluma inside; 2-ER, two-step etch-and-rinse adhesive Gluma Comfort Bond; OCT, optical coherence tomography; SEM, scanning electron microscopy.
[a] *n=1.*
[b] *Increase of 60% vs 20.01.*
[c] *Increase of 73% vs 16.74.*
[d] *Decrease of 19% related to 54.59.*
e Decrease of 39% related to 61.04.
*** Significantly different (p=0.016),*

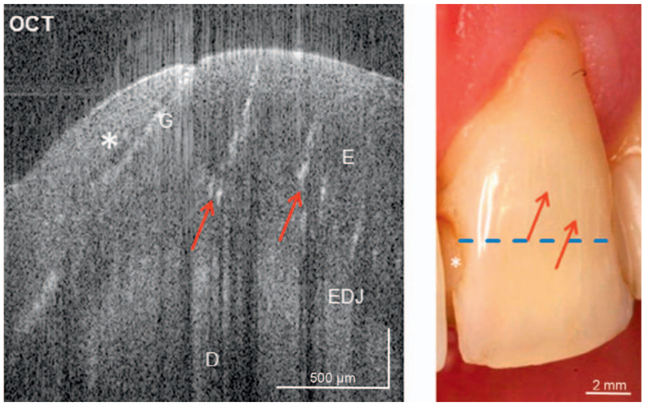

Figure 3. *OCT B-scan corresponding to the dotted blue line in the clinical image. The OCT image shows a composite restoration (*) with a marginal gap (G), which develops along the composite-enamel (E) interface. Enamel cracks (red arrows) are clearly visible. D, dentin; EDJ, enamel-dentin junction.*

SEM examination due to its limitation to visualize surface structures only. The additional findings were verified clinically (Figure 3).

DISCUSSION

OCT has been implemented in several fields of dental research in recent years from caries detection,[30] monitoring of carious lesions,[36] and remineralization processes,[32] to assessment of interfacial defects at composite restorations.[34] Features such as nondestructiveness and noninvasiveness with high-resolution imaging of dental hard tissues and composite materials distinguish OCT as a promising diagnostic tool for direct *in vivo* applications in clinical trials.[16] For example, this includes the longitudinal monitoring of surface and subsurface enamel demineralization,[37] the detection of tooth decay beneath commonly used dental sealants,[31] or the possibility of the longitudinal monitoring of the tooth-composite bond failure or the more complex assessment of composite restorations in extended clinical studies.[37]

Quantitative Margin Analysis (OCT vs SEM)

SEM in replica techniques has been typically referred to as the gold standard for quantitative margin analysis. The comparison with this technique revealed a strong correlation with OCT in *in vitro* application. *In vivo*, this decreased to a moderate correlation. Contrary to *in vitro* conditions with predefined regions of interest, it was not possible *in vivo* to ensure that identical lengths of restoration margins were evaluated. As only buccal and those interproximal margins accessible for impression taking were examined, it is conceivable that the absolute length of assessed margins differed between methods. From an OCT perspective, image acquisition is limited by the optical accessibility of tooth regions by the OCT beam. One limitation of the *in vivo* comparison is therefore that SEM analysis could have rated marginal qualities that were not rated by OCT and vice versa. This might be a potential cause of the reduced correlation between both methods *in vivo*. Moreover, it could be an explanation for the significantly higher percentages of PLs detected with SEM.

The higher spatial resolution of the SEM had no impact under the conditions of this study. The surface texture of epoxy replicas, the thickness of the deposited layer of gold, and the low 200-fold magnification used, restricted spatial resolution within the SEM images. Additional artifacts in the impressions may also affect the SEM analysis. Furthermore, OCT signaling depends on differences in refractive index, and this implies that gaps can also be recognized, even if the gap widths are below the underlying spatial resolution limit.[38]

Evaluation of Adhesive Systems

The alternative hypothesis that increased numbers of clinical failures and margin gaps occur if the one-step self-etch adhesive was used compared with the two-step etch-and-rinse system was accepted.

After the 90-month reassessment, an enhanced cumulative failure rate in the criterion marginal integrity could be demonstrated clinically in the 1-SE group (Table 3), which was also seen in the descriptive assessment of the failure in both criteria MI + MD (1-SE: 33%, 2-ER: 11%, Table 2) of the nine restorations each, which were analyzed by SEM and OCT. This corresponded with the noncumulative findings of marginal analyses revealed by both OCT and SEM at 90 months. Significantly, more marginal gaps were measured in the 1-SE group than in the 2-ER group.

Additionally, it should be pointed out that the OCT and SEM analyses reliably confirmed the group difference for the margin parameter G with the low number of nine matched pairs of composite restorations. This is noteworthy because, at the 90-month examination, restorations which were clinically successful in the long term were selectively assessed. Restorations prone to error should have been failed earlier. These facts indicate the higher power of the quantitative margin analysis (OCT, SEM) compared with clinical evaluation. Thus, OCT could be considered a reliable, noninvasive, less labor intensive, and more cost-effective alternative to SEM.

The clinical differences after 90 months complied with the data at 12 months up to the 48-month recall.[11] In this period, the MI did not always statistically significantly decrease in the 1-SE group. The discussion section of the article concluded with the open wording "one could . . . only speculate about the further divergence or convergence of the CFRs [cumulative failure rates] (between both groups)." After 90 months, it could be stated that there was no convergence regarding marginal integrity.

The results of this study substantiate the assumption that under *in vivo* conditions the margin criterion G, which reciprocally corresponds to MI, could be a quantifiable parameter to evaluate composite restoration systems, provided that the clinical protocol in all study groups is the same. The criterion PM did not permit any differentiation between adhesives or restoration systems. In this context, our answer to the commonly-asked question of "How much PM does a composite restoration need to be clinically successful?"[4] has to be: Apparently not that much. This is illustrated by the huge range of the criterion PM for OCT (0.0% to 88.6%) and SEM (4.7% to 89.0%). Furthermore, all of the 18 assessed restorations were still in function after 90 months, with no carious lesions adjacent to the restoration margins. Only one of these restorations was clinically rated C regarding MI (1-SE). Remarkably, however, this restoration could not be identified as the one with the lowest percentage of PM either by SEM or OCT. The large variance of both parameters supports the assumption that it is impossible to predict the clinical success of a restoration based on certain percentages of PMs or Gs.[10.24] Our results also tend to not confirm that the width and depth of the marginal gap could be a more decisive factor.[14]

Relationship Between Clinical Assessment and Quantitative Margin Analysis

Although for the margin criterion G a stronger effect could be observed, a statistically proven relationship could only be deduced between MI (scores A, B, and C) and PM (SEM) (Table 4). In principle, the fewer PMs present, the worse the clinical ratings. Statistical analysis could confirm this assumption for the data acquired by SEM. One reason OCT showed a smaller, nonsignificant effect could be a consequence of the difference in margins examined. Also, in future studies increased sample sizes could enhance the significance.

Regarding marginal discoloration, no statistically proven relationship could be deduced with the quantifiable margin criteria, although marginal discoloration is most commonly caused by pigment accumulation at or in marginal imperfections.[36]

Supplemental Information by OCT

As a tomographic method, OCT is able to display additional signals derived from inner structures of dental hard tissues and composite materials such as enamel cracks and interfaces between composite increments (Figure 3).[34,35,39] An OCT examination could usefully complement clinical assessment of enamel cracks and incomplete crown fractures in the future, revealing their real extent and direction, which cannot be fully assessed clinically.

Summing up, it could be stated that OCT meets the demands for applying techniques with enhanced spatial resolution in restorative dentistry.[5,14] The noninvasive nature of this method would be especially advantageous for imaging dental structures and restorations *in vivo*.

In contrast to SEM analysis, OCT offers the advantage of real-time imaging of hard tooth tissues and composite restorations, without the time-consuming and complex intermediate preparation steps that are involved in SEM analysis.[20] Additionally, OCT offers the possibility of measuring the extension of gaps at the tooth-composite interface and the imaging of inner structures of dental hard tissues and composite materials, which provides supplemental information toward the SEM examination. This could enhance clinical evaluation, especially in long-term clinical trials. There is a need for further investigation of OCT application *in vivo*, especially regarding objectivity, reliability, specificity, and sensitivity of the technique as a possible diagnostic tool in dentistry.

This study confirmed that the MI of clinically successful restorations varies significantly. Considering marginal quality as the sole or predominant criterion for clinical success is therefore not suitable to assess the long-term clinical performance of adhesive restorations.[3,10] However, the quantifiable marginal criterion G could be a useful and more predictive parameter for evaluating restoration systems. The factors affecting clinical success seem to be much more complex in structure. OCT could be, thereby, a valuable tool for diagnosing and monitoring composite restorations *in vivo*.

CONCLUSIONS

Quantitative margin analyses using SEM or OCT correspond. OCT enables both the evaluation of the margin qualities of Class III and IV composite restorations *in vitro* as well as directly *in vivo* and the generation of supplemental morphologic information about tooth surface structures.

Corresponding to clinical evaluation (*in vivo*, cumulative failure rates), quantitative margin analysis can distinguish between adhesives or restoration systems. In long-term clinical trials, cross-sectional separation of study groups might also be achievable with a small number of subjects (selection bias), even if clinical differentiation is impossible.

The margin criterion G is a suitable parameter for evaluating restoration systems.

The marginal quality of clinically successful composite restorations varies considerably. Poor marginal quality occurs in clinically successful composite restorations, indicating that a low percentage of segments with perfect margins does not successfully predict poor clinical performance.

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Regulatory Statement

This study was conducted in accordance with all the provisions of the local human subjects oversight committee guidelines and policies of the Ethics Committee of the University of Leipzig. The approval code for this study is protocols no. 299-10-04102010, no. 087/2003, and no. 131-11-18042011.

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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Impact of Modifiable Risk Factors on Bone Loss During Periodontal Maintenance

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Clinical Relevance

Neglecting the restoration of open contacts or missing teeth, even in patients with mild periodontitis, could increase the risk of interproximal bone loss during periodontal maintenance therapy.

SUMMARY

Objectives: The aim of this study was to analyze modifiable patient risk factors from dental chart histories and radiographs for progressive mild-moderate periodontitis during periodontal maintenance (PM).

Methods and Materials: Bitewing radiographs of 442 elderly periodontal maintenance patients were taken before and after two years of periodontal maintenance. Each progressive periodontitis (PP) patient (with at least one site of posterior interproximal bone loss of ≥2 mm, n=71) was matched to a periodontitis stable (PS) patient (no sites with bone loss, n=71) of the same gender and age (±five years) to control for these variables and was compared for measurements of general patient (medical history, smoking, hygiene and compliance habits) and tooth-related (bone loss, overhangs, interproximal dimensions) factors at baseline. Fisher exact and *t*-tests were used to compare groups.

Results: While the elderly PM patients with mild-moderate periodontitis were generally stable, 71 of 442 were PP patients. No significant differences from PS patients were observed at baseline with regard to the systemic factors measured. However, the PP group had less cementoenamel junction to bone length (bone loss $p<0.0001$) and more interproximal width (2.3±1.0 mm) than did the PS group (1.7±0.6 mm, $p=0.0016$). This was reflected in more open sites without adjacent tooth contact in PP (42% vs 15%, $p=0.0006$).

Conclusions: In the short term, systemic and behavior factors are of limited value in identifying mild-moderate periodontitis patients on PM at increased risk of bone loss. However, interproximal width and lack of adjacent tooth contacts are related to the likelihood of losing interproximal bone during periodontal main-

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tenance, suggesting the need for restorative therapy.

INTRODUCTION

Periodontitis is the result of complex interrelationships between infectious agents in dental plaque and multiple host factors. Periodontal maintenance (PM) is an important part of periodontal treatment that includes procedures performed at different intervals to aid the periodontal patient in maintaining oral health.[1-5] It has been shown[6,7] that periodontal treatment followed by long-term maintenance is successful in the preservation of the majority of patients' teeth. Most patients with milder forms of periodontitis are managed in general practices on four to six-month intervals, with the expectation that all sites will remain periodontally stable (no bone loss).[8] However, following the current population in a dental school setting for two years on PM revealed that 16% of patients had at least one site with $\geq$2 mm of interproximal bone loss.

The predictability of PM may be associated with diverse conditions, especially when a patient is exposed to one or more risk factors known to influence host response.[7,9] There is evidence that age, gender, smoking, compliance with recalls, and systemic diseases such as diabetes mellitus and osteoporosis may affect the results achieved through periodontal therapy.[2,4,9-13] Meanwhile, studies[10,11,14,15] have also shown that different tooth-related factors are associated with the long-term stability of periodontal maintenance. Clinical parameters such as pocket depth, bleeding on probing, attachment loss, and tooth mobility are recorded during periodontal maintenance to measure the periodontal condition of patients.[2,16] However, other tooth-related factors that might affect the long-term outcome of periodontal maintenance are not commonly recorded or corrected.[17-19]

Bitewing radiographs (BWs) are routinely obtained during PM, and radiographic bone loss is an objective measurement and an important indicator of progressive periodontitis. Maintaining stable bone levels is one of the major goals of periodontal maintenance.[20,21] Other measurements that can be easily obtained from BWs also may be important prognostic indicators. However, to our knowledge, the relationship between different radiographic tooth-related factors and alveolar bone loss in PM patients has not been thoroughly studied. It is still controversial which tooth-related factors are predictive for bone loss during PM; specifically, whether the specific measurements of the anatomy of interproximal areas, such as interproximal width, restoration overhangs, baseline bone loss, and lack of contact, are associated with the increased likelihood of subsequent crestal bone loss during PM.

The aim of this research was to compare prominent modifiable systemic patient and tooth-related factors identifiable on chart histories and radiographs in groups of mild/moderate periodontitis patients who had either shown posterior interproximal periodontitis stability or progressive periodontal bone loss during PM. The results may help dentists develop more reliable prognoses and treatment options for PM patients.

METHODS AND MATERIALS

Four hundred forty-two patients over age 45 (to eliminate aggressive periodontitis) participating in the University of Nebraska Medical Center College of Dentistry periodontal maintenance program with at least two years of regular PM therapy were chosen as subjects under an institutional review board protocol (IRB 015-14). All patients received a standard protocol of BWs, periodontal probing, oral hygiene instructions, and scaling/root planing during PM. Since all providers were not calibrated for probing measurements, bone loss on radiographs was used to determine progressive periodontitis. Guidelines conformed to the Code of Ethics of the World Medical Association (Declaration of Helsinki). Patients were deidentified, and posterior digital BWs before (baseline) and after the two-year PM period (two-year follow-up) were measured at all posterior interproximal sites (premolar and molar) from the cementoenamel junction (CEJ) or restoration margin to the crestal bone where the periodontal ligament space became uniform. A ruler tool (MiPACS Dental Enterprice Solution, Medicor Imaging, Microtek, Hsinchu, Taiwan) was used to make the linear measurements separately by two examiners masked to patient identity. The progressive periodontitis (PP) patients were defined as having at least one site of posterior interproximal bone loss measuring $\geq$2 mm between baseline and two-year follow-up on BWs. The 2-mm threshold was chosen to reflect a clinically relevant change that could be detected on non-standardized radiographs taken in clinical practice.[22] The periodontitis stable (PS) group was defined as having all sites with posterior interproximal bone change measuring <2 mm between baseline and two-year follow-up on BWs, and PS patients were paired to a PP by age ($\pm$five years) and gender to control for these variables. Ten percent of patients were remeasured at baseline and

Table 1: *Demographic Characteristics of the Subjects*

Characteristic	Progressive Periodontitis		Stable Periodontitis		p-Value
	N (SD)	% or Range	N (SD)	% or Range	
Gender					
Female	28	39.4	29	40.9	
Male	43	60.6	42	59.2	1.00
Mean age, y	72.11 (10.59)	46-95	71.76 (10.84)	47-95	0.77

Abbreviation: SD, standard deviation.

two-year follow-up by the same examiners in order to determine the reliability of measurements in this study.

Medical and dental history questionnaires at baseline were used to obtain general systemic and behavioral risk factors previously associated with periodontitis, as follows:

1. Systemic conditions from medical history: diabetes mellitus, osteoporosis, rheumatoid arthritis;
2. Smoking: Current smoker, former smoker, or never smoker;
3. Awareness of periodontal and oral disease: loose teeth, food or floss caught between teeth, diagnosed with gum disease, treated for gum disease, gums bleed when brushed, and dry mouth;
4. Oral hygiene habits: brushing frequency per week and flossing frequency per week; and
5. Compliance with periodontal recalls: numbers of maintenance appointments within two years and average visits per year for two years.

Tooth-related factors were measured at baseline in posterior sites with bone loss of $\geq$2 mm in the PP group and were matched to a similar interproximal location (eg, molar-molar, molar-premolar) in the paired PS patient. The tooth-related factors measured were as follows:

1. CEJ to alveolar crest length;
2. Presence or absence of adjacent tooth contact;
3. Overhanging restorations of $>$1 mm;
4. Interproximal contact to alveolar crest length;
5. Width of interproximal (ITP) embrasure: measured from CEJ to adjacent CEJ; and
6. CEJ to CEJ angle relative to long axis of the tooth (horizontal CEJ-CEJ=90° angle).

Baseline severity of periodontitis of study sites and of overall posterior sites were calculated according to bone loss of the site, where normal = 0 to 2 mm CEJ to alveolar crest on BW, mild = 2 to 4 mm, moderate = 4 to 6 mm, and severe = more than 6 mm.

Comparisons of categorical factors between PP and PS groups were conducted with Fisher exact tests. Comparisons of continuous factors between PP and PS groups were conducted with *t*-tests. *p*-Values of less than 0.05 were considered to be statistically significant. SAS software version 9.4 was used for analysis (SAS Institute Inc, Cary, NC, USA). Single-measures intraclass correlations (ICCs) for absolute agreement were calculated using a two-way mixed-effects model for each of the examiners, at each of the time points, using SPSS software, version 23 (IBM Corp, Armonk, NY, USA). ICCs ranged from 0.663 to 0.881. According to Cicchetti,[23] the clinical significance values of ICCs between 0.60 and 0.74 and between 0.75 and 1.00 are "good" and "excellent," respectively.

RESULTS

Each group had 71 subjects after identification of PP patients and matching to a PS patient and interproximal location. Demographic characteristics of the subjects are presented in Table 1. No significant differences were observed since patient and control groups were matched by gender and age. The mean age in the lower 70s with mild-moderate periodontitis indicates a patient population with a slow rate of bone loss in whom an episode of clinically significant bone loss might define high-impact risk factors.

Common systemic or behavioral risk factors for PP and PS groups at baseline are presented in Table 2. In general, no significant differences were observed with regard to systemic conditions, smoking, awareness of periodontal and oral disease, oral hygiene habits, and compliance with periodontal recalls. There was a trend toward more PP in diabetic patients (p=0.13).

The tooth-related factors of PP and PS groups at baseline are presented in Table 3, Figure 1. While local plaque control and instrumentation are the cornerstones of effective PM, several other local factors were significantly different between the two groups. At baseline, mean CEJ to alveolar crest length of the PP site was 1.9 ± 1.3 mm, while CEJ to alveolar crest length of the PS site was 3.0 ± 1.6 mm (p<0.0001). This indicated normal bone height (56% of cases) in PP and early bone loss in PS (54%, p=0.001). Therefore, past periodontitis was not a risk factor in future bone loss in these mild-moderate periodontitis patients on PM. As for baseline severity

Table 2: *Common Systemic or Behavioral Risk Factors at Baseline*

Systemic or Behavioral Risk Factors	Progressive Periodontitis		Stable Periodontitis		*p*-Value
	N	%	N	%	
Systemic conditions					
Diabetes mellitus	17	24	9	13	0.13
Osteoporosis	3	4	6	9	0.33
Rheumatoid arthritis	1	1	2	3	0.62
Smoking					
Current smoker	13	19	8	11	0.34
Awareness of periodontal and oral disease					
Loose teeth	8	11	9	13	1.00
Food or floss caught between teeth	44	63	38	55	0.39
Diagnosed with gum disease	42	60	37	53	0.50
Treated for gum disease	43	61	36	51	0.31
Gums bleed when brush	10	14	11	16	0.82
Dry mouth	17	24	14	20	0.68
Oral hygiene habits					
Have trouble cleaning/flossing	4	6	6	9	0.53
	Mean (SD)		**Mean (SD)**		
Brushing frequency per week	11.8 (4.4)		10.6 (4.3)		0.12
Flossing frequency per week	5.7 (5.2)		5.5 (4.9)		0.70
Compliance with periodontal recalls					
No. of maintenance within 2 y	4.5 (2.2)		4.6 (2.3)		0.95
Average visit per year for 2 y	2.3 (1.1)		2.3 (1.2)		0.84

Abbreviation: SD, standard deviation.

of periodontitis of overall posterior sites, the results did not show a statistically significant difference between the two groups. The baseline embrasure width from CEJ to adjacent CEJ of the PP group was wider (2.3±1.0 mm) than for the PS group (1.7±0.6 mm, p=0.0016). This was reflected in more sites without adjacent tooth contacts in PP (42% vs 15%, p=0.0006), but not in tipped teeth (CEJ-CEJ angle in PP sites=91.5°±34.5° compared to PS sites=97.9°±32.1°, p=0.31; Table 3). To further focus on tooth-related factors, major systemic risk factors were removed from the analysis, with results described in Table 4. Significant findings for baseline CEJ to bone, CEJ to CEJ width, and lack of contact remained after eliminating patients with diabetes, osteoporosis, rheumatoid arthritis, or current smoking habit.

The interproximal anatomy in progressive periodontitis sites was additionally characterized in Table 5, Figure 2. Amount of open contact was evenly distributed between those with <2 mm (food impaction) and those with >4 mm (self-cleansing). The most common restoration was cast crown, similar in incidence to no restoration. The incidences of opposing plunger cusps and overhanging restorations were rare. There were slightly more PP sites in the maxilla.

DISCUSSION

At baseline, the majority of patients in each group had mild chronic periodontitis, according to the diagnostic standard used in this study. All of the subjects had finished initial periodontal therapy and had gone into PM. While these patients with mild-moderate periodontitis on PM were generally stable, 16% of the patients followed in this study showed at least one site with ≥2 mm of interproximal bone loss. Periodontal maintenance has been proven[24] effective in minimizing long-term tooth loss and controlling disease progression and relapse in patients with chronic periodontitis. However, even within compliant periodontal maintenance patients, disease progression still cannot be completely stopped.[25] While results indicated that regular PM allowed for stable and relatively normal interproximal bone levels, even mild-moderate periodontitis patients on PM should be followed closely for evidence of bone loss, and risk factors associated with this event should be considered.

Table 3: *Tooth-related Factors at Baseline*

Tooth-related Factors	Progressive Periodontitis Mean (SD)	Stable Periodontitis Mean (SD)	*p*-Value
Study sites			
CEJ to alveolar crest length. mm	1.9 (1.3)	3.0 (1.6)	<0.0001*
Overhanging restorations >1 mm	3%	8%	0.37
Distance of restoration margin to bone crest, mm	1.8 (2.1)	2.3 (2.3)	0.33
Interproximal contact to alveolar crest length, mm	5.3 (1.7)	5.1 (1.6)	0.50
Interproximal contact to alveolar crest length on adjacent tooth, mm	5.1 (1.6)	5.1 (1.5)	0.65
Width of ITP embrasure, mm	2.3 (1.0)	1.7 (0.6)	0.0016*
Severity of periodontitis bone loss			0.0011*
Normal (0-2 mm)	56%	25%	
Mild (2-4 mm)	35%	54%	
Moderate (4-6 mm)	7%	14%	
Severe (>6 mm)	1%	7%	
Lack of proximal contact	42%	15%	0.0006*
CEJ-CEJ angle, (degrees)	91.5 (34.5)	97.9 (32.1)	0.31
All posterior sites			
CEJ to alveolar crest length, mm	2.7 (0.8)	2.9 (0.7)	0.12
Severity of periodontitis bone loss			0.3743
Mild	87%	94%	
Moderate	13%	6%	
Severe	0%	0%	

Abbreviations: CEJ, cementoenamel junction; ITP, interproximal; SD, standard deviation.
** Statistically significant.*

Common systemic and behavioral risk factors among PM patients that have been reported[26-31] to be associated with progression of periodontal diseases appeared to show less impact on PP and PS groups than did local factors in the two-year follow-up period. However, there was a trend toward more PP in diabetic patients (p=0.13). Previous studies[28,32] have supported that poorly controlled diabetes acts as a risk factor in development of periodontitis and that long-term periodontal care provided in a clinical setting improves long-term glycemic control among individuals with type 2 diabetes. Working with the patient's physician may also modify glycemic control to reduce this risk factor. Unfortunately, most health questionnaires usually contain no information of hemoglobin A1C levels. This study reinforces that large populations with hemoglobin A1C information are needed to fully assess the impact of diabetes on mild-moderate periodontitis patients on PM.

It was interesting to notice that in our study more than 40% of patients at baseline did not realize that they had gum disease. This may reflect insufficient previous patient education. With a better understanding about their periodontal diseases, they may have better home care and compliance.

Currently, there are several risk factor assessment tools for the prevention of periodontitis progression based on long-term analysis. The majority of the tools are variations of a few basic approaches, in particular of the Periodontal Risk Calculator, PRC,[33] and of the Periodontal Risk Assessment, PRA,[34] using bone loss as one major parameter. The previous studies mainly focused on moderate to severe periodontitis patients. Our findings indicated

Table 4: *Tooth-related Risk Factors Without Systemic Risk Factors*

Factors	Without Diabetes PP/PS	Without Smokers	Without Diabetes, Osteoporosis, RA,and Smokers
CEJ to bone, mm	1.9/2.9 (p=0.0002)	1.8/3.0 (p<0.0001)	1.8/3.0 (p=0.0001)
CEJ to CEJ, mm	2.3/1.7 (p=0.0015)	2.3/1.7 (p=0.0014)	2.3/1.6 (p=0.005)
Lack of proximal contact, %	47/15 (p=0.0001)	45/15 (p=0.0005)	45/16 (p=0.003)

Abbreviations: CEJ, cementoenamel junction; PP, progressive periodontitis; PS, periodontitis stable; RA, rheumatoid arthritis.

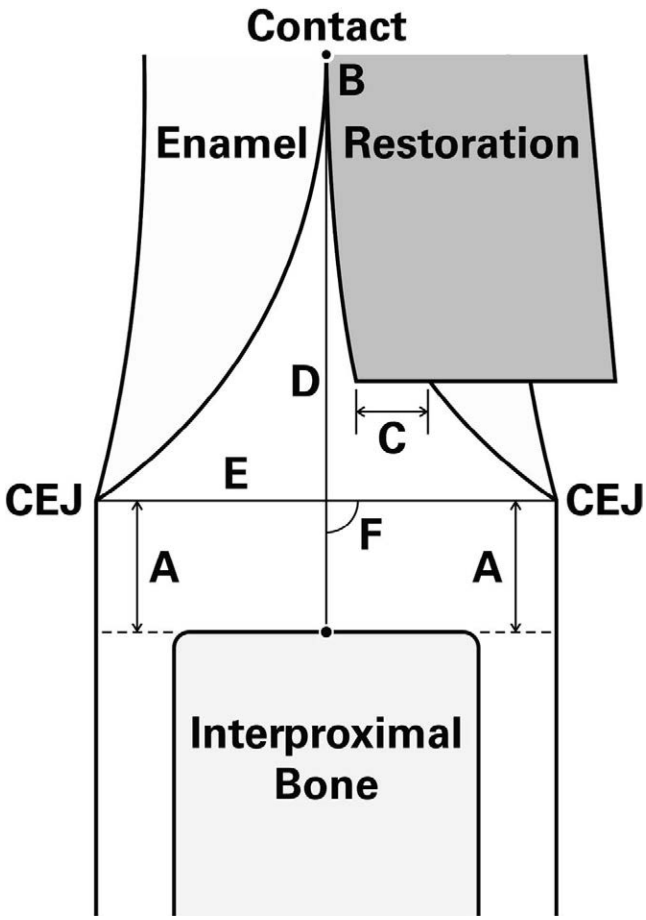

Figure 1. *Measurements for tooth-related factors. (A) CEJ to alveolar crest length; (B) Presence or absence of adjacent tooth contact; (C) Horizontal overhanging restorations of >0.25 mm; (D) Interproximal contact to alveolar crest length; (E) Width of CEJ to CEJ; and (F) CEJ to CEJ angle relative to long axis of the tooth.*

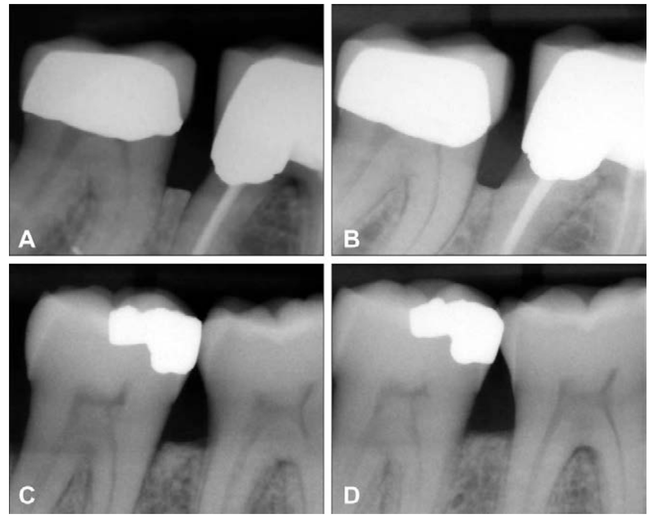

Figure 2. *Interproximal radiographic anatomy. Top panel shows molar-molar open interproximal contact and bone loss on #30 distal between baseline (A) and two years of periodontal maintenance (B). Bottom panel shows molar-molar contact and minimal molar interproximal bone change between baseline (C) and two years of periodontal maintenance (D).*

that for mild chronic periodontitis patients, bone loss and initial periodontitis severity may not be able to predict future bone loss and short-term progression of disease. Previous tools also used systemic risk factors and local soft-tissue measurements, but interproximal anatomy, as in Tables 3 through 5, was not analyzed.

Width of interproximal embrasure was wider in PP at baseline than in PS. Wider ITP may be caused by tipped teeth or open spaces between the studied tooth and adjacent tooth. Our results indicated that lack of interproximal contacts (open contact or missing tooth) played a larger role than did tipped teeth. This was true when patients with other major systemic risk factors (diabetes, osteoporosis, rheumatoid arthritis, and smoking) were removed from the analyses (Table 4). Further characterization of the interproximal anatomy of progressive periodontitis sites (Table 5) indicated that open contact that could promote food impactions (<2 mm) and those which were likely self-cleansing (>4 mm) were evenly distributed, suggesting that even wide-open interproximal areas would benefit from tooth replacement to help prevent interproximal periodontal bone loss.

Two-thirds of teeth in PP sites had restorations, most commonly cast crowns. However, horizontal overhangs were rare, especially large ones, which

Table 5: *Characterizing Interproximal Factors in Progressive Periodontitis (PP)*

Factor	Measurement	Percentage
Contact dimension	Closed	58
	Open <2 mm	20
	Open >4 mm	22
Type of restoration	None	33
	Amalgam	18
	Resin	3
	Cast crown	32
	PFM (porcelain-fused to metal)	12
	Chrome crown	2
Opposing plunger cusp	No	95
	Yes	5
Arch	Maxilla	59
	Mandible	41
Amount horizontal overhang	None	89
	0.25-1.0 mm	8
	>1 mm	3

have been shown[35] to contribute to periodontal bone loss. Likewise, the low incidence of plunger cusps did not seem to contribute to interproximal bone loss.

The relatively short period of follow up and the small sample size were limitations of our study, particularly in terms of analysis of systemic risk factors. However, interproximal periodontal anatomy easily measured on BWs showed highly significant difference in PP sites and suggests some restorative treatments to change the risk profile.

CONCLUSIONS

While PM patients with mild-moderate periodontitis are generally stable, they still should be followed closely for evidence of bone loss. Lack of interproximal contacts is related to the likelihood of losing interproximal bone during periodontal maintenance, suggesting the need for restorative therapy.

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Regulatory Statement

This study was conducted in accordance with all the provisions of the local human subjects oversight committee guidelines and policies of the University of Nebraska Medical Center IRB. The approval code for this study is IRB 015-14.

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

Effect of Different Adhesive Strategies and Time on Microtensile Bond Strength of a CAD/CAM Composite to Dentin

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Clinical Relevance

The use of a dual-cure activator is recommended when a universal adhesive system in self-etching mode is associated with an amine-based resin cement.

SUMMARY

Purpose: The aim of this study was to evaluate the effect of adhesive strategy and time on the microtensile bond strength of a computer-aided design/computer-aided manufacturing (CAD/CAM) composite to dentin.

Methods and Materials: Sixty CAD/CAM composite blocks were bonded to human dentin with simplified bonding agents using etch-and-rinse and self-etching approaches and amine-based and amine-free resin cements, with and without the application of a dual-cure activator (DCA; n=10): SBP-ARC (Adper Single Bond Plus + RelyX ARC), SBP-RXU (Adper Single Bond Plus + RelyX Ultimate), SBP-DCA-RXU (Adper Single Bond Plus + DCA + RelyX Ultimate), SBU-ARC (Scotchbond Universal + RelyX ARC), SBU-RXU (Scotchbond Universal + RelyX Ultimate), and SBU-DCA-ARC (Scotchbond Universal + DCA + RelyX ARC). Each specimen was light cured for 40 seconds under load and stored in distilled water at 37°C for seven days. Stick-shaped specimens (1.0 mm^2) were obtained. Half of the specimens underwent microtensile bond strength testing, and the other half were subjected to the same tests after six months of storage. Failure mode was determined using an optical microscope (40×). The data were analyzed by a two-way analysis of variance followed by the Games-Howell test and Student *t*-test (preset alpha of 0.05).

Results: After seven days, SBU-RXU presented the highest mean bond strength, statistically

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different from only SBU-ARC ($p<0.05$). Most of the groups exhibited a statistically significant reduction in bond strength after 6 months ($p<0.05$), except SBP-RXU and SBU-ARC ($p>0.05$).

Conclusion: The adhesive strategy, with different associations between adhesive systems and resin cements, as well as the use of a DCA, affected the bond strength of both amine-free and amine-based resin cements to a CAD/CAM composite.

INTRODUCTION

Adhesive cementation is a technique-sensitive, complex procedure involving the use of a bonding agent in conjunction with a resin cement that requires various clinical steps to ensure adequate bond strength to dental structures.[1] These materials must not only adhere to dental structures but also have specific mechanical (flexural and compressive strength) and optical properties (shade and opacity), as well good handling characteristics and clinically acceptable working time.[2]

The light intensity from the curing device may be attenuated or totally blocked, depending on the thickness, color, and opacity of the indirect restorative material.[3-5] Furthermore, polymerization activation depends on the wavelength and intensity of the light that reaches the material.[6,7] Hence, use of dual-cure adhesive systems in conjunction with dual-cure resin cements may be necessary for cementation of indirect restorations in areas where it is difficult or impossible for light to penetrate.[8]

In dual-cure systems, polymerization is initiated partly by the formation of free radicals produced by the chemical reaction between benzoyl peroxide and the tertiary amine and partly by light-curing activation, which depends on photons to excite the photoinitiator.[9] Although resin-based materials also contain tertiary aliphatic amines in the initiator system to ensure that free radicals are formed over a more extended period, these amines are not inactivated by acid monomers in simplified adhesive systems.[10,11] Self-cure and dual-cure resin-based materials that contain basic amines are incompatible with the high concentration of acidic monomers in simplified self-etching approach.[12] The interaction between the monomers and tertiary amine results in the latter being consumed, reducing the availability of free radicals for the polymerization reaction.[13] It has also been reported that single-step self-etch adhesive systems act as permeable membranes that allow water to diffuse through the interface, one of the leading causes of premature failure of the resin cement/dentin bond.[12,14] To avoid this problem, some self-etching adhesive systems contain dual-cure activators in their composition or as separate solutions to be mixed with the bonding agent before it is applied in cementation procedures.

With the increasing demand for a simpler and more versatile adhesive, a new type of adhesive system has emerged on the dental market that allows the clinician to choose the adhesive strategy and the number of steps used to treat the dental substrates. These so-called "universal" or "multi-mode" adhesive systems can be used in a conventional approach called "total etch" or "etch-and-rinse," in which both enamel and dentin are previously acid etched; in a "selective etching" approach, in which only the enamel is acid etched but the dentin is etched by the acidic monomers in the adhesive system; and in a "self-etch" approach, in which the acidic monomers etch and prime both enamel and dentin at the same time.[15,16] In addition to dimethacrylate monomers and acidic functional monomers, universal adhesive systems usually contain solvents, filler particles, and initiators. Some commercial brands include silane, allowing them to be used in indirect restorative procedures, such as cementation of ceramics, zirconia, indirect resins, and metal restorations.[17,18]

Scotchbond Universal Adhesive must be mixed with a dual-cure activator (Scotchbond Universal DCA, Dual-Cure Activator, 3M ESPE, St Paul, MN, USA) containing sodium p-toluenesulfinate and ethanol, when an amine-based resin cement is used. However, the manufacturer does not recommend its use with RelyX Ultimate cement, because it was developed with a redox system that uses sodium persulfate and tert-butyl peroxy-3,5,5-trimethylhexanoate to suppress adverse interactions between the adhesive system and dual-cure or chemically activated resin cements. As the cement already contains an activator that copolymerizes when it comes into contact with the adhesive layer, there is no need for additional activators (information provided by the supplier, 3M ESPE).

The effectiveness of dual-cure adhesive systems to bond posts and indirect restorations to dentin has been extensively studied in the literature, but the outcomes are controversial. One study showed that the bond strength of light-cure was superior to that of dual-cure adhesive systems (when a dual-cure activator was mixed) because the concentration of photoinitiator and functional monomers is reduced,

Table 1: *Experimental Groups Used in the Study*

Group	Adhesive Strategy		
	Bonding Agent	*DCA*	*Resin Cement*
SBP-ARC	Adper Single Bond Plus	No	RelyX ARC
SBP-RXU	Adper Single Bond Plus	No	RelyX Ultimate
SBP-DCA-RXU	Adper Single Bond Plus	Yes	RelyX Ultimate
SBU - RXU	Scotchbond Universal	No	RelyX Ultimate
SBU - ARC	Scotchbond Universal	No	RelyX ARC
SBU - DCA - ARC	Scotchbond Universal	Yes	RelyX ARC

adversely affecting the degree of conversion and bond strength to dentin.[8] However, the bond strength of dual-cure adhesive systems with dual-cure activators can be more uniform in different parts of the dental structure where the light is attenuated.[19] Further studies are therefore required to clarify the impact of a dual-cure activator on the effectiveness of simplified adhesive systems used in conjunction with dual-cure resin cements.

The aim of this study was to evaluate the effect of different adhesive strategies, including the addition of a dual-cure activator, and time on the microtensile bond strength of a computer-aided design/computer-aided manufacturing (CAD/CAM) composite to dentin using simplified total-etch and self-etching adhesive systems. The hypotheses to be tested were that 1) there would be no differences in bond strength of CAD/CAM composite to dentin when different adhesive strategies were used and 2) there would be no differences in bond strength between the groups after a seven-day or a six-month water storage.

METHODS AND MATERIALS

Sixty healthy human third molars were obtained from the tooth bank after the research protocol had been approved by the local Committee for Ethics in Research (No. 759.419). The teeth had been stored in 0.5% chloramine-T at 4°C for up to six months after extraction.

Preparation of the Teeth

The occlusal third of the crowns was removed with a precision sectioning cutter (Isomet 1000, Buehler, Lake Bluff, IL, USA) and a wafering diamond blade (Extec Corp, Enfield, CT, USA) under water cooling to expose the midcoronal dentin. The surfaces of the exposed dentin were wet polished with 600-grit SiC paper for 30 seconds and rinsed under running water for 60 seconds. The specimens were then gently air dried for three seconds so that the surface was slightly shiny. The teeth were randomly allocated to six groups (n=10) according to the adhesive system/resin cement combination used (Table 1). The materials used, their composition, and the procedures for application are shown in Table 2.

Pretreatment of the Indirect Restorative Material

CAD/CAM composite blocks (Lava Ultimate A2-HT, 3M ESPE) were sectioned with a diamond blade in a precision cutter to produce 3-mm-thick specimens with a 12-mm × 12-mm cross section. The upper surface of each slice was sandblasted with 50 μm alumina particles under a pressure of 2 bar for 10 seconds and then cleaned with distilled water in the ultrasonic bath for 10 minutes. A silane coating (RelyX Ceramic Primer, 3M ESPE) was applied for 60 seconds and then air dried for 5 seconds.

Bonding Procedures

The enamel and dentin surfaces were etched with 32% phosphoric acid (Scotchbond Universal Etchant, 3M ESPE) for 30 seconds and 15 seconds, respectively. The etchant gel was rinsed with water spray for 30 seconds, and excess moisture was removed by blotting with tissue paper. The total-etch bonding agent (Adper Single Bond Plus, 3M ESPE) was applied to the etched enamel and dentin surfaces with gentle agitation for 15 seconds using a fully saturated applicator and gently air dried for five seconds to evaporate the solvent. The universal adhesive system (Scotchbond Universal Adhesive, 3M ESPE) was applied using the selective enamel etch mode that relies on separate enamel etching and dentin self-etching. A 32% phosphoric acid was applied to the enamel for 30 seconds and rinsed with water spray. Any excess moisture was removed by blotting with tissue paper, keeping the dentin moist. A single coat of the bonding agent was applied to the dentin (and enamel) by rubbing it onto the surface for 20 seconds with a fully saturated disposable

Table 2: *Description of the Materials Used in the Study With Trade Names, Manufacturer, Composition, and Application Procedures*

Material Trade Name, Manufacturer (Batch No.)	Composition[a]	Application Mode[a]
Adper Single Bond Plus, 3M ESPE (N456049)	Bis-GMA, UDMA, HEMA, copolymer of acrylic acid and itaconic acid, silanized colloidal silica particles, ethanol, water, and photoinitiator	Etch enamel and dentin with 32% phosphoric acid for 30 s and 15 s, respectively, and rinse with water. Dry by blotting, keeping dentin moist. Rub one coat of adhesive onto the dentin surface for 15 s and air-dry gently for 5 s.
Scotchbond Universal, 3M ESPE (595105)	Bis-GMA, 10-MDP, dimethacrylate resins, HEMA, copolymer of acrylic and itaconic acids, silane-treated silica, ethanol, water, initiators, and silane	Etch enamel with phosphoric acid for 30 s and rinse with water, leaving the dentin slightly moist. Rub one coat of adhesive onto the dentin surface for 20 s and air-dry gently for 5 s.
DCA, Dual-Cure Activator, 3M ESPE (509461)	Sodium p-toluenesulfinate and ethanol	Mix a drop of co-initiator with a drop of Scotchbond Universal for 5 s and apply to the surface of the tooth for 20 s by rubbing; air-dry gently for 5 s to evaporate the solvent.
RelyX Ceramic Primer, 3M ESPE (N561569)	Methacryloxypropyltrimethoxysilane, ethanol, and water	Apply to resin nanoceramic for 1 min and air-dry for 5 s.
RelyX ARC, 3M ESPE (N545532)	Bis-GMA, TEGDMA, pigments, initiators, silica, and zirconia	Mix A and B pastes in equal quantities (two clicks) with a spatula for 20 s.
RelyX Ultimate, 3M ESPE (601450)	Base paste: silane-treated glass powder; 2-propenoic acid; 2-methyl-, 1,1′-[1-(hydroxymethyl)-1,2- ethanediyl] ester; reaction products with 2-hydroxy-1,3-propanediyl dimethacrylate and phosphorous oxide; TEGDMA; silane-treated silica; oxide glass chemicals; sodium persulfate; tert-butyl peroxy-3,5,5-trimethylhexanoate; and copper (II) acetate monohydrate Catalyst paste: silane-treated glass powder; dimethacrylate; silane-treated silica; 1-benzyl-5-phenyl-barbic-acid; calcium salt; sodium p-toluenesulfinate;1,12-dodecane dimethacrylate; calcium hydroxide; 2-propenoic acid, 2-methyl-,[3-methoxypropyl)imino]di-2,1-ethanediyl ester; and titanium dioxide	Mix A and B pastes in equal quantities (two clicks) with a spatula for 20 s.
Lava Ultimate 3M ESPE (N538333)	Inorganic phase: silica and zirconia nanoparticles (approximately 80% by weight) Organic phase: UDMA and Bis-EMA (approximately 20% by weight)	Sandblast with aluminum oxide for 10 s and clean in ultrasonic bath for 10 s. Apply RelyX Ceramic Primer for 1 min and air-dry for 5 s.

Abbreviations: 10MDP, 10-methacryloyloxydecyl dihydrogen phosphate; Bis-EMA, bisphenol A polyethylene glycol dimethacrylate; Bis-GMA, bisphenol A glycidyl methacrylate; HEMA, 2-hydroxyethyl methacrylate; TEGDMA, triethylene glycol dimethacrylate; UDMA urethane dimethacrylate.
[a] Data supplied by the manufacturer.

applicator and then gently air dried for five seconds or until the liquid no longer moved on the surface.

A single drop of the dual-cure activator was mixed during five seconds with a drop of the adhesive system for the groups SBP-DCA-RXU and SBU-DCA-ARC. The mixture was then applied to the dentin as described previously. The resin cements were handled according to the manufacturer's instructions and applied to the surface of the CAD/CAM composite blocks, which were then placed on the treated dentin under a constant seating force of 1 kg for one minute.[20,21] A light-emitting diode curing unit (Elipar FreeLight 2, 3M ESPE) with approximately 700 mW/cm^2 irradiance was activated for 40 seconds on the top and four sides of the specimen once the load had been removed, giving 200 seconds total activation time. The specimens were then stored in distilled water at 37°C for seven days.

Microtensile Bond Strength Testing

After storage, the specimens were sectioned in the x- and y-direction using a high-precision diamond saw (Extec Corp) in a precision cutter (Isomet 1000, Buehler) to obtain stick-shaped micro-specimens with a cross-sectional area of approximately 1 mm^2. Half of the micro-specimens underwent microtensile bond strength tests immediately after cutting, and the other half were stored in distilled water

Table 3: *Mean Values (±Standard Deviation) of Microtensile Bond Strength in MPa, Number of Specimens Tested (n), and Number of Pretesting Failures (ptf) in Each Group After Storage for Seven Days and Six Months*[a]

Group	7 d		6 mo	
	Mean ± SD	n/ptf	Mean ± SD	n/ptf
SBP-ARC	19.07 ± 8.25 aA	50/0	14.28 ± 6.51 aB	43/2
SBP-RXU	18.52 ± 11.06 abA	50/0	16.46 ± 8.17 aA	45/3
SBP-DCA-RXU	19.42 ± 10.37 aA	50/0	12.78 ± 7.33 aB	50/0
SBU-RXU	23.12 ± 10.94 aA	50/0	16.76 ± 7.20 aB	42/1
SBU-ARC	13.35 ± 6.32 bA	50/0	12.98 ± 8.28 aA	41/6
SBU-DCA-ARC	19.67 ± 10.19 aA	50/0	15.4 ± 8.90 aB	43/2

Abbreviations: SBP, Scotchbond Multipurpose; SBU, Scotchbond Universal; ARC, RelyX ARC; RXU, RelyX Utlimate; DCA, Dual-cure activator.
[a] *Different lowercase letters indicate significant differences in column ($p<0.05$). Different uppercase letters indicate significant differences in row ($p<0.05$).*

at 37°C and tested after six months. The thickness of the adhesive interface was measured with a digital caliper (Absolute Digimatic Caliper, Mitutoyo Corp, Kawasaki, Japan) to calculate individual areas of the specimens' interface. The specimens were fixed in a microtensile jig with a cyanoacrylate gel (Loctite 454 Gel, Henkel North America, Rocky Hill, CT, USA). Microtensile bond strength testing was performed in a universal test machine (Instron DL2000, Grove City, PA, USA) with a crosshead speed of 0.5 mm/min. The results in kgf were converted to MPa based on the cross-sectional area of each specimen.

Failure Mode Analysis

The failure mode for each specimen was determined using an optical microscope at 40× magnification (BX60, Olympus Corp, Tokyo, Japan) and classified according to the structures involved as follows: cohesive failure in the dentin, cohesive failure in the CAD/CAM composite, cohesive failure in the cement, adhesive failure between the dentin and cement, adhesive failure between the cement and the CAD/CAM composite, and mixed failure (two or more structures involved).

Scanning Electron Microscopy

The most representative failures of each group were selected for analysis using scanning electron microscopy (SEM). The fractured specimens were cleaned in an ultrasonic bath with distilled water for 15 minutes and kept in a vacuum desiccator with silica for seven days. They were then coated with Au-Pd alloy and examined under SEM at 300× and 1500× magnification (Vega 3, Tescan Orsay Holding, Brno, Czech Republic).

Statistical Analysis

Each tooth was considered a sampling unit, and the mean values for specimens from the same tooth were used to calculate the mean microtensile bond strength for the group in both storage times. The data were analyzed for normality with the Kolmogorov-Smirnov test and homogeneity of variance with Levene's test. Two-way analysis of variance ("adhesive strategy" and "storage time") was used followed by the Games-Howell post hoc test and for each possible comparison. Student *t*-test was performed to compare differences between group means at seven-day and six-month storage times. A significance level of 5% was used for all the tests. The data were analyzed in SPSS 24.0 (IBM Software, New York, NY, USA).

RESULTS

Statistically significant differences were observed for the factors "adhesive strategy" and "storage time" ($p<0.05$), but no significant interaction was found between the factors ($p= 0.096$).

The mean microtensile bond strength, number of specimens tested, and number of pretest failures for each group are shown in Table 3.

After seven days, the lowest bond strength was observed for the SBU-ARC group, which did not differ statistically from SBP-RXU ($p>0.05$). After six months, there was no statistically significant difference in bond strength between any of the groups ($p>0.05$). Most of the groups exhibited a statistically significant reduction in mean bond strength between the seven-day and six-month assessments ($p<0.05$), except SBP-RXU and SBU-ARC ($p>0.05$).

Although there were no pretest failures after seven days, after six months all the groups except SBP-DCA-RXU exhibited this type of failure. When a pretest failure occurred, a value of zero was assigned to the specimen when the mean for the tooth in question was calculated.

The frequency distributions of the failure modes for each group expressed as a percentage of the total number of specimens in the group after seven days

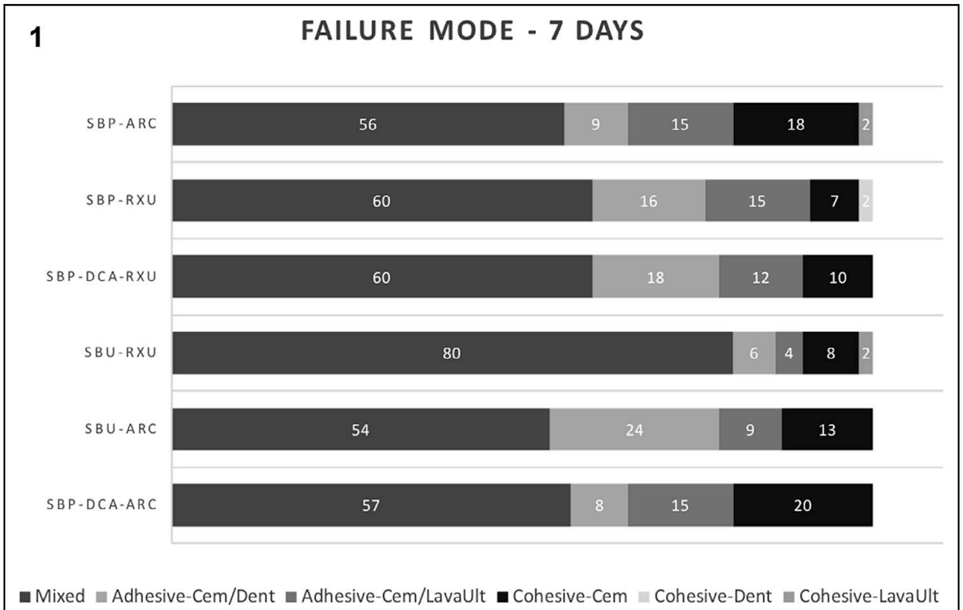

Figure 1. *Failure mode distribution (%) for the groups after seven days.*

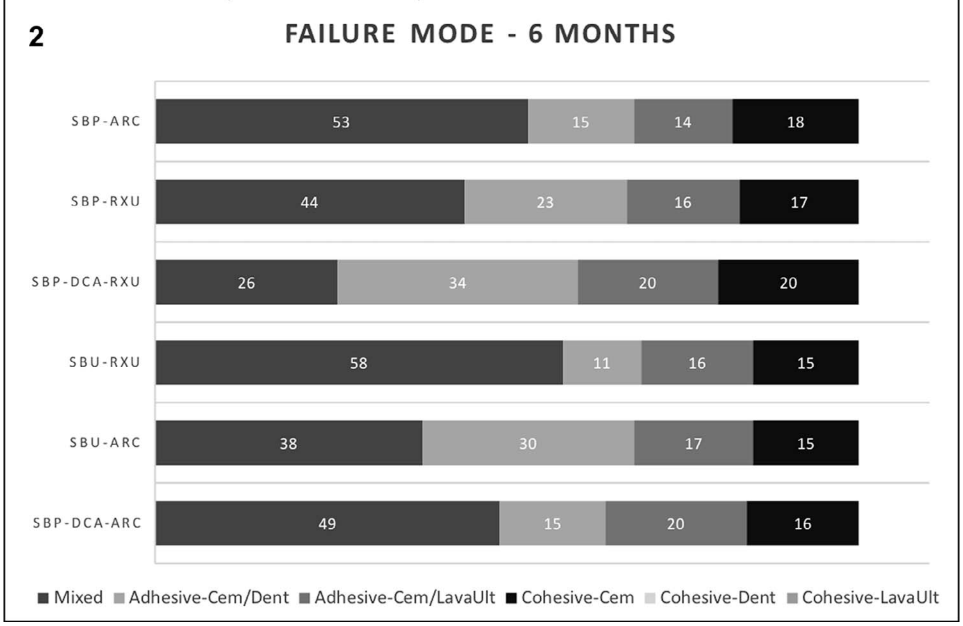

Figure 2. *Failure mode distribution (%) for the groups after six months.*

and six months are shown in Figures 1 and 2. The most common type of failure in all the groups at both time points was the mixed failure when more than two structures were involved. Adhesive failures between the cement and dentin and cohesive failures in the cement were more common after six-month water storage. Figures 3 to 8 demonstrate the most frequently type of failures found in the tested groups with detailed images of the adhesive interfaces.

DISCUSSION

This study aimed to assess the effectiveness of a dual-cure activator used with a conventional total-etch or a universal adhesive system with self-etching approach and two different resin cements, one of which was based on a new redox system and amine free. An unbalanced factorial model was used for the analysis. In two groups (SBP-ARC, SBU-RXU), the manufacturer's standard recommendations were followed, and in the remaining groups, the adhesive system and resin cement were used with and without a dual-cure activator. The classic combinations were not subjected to the use of dual-cure activator because there is no recommendation for this additional step.

Both study hypotheses were rejected as there were differences in bond strength to dentin between the groups after seven days, and in one group, the mean bond strength after six months of storage in water was significantly lower than that after seven days.

Bonding using a self-etching technique is based on two mechanisms: micromechanical interlocking (monomer penetration in interfibrillar spaces) and chemical interaction between acidic functional monomers and hydroxyapatite.[22] With this mode, the bonding procedure is faster and less critical because it does not involve moisture control, unlike techniques that require the etching to be performed beforehand.[23] Scotchbond Universal Adhesive contains the functional monomer 10-MDP, which promotes chemical interaction with the calcium in the dental structure,[24,25] making bonding more hydrolytic stable.[26,27] Recent studies have shown that this adhesive provides higher bond strength when used in self-etch mode on dentin.[13,28-30]

In the present study, the bond strength of the self-etch universal adhesive system used with the amine-free dual cement (SBU-RXU) was not statistically different from that obtained with the conventional adhesive system used in total-etch mode with the amine-containing resin cement (SBP-ARC). Both groups represented classic approaches recommended by the manufacturer. However, when the materials were switched (SBU-ARC and SBP-RXU), without the use of a dual-cure activator, the bond strength was reduced. The lower mean bond strength observed for the SBU-ARC group after seven days may be a result of the interaction between the acidic monomers in the self-etch mode adhesive system and the tertiary amine in the conventional resin cement.[12,31] This interaction may lead to amine consumption reducing the extent and rate of polymerization and increasing premature bonding failures to dentin, as reported in previous studies.[14,32]

Although the recommended combinations of adhesive systems and resin cements tested in groups SBP-ARC and SBU-RXU were effective after seven days, the bond strength was reduced after six months of water storage. This finding may be a result of increased water sorption and the following

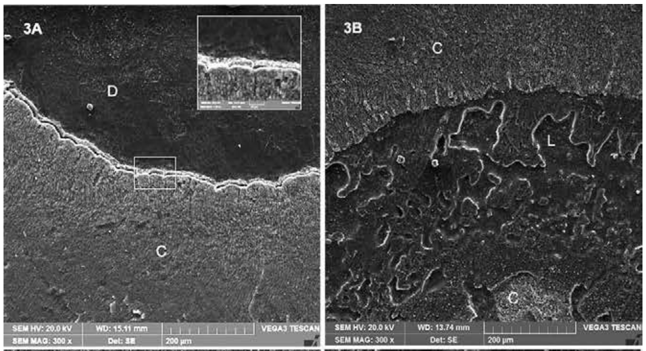

Figure 3. *(A*): Specimen from group SBP-ARC showing mixed failure with dentin (D) and resin cement (C) exposure after seven days. (B): Counterpart of the same specimen showing resin cement (C) remaining on the CAD/CAM composite surface (L).*

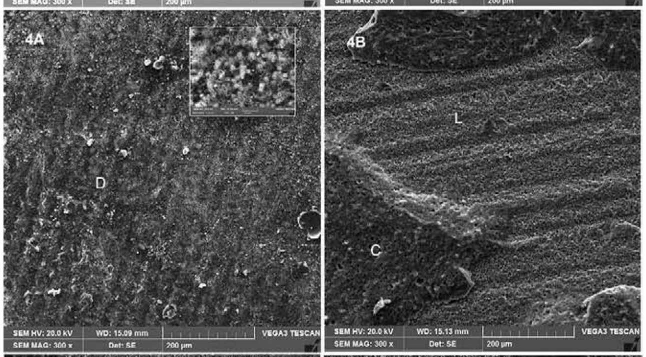

Figure 4. *(A*): Specimen from group SBP-RXU showing mixed failure with dentin (D) exposure after seven days. (B): Counterpart of the same specimen showing resin cement (C) remaining on the CAD/CAM composite surface (L).*

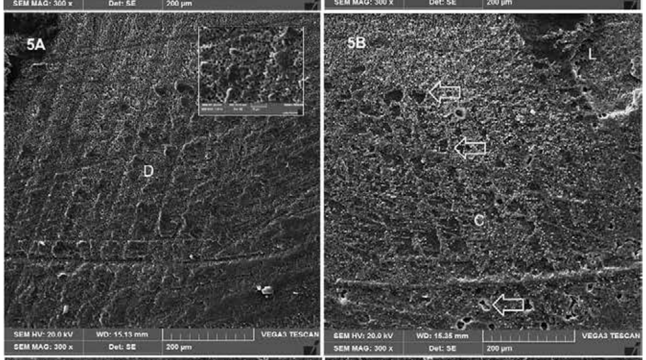

Figure 5. *(A*): Specimen from group SBP-DCA-RXU showing adhesive failure with dentin (D) exposure after six months. (B): Counterpart of the same specimen showing voids and porosities (arrows) in the resin cement (C) and areas of CAD/CAM composite exposure (L).*

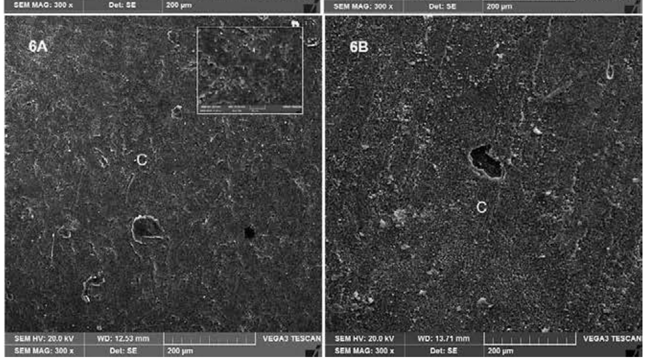

Figure 6. *(A*): Specimen from group SBU-RXU with a cohesive failure in the resin cement layer (C) after six months. (B): Counterpart of the same specimen showing the resin cement (C) covering the CAD/CAM composite surface.*

** Inset is 1500x.*

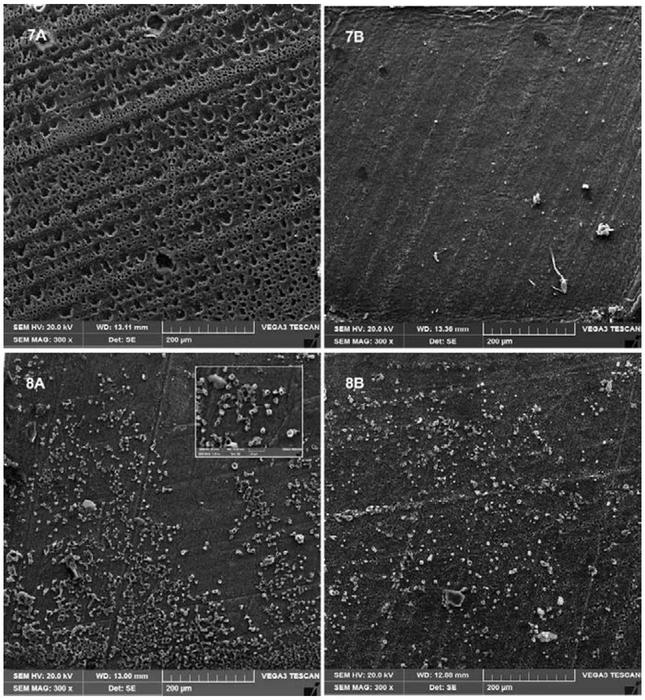

Figure 7. *(A): Specimen from group SBU-ARC showing adhesive failure with voids and porosities in the adhesive interface after seven days. (B): Counterpart of the same specimen with the CAD/CAM composite surface free of resin cement.*

Figure 8. *(A*): Specimen from group SBU-DCA-ARC with adhesive failure showing voids on the dentin surface (D) after seven days. (B): Counterpart of the same specimen showing the CAD/CAM composite surface with remnants of resin cement.*

** Inset is 1500x.*

solubilization of resin monomers causing breakdown of the polymer chains.[33,34] This failure could also occur because sometimes adhesive systems do not fully infiltrate the exposed collagen mesh and the solvent (in this case ethanol) fails to volatilize completely, adversely affecting dentin bond strength.[35]

In the present study, all of the groups with the amine-free resin cement had similar results independently of the adhesive system and whether or not a dual-cure activator was used. The association between Scotchbond Universal Adhesive in the self-etch mode and RelyX Ultimate (SBU-RXU) achieved the highest short-term bond strength. This association combines the low technique sensitivity of the bonding approach with the convenience of dispensing the use of a dual-cure activator to improve polymerization. When the activator inside RelyX Ultimate comes into contact with the Scotchbond Universal adhesive layer, it ensures adequate polymerization of the adhesive, even without light. Recent studies have shown the superiority of this combination over other resin cement systems.[20,21,36-40]

The effect of dual-cure activators on polymerization of dual-cure resin cements has been the subject of much research in the past decade.[3,11,13,19,41-45] Some studies[13,42,46,47] have shown that dual-cure activators have a limited effect on the degree of conversion of chemically activated adhesive systems and argue that the effectiveness of polymerization in dual-cure systems is highly dependent on the adhesive system used.[42,43] Moreover, the higher acidic monomer content in the partially polymerized adhesive layer can interfere with the amine in the chemically cure systems, potentially resulting in less amine being available for the polymerization process even when dual-cure activators are used.[42]

Scotchbond Universal is considered a mild self-etch adhesive with a pH of 2.7,[25,48] which reaches 2.9 after the dual-cure activator is added.[49] According to the manufacturer, the dual-cure activator (pH=7) was developed to optimize copolymerization with self-cure and dual-cure resin cements, other than RelyX Ultimate. Indeed, the results of this study show a significant increase in bond strength when the dual-cure activator was used with the universal adhesive and the amine-containing resin cement compared with that of the same combination but without the dual-cure activator (SBU-ARC). The group SBP-DCA-RXU was tested to evaluate whether the dual-cure activator would improve the performance of the two-step total-etch adhesive with the amine-free resin cement. However, although the results for this group were similar to those for the group with the same adhesive and resin cement without the dual-cure activator (SBP-RXU) after seven days, the results for that group were significantly worse after six months. This was confirmed by the SEM analysis, having disclosed porosities in the cement surface (Figure 5B) probably as a result of an increase in the amount of residual solvent at the interface, which can dilute the functional monomers and affect the long-term bonding performance.[34]

In the present study, although the CAD/CAM composite blocks with a mean thickness of 3 mm undoubtedly attenuated the light, this attenuation was probably made up for by the longer light-curing time (200 seconds) and the five different positions in which the light-curing unit was held for each specimen. Also, polymerization of the adhesive system and the resin cement was carried out simultaneously to avoid problems with poor seating of indirect restorations due to a thicker adhesive film.[50,51] Although recent studies have shown that light-curing of the adhesive system before application of the resin cement can be decisive in determining the dentin bond strength of indirect restorations,[20,21] it should be pointed out that this procedure can be used only when the adhesive is very thin, so the fit of the restoration is not affected.

Observation of the failure modes after the microtensile bond strength tests revealed a large number of mixed failures in all the tested groups. After six months of water storage, there was an increase in the number of adhesive failures possibly as a result of degradation of the exposed adhesive interface by water inflow, leading to hydrolysis of collagen fibers. The observation of voids and porosities (Figures 7A, 8A) appeared to indicate that water reached the interface and inhibited the polymerization of resin components, affecting the bond strength.[33,34,52]

Adequate selection of materials in adhesive cementation is fundamental to ensure clinical success of indirect restorations and should be based on their chemical composition and compatibility, as well as on their mechanical and optical characteristics. The manufacturers' recommendations should be followed strictly by the clinician since some associations between adhesive systems and resin cements are not compatible and could jeopardize the effectiveness of the cementation procedure.

CONCLUSIONS

Within the limitations of this *in vitro* study, it can be concluded that the adhesive strategy, with different associations between adhesive systems and resin cements, as well as the use of a dual-cure activator, affected the bond strength of both amine-free and amine-based resin cements to a CAD/CAM composite.

Regulatory Statement

This study was conducted in accordance with all the provisions of the local human subjects oversight committee guidelines and policies of approval of the Research Ethical Committee of PUCPR. The approval code for this study is 759.419.

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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Ferrule Design Does Not Affect the Biomechanical Behavior of Anterior Teeth Under Mechanical Fatigue: An *In Vitro* Evaluation

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Clinical Relevance

The presence of the ferrule and the uniformity of the ferrule might not affect the fracture resistance and failure mode of fiber-post retained composite restorations of anterior teeth.

SUMMARY

Objectives: To investigate the survival and failure mode of fiber-post resin restorations over preparations with different ferrule designs when submitted to a fatigue load test.

Methods and Materials: Fifty bovine incisors were selected and divided into five groups (n=10) according to ferrule design: a no-ferrule group, a 2-mm circumferential ferrule group, a 2-mm buccal ferrule group, a 2-mm lingual ferrule group, and a 2-mm buccal and lingual ferrule group. The fiberglass post was cemented and the composite core was built up and prepared, followed by cementation of a full composite crown. The samples were subjected to a cyclic fatigue test with loading applicator at 135°; a staircase approach was used until fracture. Survival (cycles to fracture) and failure modes were recorded. Survival data were analyzed with the log-rank test, while Kruskal-Wallis and Fisher exact tests were used to analyze failure mode data (α=0.05).

Results: The median number of cycles to fracture ranged from 215,000 to 236,153. The log-

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rank test showed no statistically significant difference in survival rates among the groups (*p*=0.82). Regarding failure mode, three types were observed: I, post and/or core fracture; II, root fracture in the cervical third; and III, root fracture in the middle third. No statistical difference was observed among the groups (Kruskal-Wallis test, *p*=0.147).

Conclusion: The ferrule design had no effect on fatigue resistance or failure mode of endodontically treated incisor teeth restored with a fiber post, composite core buildup, and composite crown.

INTRODUCTION

The amount of remaining, sound coronal tissue has been reported as an important factor affecting the biomechanical behavior of post-retained restoration of endodontically treated teeth.[1] When a considerable amount of remaining coronal dentin is preserved, a 360° collar surrounding the parallel walls of dentin and extending coronally to the shoulder of the preparation can be used. This is called the ferrule effect,[2] which protects the root from fractures by reducing the stress concentration generated by masticatory function.[3]

A recent systematic review and meta-analysis of *in vitro* studies demonstrated the protective effect that a complete circumferential ferrule provides to endodontically treated teeth.[4] It enhances fracture resistance and, depending on its height, prevents unrepairable or catastrophic failures, which determines the tooth's extraction.[5] Unfortunately, it is not always possible to prepare the complete circumferential ferrule when restoring endodontically treated anterior teeth, mainly because of significant tooth structure loss, especially in the proximal areas. However, a partial ferrule might be better than the complete absence of a ferrule.

Previous studies assessing the effect of a partial ferrule upon the biomechanical properties of endodontically treated teeth have shown controversial results.[6-13] Some studies have reported that a partial ferrule, on the lingual/palatal side of the root, results in higher fracture resistance when compared with a complete circumferential ferrule.[6-9] A recent investigation has demonstrated that a complete 2-mm ferrule provides higher fracture resistance than a ferrule missing on a single proximal; however, this missing wall can be compensated for if more than 3 mm of the height of the remaining walls can be preserved.[10] Another recent finite element study has also demonstrated that a uniform ferrule tends to be more favorable than a localized higher ferrule in anterior endodontically treated teeth.[11] Conversely, others have reported that ferrule location had no significant effect on fracture resistance. It should be noted, however, that the presence of a ferrule is always associated with a more favorable failure mode.[12,13]

In addition to conflicting results, another issue must be taken into account when analyzing these studies. All studies using static loading test arrangements test the maximum load capability of the tooth.[14] However, static loading is poorly correlated to clinical situations and hence not clinically relevant. On the other hand, tests in which a subcritical dynamic (cyclic) load is applied yield the fatigue phenomenon, which better reproduces biomechanical clinical situations. Some *in vitro* studies have reported a positive effect of ferrule on the biomechanical behavior of post-restored teeth under a fatigue load.[15-17] However, until now, there have been no studies—to the best of the present authors' knowledge—that have investigated ferrule design under any dynamic loading protocol.

Therefore, the objective of this study was to assess the effect of ferrule design on the fatigue resistance and failure mode of endodontically treated bovine incisors restored with fiberglass posts, composite core buildups, and all-composite crowns. The tested hypothesis was that ferrule design does not affect the fatigue resistance and the failure mode of endodontically treated incisors restored with fiberglass posts, composite core buildups, and all-composite crowns.

METHODS AND MATERIALS

Fifty bovine incisors with similar dimensions were randomly selected and cleaned with a hand scaler. The dimensions and shapes of the bovine roots used were similar to those found in human maxillary central incisors.[18] The teeth were analyzed using 4× loupe magnification (Stemi 2000-C, Carl Zeiss, Gottingen, Germany) and were free of fractures or cracks. The buccal-lingual and mesiodistal widths were measured, and the mean widths of teeth were calculated. Teeth presenting widths deviating more than 10% from the average were replaced. The crowns were removed, resulting in 17-mm-long roots, which were numbered from 1 to 50 (by the generation of five random sequences of 10 numbers[19]) and allocated to be prepared according to ferrule design. The incisors were thus divided into five groups: NF, teeth with no ferrule (15-mm-length

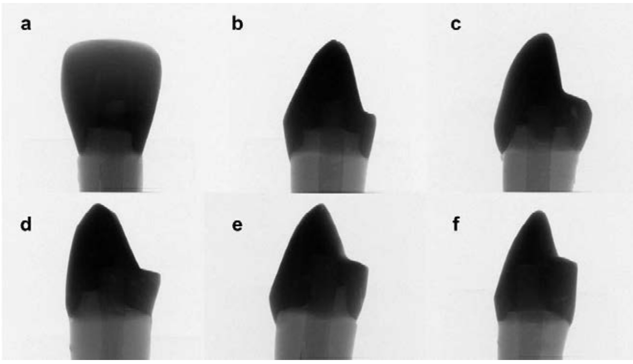

Figure 1. *Images of specimens used in the present study obtained by micro computed tomography illustrating the ferrule designs. (a): Complete ferrule, buccal view. (b): Complete ferrule, lateral view. (c): Ferrule on the buccal and lingual sides. (d): Ferrule only on buccal side. (e): Ferrule only on lingual side. (f): No ferrule.*

root); CF, teeth with a 2-mm circumferential complete ferrule; BF, teeth with a 2-mm ferrule only on the buccal side of the root; LF, teeth with a 2-mm ferrule only on the lingual side of the root; and BLF, teeth with a 2-mm ferrule only on the buccal and lingual sides of the root.

Root canal treatment was performed starting with No. 2 and 3 Gates Glidden drills (Dentsply Maillefer, Ballaiges, Switzerland) in the cervical and middle thirds of roots and with K-files (Dentsply Maillefer, Ballaiges, Switzerland) in the apical third of the root, limited to 1 mm short of the apex. The canals were rinsed with a 2.5% sodium hypochlorite solution and filled with gutta-percha points (Dentsply Maillefer) and calcium hydroxide–based cement (Sealer 26; Dentsply, Petrópolis, RJ, Brazil) using a lateral condensation technique. Each root was then embedded in a self-polymerized acrylic resin (VIPI Flash, VIPI, Pirassununga, Brazil) cylinder. Roots in the NF group were embedded 2 mm below the cervical limit, while the others were embedded 4 mm below. The periodontal ligament was simulated by using polyether impression material[20] (Impregum Soft; 3M ESPE, St Paul, MN, USA).

Teeth with a length of 17 mm were demarcated 2 mm below the cervical limit to enable the preparation of a 2-mm circumferential ferrule with a diamond bur No. 4137 (KG Sorensen, Barueri, SP, Brasil). The cervical tooth preparation was performed by using a half diameter of the diamond bur, resulting in a 1-mm-thick round cervical limit and 2-mm ferrule height. A flat end diamond bur No. 3131 (KG Sorensen, Barueri, SP, Brazil) was used to reduce the ferrule buccally, palatally, or biproximally, according to the desired design. BF group teeth had their ferrule reduced on their lingual side, LF group teeth had it reduced on their buccal side, and BLF group teeth had it reduced on both proximal sides (Figure 1). After ferrule preparation, the gutta-percha filling was partially removed with warm endodontic pluggers (SS White Duflex, Rio de Janeiro, Brazil), leaving 5 mm of gutta percha apically. The Largo drill No. 5 (Dentsply-Imp, Indústria e Comercio Ltda, Petrópolis, RJ) and Exacto specific drill No. 3 (Angelus, Londrina, PR, Brazil) were used for post space preparation. A prefabricated fiberglass post (Exacto No. 3, Angelus, Londrina, PR, Brazil) was etched with hydrogen peroxide[21] and cemented into the root canal with self-adhesive resin cement (RelyX Unicem 2, 3M ESPE). Composite resin cores (Filtek Z-350, 3M ESPE) were built up and standardized for each tooth as described by da Silva and others.[18] All teeth were prepared with a 1.5-mm axial reduction and 6° of axial convergence using a diamond bur No. 4138 (KG Sorensen), so all teeth remained with a 6.0-mm-height composite core. A high-speed handpiece with air-water spray was used in all preparations.

Impression of the coronal portion of the specimen was taken using a two-step technique involving condensation silicone impression material (Clonage, DFL, Rio de Janeiro, Brazil). After one hour, the impressions were poured with type IV stone (GC Fujirock EP, GC America, Alsip, IL, USA). Standardized composite crowns with a circumferential thickness of approximately 1.5 mm and a lingual stop of 1 mm to facilitate the load application were fabricated directly over the stone molds with a light-cured nanohybrid composite (Filtek Z-350 XT 3M) using the modified technique described by Krejci and others.[22] The composite crowns were then air abraded using 50-μm aluminum oxide particles (aluminum oxide; Pasom, Mairiporã, SP, Brazil) for 10 seconds, treated with a one-bottle silane coupling agent (Silano, Angelus Science and Technology, Londrina, Brazil) for one minute, and, finally, adhesively luted to the preparation using a self-adhesive resin cement (RelyX Unicem, 3M ESPE).[23]

For mechanical cycling, the specimens were submitted to an accelerated fatigue-testing protocol.[24,25] They were loaded one at a time in an MTS servo-hydraulic testing machine (Bionix, servohydraulic test system) at an angle of 135° to the long axis of each tooth. Cyclic isometric loading was applied on the palatal surface of the crown using a round-shaped metallic tip (Figure 2). A frequency of 2 Hz was used, starting with a load of 50 N for 5000 cycles (preconditioning phase), followed by stages of

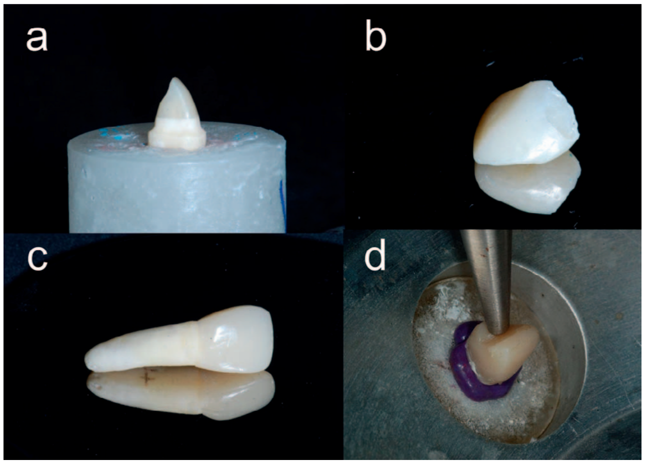

Figure 2. *Specimen build up and testing. (a): Specimen with complete ferrule and core in composite inserted into resin cylinder. (b): All-composite crown. (c): Restored tooth. (d): Loaded application over the lingual surface of specimen.*

100 N, 150 N, 250 N, 350 N, 450 N, and 550 N at 70,000 cycles each. For the survival analyses, the number of cycles it took for the specimens to fail were recorded. After each set of 70,000 cycles, the specimens were evaluated for the presence of cracks in the root and/or the restoration by a calibrated operator (50× magnification, DM2500, Leica Microsystems, Wetzlar, Germany). If there was still no failure observed, the specimen was loaded again for the next 70,000-cycle round. For each root, the test was carried out until failure. When failure occurred, the specimens were analyzed under a stereomicroscope (50× magnification, DM2500, Leica Microsystems) to determine the failure mode.[26] The failures were classified as I, post and/or core fracture; II, root fracture in the cervical third; III, root fracture in the middle third; IV, root fracture in the apical third; and V, vertical root fracture. In addition, the failure mode was dichotomized; specimens presenting types I and II were classified as reparable or favorable, whereas specimens that presented class III, IV, or V were classified as irreparable or unfavorable fractures.

Survival rates were estimated by Kaplan-Meier, and the log-rank test was used to detect any differences between groups. The Kruskal-Wallis test was used to detect any failure pattern differences, while Fisher exact test was used to test if the ferrule design was associated with failure mode (favorable or unfavorable). RStudio software (2016) version 1.0.136 was used, and the significance level was set at $\alpha=0.05$ for all analyses.

Table 1: *Median Number of Cycles to Failure and Corresponding Survival Rate*

Group	Median (95% LCI)	Survival Rate, % (SE)
No ferrule	215,220 (145,008)	40% (0.15)
Without ferrule	215,000 (215,000)	40% (0.15)
Buccal ferrule	236,153 (215,000)	50% (0.15)
Lingual ferrule	215,002 (215,000)	40% (0.18)
Bucco-lingual ferrule	215,000 (191,134)	40% (0.15)
Complete ferrule	215,220 (145,008)	40% (0.15)

Abbreviations: LCI, lower bound confidence interval (since all tests went on until a fracture occurred, the upper bound of the confidence interval is not calculated); SE = standard error.

RESULTS

Table 1 shows the median number of cycles to fracture for all groups, as well as their corresponding survival rates. Kaplan-Meier survival estimates for each group are presented in Figure 3. Differences were not statistically significant (log-rank test, $p=0.82$). Only three types of failures (types I, II, and III) were observed. Figure 4 shows the distribution according to ferrule design. Differences were not statistically significant (Kruskal-Wallis test, $p=0.147$). Furthermore, ferrule design was not associated with a difference in proportion between reparable/irreparable failures (Fisher exact test, $p=0.48$). Qualitative analyses of failure mode showed that most root fractures occurred on the proximal side of the root. Some fractures seemed to start at the proximal side, extended 2 to 3 mm apically, then changed direction toward the buccal side of the root and ended at the opposite proximal side (Figure 5).

DISCUSSION

Regarding the biomechanical behavior of endodontically treated bovine incisors with post-retained restorations, we found that an incomplete ferrule design does not affect the fatigue resistance and failure mode. Therefore, both hypotheses of this study were accepted.

To the best of our knowledge, this was the first study to use an accelerated fatigue testing protocol and survival analyses to investigate the effect of incomplete ferrule designs on mechanical resistance of post-retained restorations. It has been stated that this methodology results in stronger correlation between *in vitro* fatigue testing findings and clinical outcomes than others using static loading.[27,28] In addition to being well-related to clinical conditions, the accelerated fatigue method has other advantag-

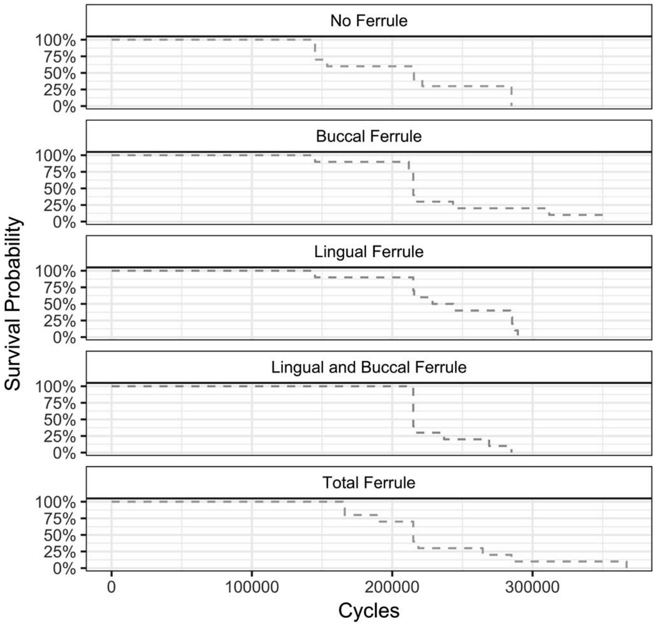

Figure 3. *Kaplan-Meier survival estimate. Note the similarity of curves among the experimental groups.*

es: it shortens the test time and, consequently, decreases costs. Furthermore, it can simulate the accelerated life cycle of the restored tooth, which could be impossible with other fatigue-testing methods because the tooth or post restoration might not fail if loaded below its endurance limit.[23]

Because most *in vitro* studies reported a positive effect of ferrule on the biomechanical behavior of post-restored teeth,[4,15-17] we expected to find a difference in survival at least between the complete circumferential ferrule and the no-ferrule groups. It can be speculated that the positive effect of ferrule was not demonstrated in the present study because of the reduced sample size used and the high data variability. However, data suggest that these factors may not be the main reason behind the findings of the present study. The observed effect size was very low for both the number of cycles to failure and the survival rate. For the former, the biggest median number of cycles to failure difference was 21,153 cycles, which occurred between the LF (236,153 cycles) and the CF and BLF groups (215,000) cycles. For the latter, the largest survival rate group difference was 10%. Other studies that reported statistically significant differences had much larger effect sizes. Ma and others[16] reported a statistical difference between no-ferrule, 0.5-mm ferrule, and 1-mm ferrule designs with an effect size that varied from 154,925 load fatigue cycles (mean difference between no-ferrule and 0.5-mm ferrule groups) to 262,659 cycles (mean difference between no-ferrule

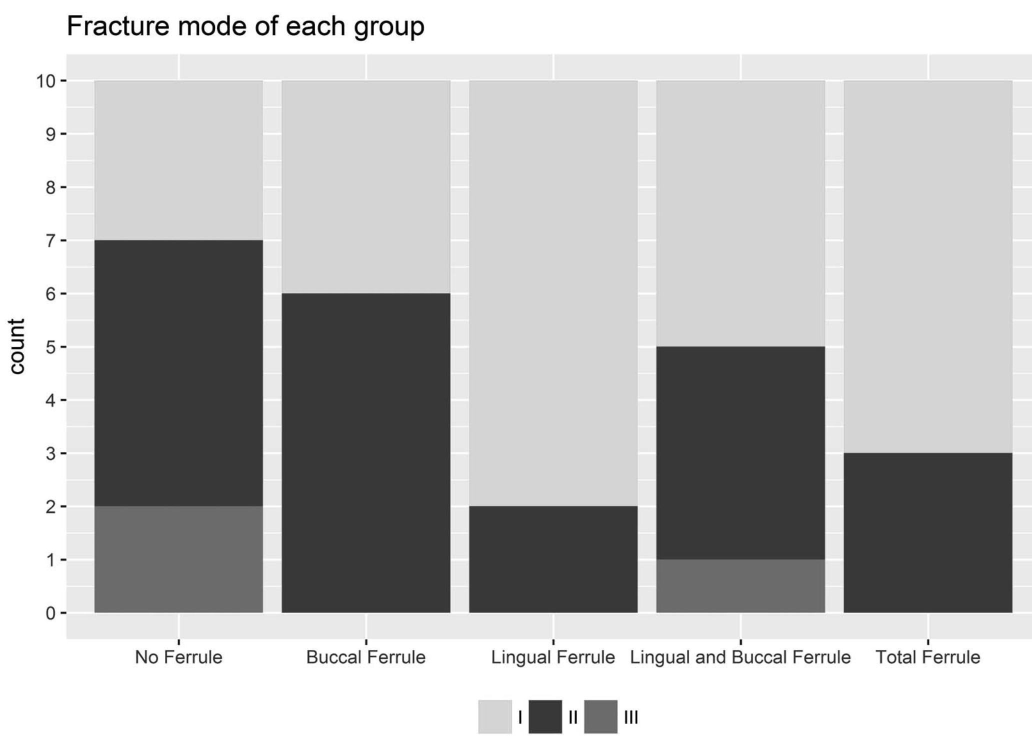

Figure 4. *Distribution of failure modes according to ferrule design. I, post and/or core fracture; II, root fracture in the cervical third; III, root fracture in the middle third.*

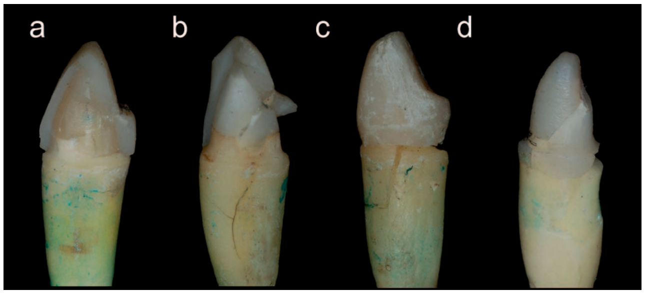

Figure 5. *Representative figures of fracture modes. (a): Fracture involving crown and core. (b): Fracture involving crown, core, and root, vertically until medium third. (c): Fracture of root starting at the proximal side and extending to buccal surface toward medium third. (d): Fracture of core with slight involvement of cervical third of root at lingual surface.*

and 1-mm ferrule groups). Libman and Nicholls[15] also reported a statistically significant effect of ferrule upon the fatigue resistance of post-restored teeth, with their smallest effect size being 70,511 cycles to failure (mean difference between 1-mm ferrule and 2-mm ferrule).

Another factor that may help to explain both the survival rate and the failure mode results is the use of adhesively luted all-composite crowns and fiberglass posts.[10] Fiberglass posts with a similar elastic modulus to dentin improve the stress distribution along the root, while more rigid post systems are usually associated with higher stress concentration areas—normally at the cervical area—that are prone to result in unfavorable failure modes.[29] Similarly, all-composite crowns have a similar elastic modulus to dentin, which may have further contributed to a better distribution of stress on the fiberglass post–restored tooth. An important advantage of fiber posts is the possibility of building up direct restoration with composite because this procedure reduces the cost of treatment when compared with using indirect restorations. Because this approach presents similar biomechanical behavior to indirect composite crowns, we chose to use indirect restorations in this study to standardize the restorative procedures and reduce the risk of bias. Therefore, we believe that using only restorative materials with a similar elastic modulus to dentin and adhesively integrated to the remaining tooth structure might strongly explain the findings observed in the present study. It is important to emphasize that an important advantage of using fiber posts is that they enable restoration of the extensively destroyed tooth using composite, and this approach reduces the number of sessions required to end the restorative procedure as well as the cost of treatment.

Because there is a lack of studies evaluating incomplete ferrule designs and adhesively luted composite crowns, comparisons with other studies is difficult. A recent systematic review and meta-analysis regarding the ferrule effect of both *in vitro* and clinical studies reported that the presence of ferrule was not related to higher survival of incisor and molar teeth, which is in accordance with our results.[4] On the other hand, premolar survival was positively influenced by the presence of ferrule in clinical studies. Another observation is that ferrule enhanced the fracture resistance of all types of teeth in several *in vitro* studies. Again, this discrepancy may be due to the fact that the *in vitro* studies used static loading, while the teeth were submitted to a cyclic load in our study, better simulating the clinical conditions. Other studies that also investigated incomplete ferrules on incisor teeth reported that a palatal ferrule effectively enhanced the teeth's fracture resistance (with better results than a circumferential ferrule).[6-8] Conversely, other studies reported no difference regarding ferrule designs.[12,13] It is important to emphasize that all these studies used a static loading setting, and these differences in experimental setup can strongly affect the results.

Despite being time-consuming and expensive, cyclic tests are important because they better simulate oral conditions. A possible limitation of our study design is the fact that the test was performed under dry conditions; the presence of humidity, which would make the conditions even closer to that of the oral environment, might influence the biomechanical behavior of endodontically treated teeth. Therefore, more mechanical fatigue studies—with different post systems and/or types of crowns, on different types of teeth, and under conditions closer to those of the oral cavity—are needed to better elucidate the effect of incomplete ferrule designs on the biomechanical behavior of post-retained restorations.

CONCLUSION

Within the limits of the present study, we conclude that the ferrule design does not affect the biomechanical behavior of endodontically treated incisor teeth restored with fiberglass post–retained restorations under cyclic loading.

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Regulatory Statement

This study was conducted in accordance with all the provisions of the local human subjects oversight committee guidelines and policies of approval of the Federal University of Sergipe.

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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Effect of Calcium-phosphate Desensitizers on Staining Susceptibility of Acid-eroded Enamel

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Clinical Relevance

Calcium-phosphate desensitizers have a remineralization effect on acid-eroded enamel that shows resistance to extrinsic staining.

SUMMARY

Objective: To investigate the effect of calcium-phosphate–based desensitizers, Teethmate AP paste (TMAP) and Teethmate Desensitizer (TMD) (Kuraray Noritake Dental, Tokyo, Japan), on the prevention of staining on acid-eroded enamel.

Methods and Materials: Forty polished enamel samples (4×4×1 mm) from bovine incisors were randomly divided into five groups (n=8). After immersion in 50 mL of 0.5% citric acid (pH 2.5) for 15 minutes to form acid-eroded surfaces, the surfaces were subjected to different treatments with TMAP, TMD, and NaF (0.21% means 950 ppm) for five minutes. Another eroded group was not treated with desensitizer. For the control group, the samples were not eroded or treated. All the samples were stored in artificial saliva (AS) at pH 7.2 for 24 hours at 37°C. The TMAP, TMD, or NaF was reapplied at eight and 16 hours during the 24 hours of storage time. The surface roughness (Sa) was evaluated following ISO 25178 for surface texture using confocal laser scanning microscopy (VK-X 150 series, Keyence, Osaka, Japan) before acid erosion, after acid erosion, and after 24 hours of incubation in AS. Afterward, the color difference was measured with a dental colorimeter (Shade Eye NCC, Shofu, Kyoto,

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Japan) before and after staining with tea solution.

Results: One-way repeated measures analysis of variance showed that acid erosion significantly increased Sa ($p<0.001$). TMAP- and TMD-treated groups exhibited lower Sa values than the NaF group and the no-desensitizer treatment group. The greatest staining was observed in the NaF group and the no-desensitizer group, while the TMAP and TMD groups significantly decreased the formation of stains.

Conclusions: Acid-eroded enamel increased surface roughness and tended to absorb more stains. However, the application of TMAP and TMD moderated the roughness and thus prevented the formation of extrinsic stains.

INTRODUCTION

Dental erosion is a chronic loss of dental hard tissue due to chemical removal of minerals by acid dissolution. Erosion is fundamentally different from caries because the erosive process does not involve acid of bacterial origin.[1] Risk factor assessment for dental erosion includes frequent use of acidic dietary products, gastroesophageal reflux disease, prolonged use of chewable acidic medications (especially vitamin C and aspirin), low saliva flow rate, and inadequate saliva buffering capacity.[2,3] In recent years, the changing lifestyle, easy availability, and consumption of acidic drinks have become the main etiological factor in erosion, making this condition a major problem in oral health.[4] The erosive potential of drinks is influenced by numerous factors, such as the pH, calcium and phosphate contents, and exposure time. The low pH of beverages is one of the most important factors in the erosion of enamel.[5] Erosion starts with enamel surface softening in the early stage, and enamel tissue loss develops progressively with continued erosive challenges.[1] If the acid challenge persists, the prism cores and interprismatic areas are further dissolved, resulting in a loss of hydroxyapatite crystals, calcium, and phosphate ions.[6] Softened enamel tissue is susceptible to abrasive wear. Brushing after erosive challenges accelerates enamel tissue loss.[7]

Three-dimensional areal measurements have been reported to quantify the microstructural surface of enamel and changes that occur during erosion *in vitro*.[8-11] Previous studies reported that polished eroded enamel samples exhibited an increase in diffuse reflection and surface roughness, showing a strong relationship between erosion and surface roughness.[12-14] A significant correlation was observed between pH changes and surface roughness on the enamel surface after exposure to soft drinks and orange juice in a previous study by Fujii and others.[15] Acid-eroded enamel could be more susceptible to stain absorption, leading to surface staining and discoloration. which is a major esthetic problem.[16-18] Increased roughness on enamel surface is related to differences in color stability of the surface.[17,18]

Fluoride has been shown to provide protection of dental erosion and reduce its progression as well as reduce and prevent hypersensitivity.[19-21] A study by Fowler and others showed that dentifrices containing at least 1400-ppm fluoride can remineralize enamel eroded by citric acid.[20] A more recent study by Junko and others showed that enamel remineralization with fluoride increases surface hardness and decreases surface roughness, which can in turn prevent stain absorption.[22]

Calcium-phosphate–containing products are also considered a treatment for dental erosion and for the prevention of hypersensitivity.[23-25] Kashkosh and others identified that the surfaces became significantly rough after erosion and then became significantly smoother after application of calcium-phosphate–containing products.[26] The calcium and phosphate ions leach out from these calcium-phosphate–containing materials. The mineral phase on the enamel/dentin surface becomes "supersaturated" with calcium and phosphate for remineralization.[23-26] As a result, the calcium phosphate minerals fill the voids in the eroded enamel surface and increase the surface hardness and decrease the surface roughness of the eroded enamel.[27]

More recently developed calcium-phosphate desensitizers are based on tetracalcium phosphates (TTCP) and dicalcium phosphate anhydrous (DCPA).[28-30] Dissolution of TTCP and DCPA can lead to supersaturation of calcium and phosphate, spontaneously forming hydroxyapatite (HA).[28-30] Although there have been studies on the effect of calcium-phosphate–containing desensitizers on remineralization and enamel surface roughness, their effectiveness in preventing or decreasing stain formation on eroded enamel surfaces is still unknown. To date, there has been no study on TTCP- and DCPA-based desensitizers regarding their effect in preventing staining on eroded enamel surfaces.

Therefore, the aim of this study was to investigate the effects of TTCP- and DCPA-based desensitizers on the reduction of staining on acid-eroded enamel.

Table 1: *Components and Their Ingredients*

Products and Manufacturers	Composition
Teethmate AP (TMAP) (Kuraray Noritake Dental, Tokyo, Japan)	Dicalcium phosphate anhydrate (DCPA) Tetracalcium phosphate (TTCP) 950-ppm sodium fluoride (NaF) Glycerin Polyethylene glycol
Teethmate Desensitizer (TMD) (Kuraray Noritake Dental, Tokyo, Japan)	Powder: DCPA TTCP Liquid: water, preservative
0.21% sodium fluoride (NaF) solution (Wako Pure Chemical, Osaka, Japan)	950-ppm NaF

The null hypothesis was that there is no difference in stain resistance on acid-eroded enamel after treatment with TTCP- and DCPA-based desensitizers vs 950-ppm fluoride solution.

METHODS AND MATERIALS

Materials and Specimen Preparation

The products, manufacturers, and components of materials used in this study are listed in Table 1. The labial surfaces of bovine incisors were ground to leave flat enamel surfaces of approximately 1 mm in thickness and were polished using silicon carbide papers from 600 to 2000 grit and 3-μm diamond pastes under running water. Two specimens (4×4×1 mm) were obtained from each flattened surface. The polished enamel surfaces were cleaned ultrasonically in deionized water for five minutes to remove any trace of the polishing materials. The specimens were distributed into five groups (n=8) as shown in Table 2. For the acid erosion challenge, the specimens were immersed in 50 mL of 0.5% citric acid solution at pH 2.5 for 15 minutes.

Surface Roughness Assessment and Morphological Changes

All the specimens were subjected to surface roughness (Sa) analysis using a confocal laser scanning microscope (CLSM) (VK-X 150 series, Keyence Corporation, Osaka, Japan) to assess a baseline Sa before acid exposure. The Sa (μm), or the extension of Ra (arithmetical mean height of a line) to a surface, is defined as $Sa = 1/A \iint_A |Z(x, y)| dxdy$, whereas A = the defined area, Z = the absolute value of the height of the points, and x, y = the measurement unit of the XY stage. The Sa measurement used in this study is the ISO 25178 surface texture parameter. It expresses, as an absolute value, the difference in height of each point compared to the arithmetical mean of the surface. Three measurement units (each 273×204 μm), equally spaced 1 mm apart, were selected from each sample. The mean Sa of the three Sa values was used to represent the surface roughness of the samples.

Surface Treatments

The detailed treatment procedures are shown in Table 2. For group 1, the surfaces were treated with 1-mm thickness of Teethmate AP paste (TMAP) (Kuraray Noritake Dental, Tokyo, Japan) by rubbing with an applicator for five minutes. The TMAP was rinsed with deionized water. For group 2, Teethmate Desensitizer (TMD) (Kuraray Noritake Dental, Tokyo, Japan) powder and liquid were mixed for 15 seconds to form a slurry and applied on the enamel surface with continued rubbing motion for 30 seconds using a microbrush, left for five minutes, and then was rinsed off with deionized water for two seconds. For group 3, the specimens were immersed in 2.1 g/L (0.21%) sodium fluoride solution for five minutes. All the specimens were stored at 37°C for 24 hours in artificial saliva (AS) containing 150 mM KCl, 0.9 mM NaH_2PO_4, and 1.5 mM $CaCl_2$ (pH 7.2) using an incubation shaker (Personal-11, Taitec, Saitama, Japan) at 80 rpm. Group 4 consisted of acid-eroded samples with no desensitizer treatment. Group 5 was not subjected to acid erosion or desensitizer treatment and served as a control.

The TMAP, TMD, and NaF were reapplied in the same manner on the enamel surfaces at eight and 16 hours during the 24-hours AS incubation period. Specimens from groups 4 and 5 were stored in AS without any treatment. The AS was changed at eight and 16 hours to maintain solution freshness.

After 24 hours, all specimens were removed from the AS, gently air-dried, and measured for Sa. The differences in Sa between baseline (prior to acid erosion), after acid erosion, and after 24 hours of incubation with/without treatment were calculated for all specimens and used for statistical analysis. Topography images of all the surfaces were taken using the CLSM.

Table 2: *Treatment Groups*

Group	Acid Erosion for 15 Min	First Treatment for Five Min	AS Incubation for Eight Hours	Second Treatment for Five Min	AS Incubation for Eight Hours	Third Treatment for Five Min	AS Incubation for Eight Hours	Staining for Seven Days
1	+	TMAP	+	TMAP	+	TMAP	+	+
2	+	TMD	+	TMD	+	TMD	+	+
3	+	0.21% NaF	+	0.21% NaF	+	0.21% NaF	+	+
4	+	−	+	−	+	−	+	+
5	−	−	+	−	+	−	+	+

Abbreviations: AS, artificial saliva; TMAP, Teethmate AP; TMD, Teethmate Desensitizer; NaF, sodium fluoride.

Color Stability Assessment

The baseline color was assessed using the CIE Lab system with a dental colorimeter (Shade Eye NCC, Shofu, Kyoto, Japan). The CIE L*a*b* values were recorded before staining as baseline data. Photographs of the tooth surfaces were taken with a digital camera before and after staining.

The staining solution was created by immersing a tea solution that was prepared with two tea bags (Lipton Yellow Label Teabag, Unilever Japan, Tokyo, Japan) in 100 mL of boiling water for five minutes. The specimens were stored in an incubator for seven days at 37°C. The solution was changed on the fourth day. After seven days of immersion, the stained specimens were dried gently, and the color was measured again. Photographs were also taken. The color difference (ΔE) from the values obtained at the baseline and after staining was calculated according to the following equation:

$$\Delta E = \left[(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2\right]^{1/2}$$

Statistical Analysis

The Sa data for all groups were subjected to one-way repeated measures analysis of variance (ANOVA) to compare differences in Sa. One-way ANOVA was performed to compare ΔE followed by the Tukey multiple comparison test at the 0.05 level of significance for *post hoc* analysis.

RESULTS

Surface Roughness and Color Stability Analysis

Baseline Sa was not significantly different among all groups. One-way repeated measures ANOVA showed that the acid erosion significantly increased Sa ($p<0.001$). The Sa decreased for all acid-eroded groups after treatment with desensitizing agents and immersion in AS. The decrease in Sa was significant for TMAP (group 1) ($p<0.001$) and TMD (group 2) ($p=0.002$), while the decrease in Sa was not significant for NaF (group 3) ($p>0.05$) and the no-desensitizer treatment (group 4) ($p>0.05$). The Sa measurement of the control group (group 5) was not significantly different from the baseline measurement ($p>0.05$) (Figure 1a).

For ΔE (Figure 1b), TMAP treatment showed the least staining, which was not significantly different from group 5 ($p>0.05$). TMD treatment showed a slightly higher degree of staining than group 5 ($p<0.05$). NaF significantly showed a higher degree of discoloration than that of group 5 ($p<0.001$). The discoloration of the NaF group was not significantly different from that of group 4 (acid eroded but no treatment) ($p>0.05$).

DISCUSSION

The conditions of the current study were made to simulate acid erosion and staining in the oral cavity. We used bovine enamel because it has been verified in a number of *in vitro* studies to be an excellent alternative to human enamel in the evaluation of the effect of anticariogenic agents on enhancing enamel remineralization and inhibiting enamel demineralization.[31] Citric acid, commonly found in lemon juice and orange juice, was used as erosive potential in this study to simulate acidic challenge because of its being an important constituent of various acidic beverages.[32] The staining procedure utilized a tea beverage to induce discoloration on tooth because tea has no potential for calcification/decalcification.[33]

To evaluate discoloration, the present study used photography and a dental colorimeter that can generate parametric data that can be easily applied for statistical analysis. This method produces more objective results than the visual method.[34] L* represents the psychometric lightness from black to white, and the a* axis is red on the positive side and green on the negative side. The b* axis is blue on the positive side and yellow on the negative side.[35]

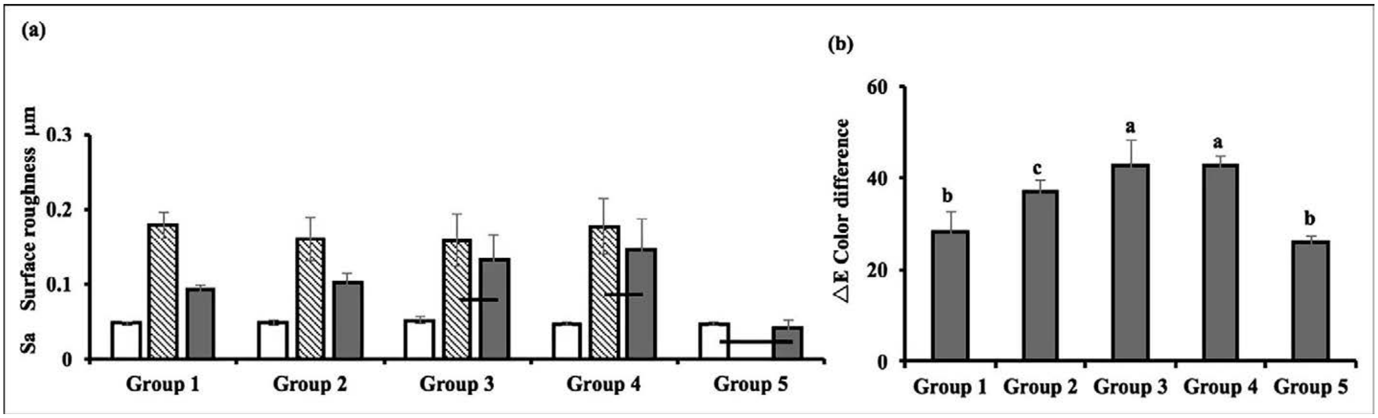

Figure 1. *(a): Mean (SD) enamel surface Sa at baseline and after erosion in citric acid ($p<0.001$) and after treatment with TMAP and TMD ($p<0.001$). Bars show no significant difference. White colors show baseline for all groups, line patterns show acid erosion groups, and gray colors indicate treatment for TMAP (group 1), TMD (group 2), NaF (group 3), with no desensitizer (group 4), and control group (group 5). (b): Mean △E, color measurement of discoloration in tea staining for seven days. Same characters show no significant difference.*

As expected, exposure to citric acid (pH 2.5) for 15 minutes significantly increased surface roughness and color difference due to minerals being leached out.[16-18,36,37] Enamel eroded by citric acid exhibited a pattern of demineralization with interprismatic mineral loss (Figure 2b), producing a roughened surface. The structural defects and porosities caused by mineral loss readily facilitate the diffusion of staining agents or chromogenic pigments.[16] A rough surface is generally considered more susceptible to staining, as the surface area for mechanical retention of discoloration pigments is increased, causing esthetic problems.[17,18,38,39]

The present study assessed the effect of two TTCP- and DCPA-based desensitizers (TMAP and TMD) to prevent staining on acid-eroded enamel surface and compared it with that of NaF, which is one of the most common agents used for remineralization of acid-eroded enamel.

The decrease in Sa of the acid-eroded groups after the application of TMAP, TMD and NaF is due to mineral precipitation as evidenced by the optical images taken with CLSM (Figure 2c,d,e). The enamel surfaces shown in Figure 2c,d were smoother than those on the acid-eroded enamel surface shown in Figure 2b,e,f. However, only the TMAP and TMD groups showed a significant decrease in surface roughness, with TMAP showing the lowest Sa value. The same result was observed for color change (ΔE), which indicated that the TMAP and TMD groups showed a significantly low ΔE. TMAP showed the lowest ΔE value among the tested groups. The results indicated that the lower the surface roughness value (smoother surfaces), the lesser the discoloration (more resistant to staining).[38]

These results can be explained by the components of the two calcium-phosphate–based desensitizers (Table 1). Both desensitizers contain TTCP and DCPA, which have different mechanisms of action

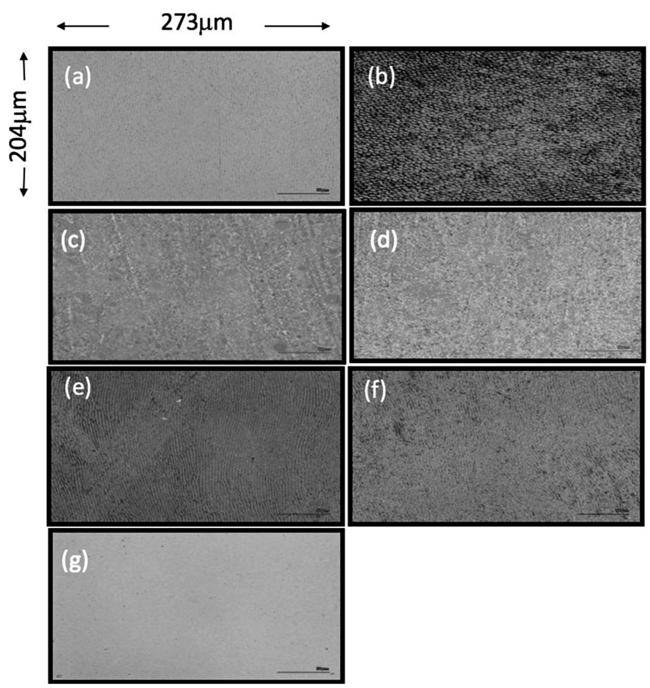

Figure 2. *Representative CLSM optical images of the bovine enamel surface texture before, after erosive challenges, and after treatment. (a): Baseline (before erosion) showed no morphological change. (b): Acid erosion for 15 minutes showed the typical honeycomb acid dissolution patterns on the enamel surface due to the loss of minerals. (c): Treatment with TMAP. (d): Treatment with TMD showed significant decrease in surface roughness. Treated surface was noticeably smoother than acid eroded enamel. (e): Treatment with 0.21% NaF treatment showed rough appearance of the enamel surface. (f): Acid-eroded enamel with no desensitizer treatment was not significantly different with 0.21% NaF treatment. (g): Control group stored in AS did not exhibit any morphological change.*

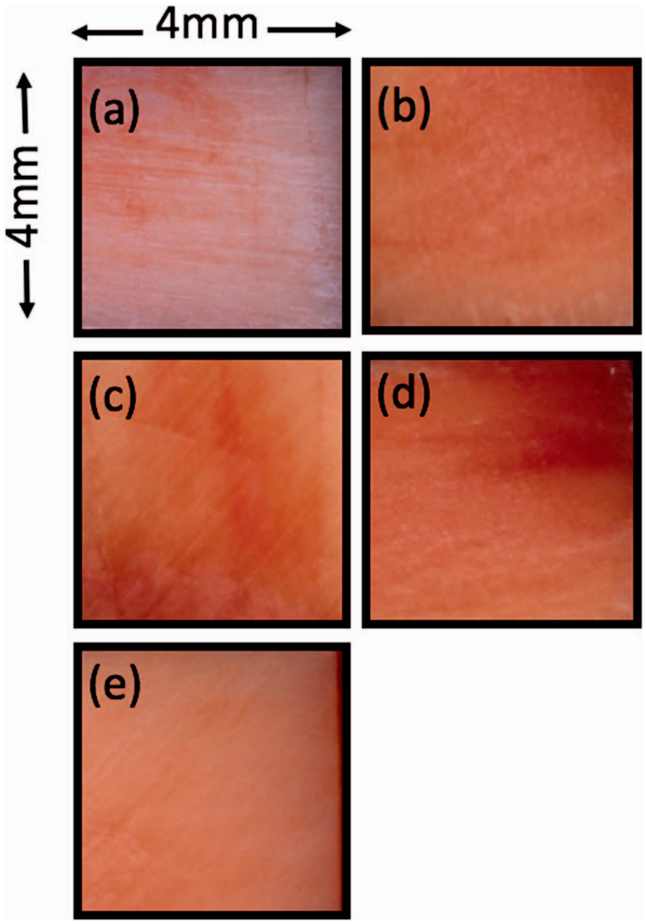

Figure 3. *Representative digital camera photos of the degree of staining on the acid-eroded enamel surfaces as to treatment groups. (a): Treatment with TMAP showed less staining. Staining was similar to control group because of smooth surface. (b): Treatment with TMD showed a slightly higher staining than control group. (c): Treatment with 0.21% NaF showed greater staining than control group. (d): No-desensitizer treatment indicated similar staining with 0.21% NaF treatment. (e): Control group.*

from other conventional desensitizers. The dissolution of TTCP and DCPA would lead to a supersaturation of calcium and phosphate ions with respect to hydroxyapatite. This increase in calcium and phosphate ion concentration leads to the formation of hydroxyapatite-like crystals,[28-30] mineralization, and consequently a decrease in surface roughness. The lower Sa values or smoother surfaces after treatment for TMAP compared to TMD may be due to the additive effect on enamel remineralization of the 950-ppm fluoride present in TMAP.

Figures 2c and 3a (TMAP) and Figures 2d and 3b (TMD) show the remineralized surfaces with the formation of a superficial homogeneous layer similar to that of intact enamel (Figure 2e,g), thereby minimizing discoloration.

A notable finding is that NaF (Figure 2e) did not significantly decrease Sa, nor did it prevent staining, as it showed the highest ΔE (Figure 3c), similar to that of group 4 (no desensitizer) (Figures 2f and 3d). This corresponds to the results of a previous study showing that fluoride alone is insufficient to cause significant remineralization.[40] In that study, it was reported that fluoride can induce remineralization only in the presence of adequate amounts of calcium and phosphate ions in the saliva; therefore, the enamel must be exposed to saliva long enough to enable the saturation of ions for fluoroapatite or fluorohydroxyapatite formation on the enamel surface.[40] In the present study, 24 hours of immersion in artificial saliva might be insufficient to attain enough concentration of calcium and phosphate ions to form fluoroapatite. The microporosities formed after acid erosion and fluoride application were not homogeneously remineralized, allowing stains to develop on the enamel surface within 24 hours.

Group 4, which did not receive any desensitizer treatment, exhibited almost the same Sa and staining as the NaF group, which might be indicative of the possible formation of remineralization from the calcium and phosphate ions present in the artificial saliva. However, remineralization was too little to prevent severe discoloration. According to Buzalaf and others,[41] one of the most important factors in the repair of softened enamel is saliva, as it contains calcium and phosphates to induce natural remineralization. However, natural remineralization through saliva alone is a very slow process, and thus calcium phosphate technologies and fluorides are employed to hasten the remineralization process.[42,43]

Group 5 (control), which was not subjected to acid erosion and did not receive any treatment, showed similar Sa compared with baseline and then indicated the lowest staining, which was not significantly different with group 1 because of the smooth surface.

The results of the present study show that desensitizers containing TTCP and DCPA (TMAP and TMD) are more effective in decreasing surface roughness and discoloration than sodium fluoride. These agents have clinical benefits, as they can prevent discoloration due to effective remineralization of eroded enamel.

CONCLUSIONS

Acid erosion increases surface roughness, which subsequently increases staining. TTCP- and DCPA-based desensitizers may produce HA formation and precipitation on eroded surfaces and therefore are effective in inhibiting enamel erosion and increasing resistance to tea stain absorption into acid-eroded surfaces.

Acknowledgement

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Regulatory Statement

This study was conducted in accordance with all the provisions of the local human subjects oversight committee guidelines and policies of approval of the Tokyo Medical and Dental University.

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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Effect of Simulated Pulpal Microcirculation on Temperature When Light Curing Bulk Fill Composites

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Clinical Relevance

Ex vivo studies should simulate pulpal microcirculation when attempting to measure the temperature rise that occurs during light curing. The greatest potential for an intrapulpal temperature rise occurs when the adhesive is light cured.

SUMMARY

Objectives: To evaluate the effect of light curing bulk fill resin composite restorations on the increase in the temperature of the pulp chamber both with and without a simulated pulpal fluid flow.

Methods and Materials: Forty extracted human molars received a flat occlusal cavity, leaving approximately 2 mm of dentin over the pulp. The teeth were restored using a self-etch adhesive system (Clearfil SE Bond, Kuraray) and two different bulk fill resin composites: a flowable (SDR, Dentsply) and a regular paste (AURA, SDI) bulk fill. The adhesive was light cured for 20 seconds, SDR was light cured for 20 seconds, and AURA was light cured for 40 seconds using the Bluephase G2 (Ivoclar Vivadent) or the VALO Cordless (Ultradent) in the

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standard output power mode. The degree of conversion (DC) at the top and bottom of the bulk fill resin composite was assessed using Fourier-Transform Infra Red spectroscopy. The temperature in the pulp chamber when light curing the adhesive system and resin composite was measured using a J-type thermocouple both with and without the presence of a simulated microcirculation of 1.0-1.4 mL/min. Data were analyzed using Student *t*-tests and two-way and three-way analyses of variance (α=0.05 significance level).

Results: The irradiance delivered by the light-curing units (LCUs) was greatest close to the top sensor of the MARC resin calibrator (BlueLight Analytics) and lowest after passing through the 4.0 mm of resin composite plus 2.0 mm of dentin. In general, the Bluephase G2 delivered a higher irradiance than did the VALO Cordless. The resin composite, LCU, and region all influenced the degree of cure. The simulated pulpal microcirculation significantly reduced the temperature increase. The greatest temperature rise occurred when the adhesive system was light cured. The Bluephase G2 produced a rise of 6°C, and the VALO Cordless produced a lower temperature change (4°C) when light curing the adhesive system for 20 seconds without pulpal microcirculation. Light curing SDR produced the greatest exothermic reaction.

Conclusions: Using simulated pulpal microcirculation resulted in lower temperature increases. The flowable composite (SDR) allowed more light transmission and had a higher degree of conversion than did the regular paste (AURA). The greatest temperature rise occurred when light curing the adhesive system alone.

INTRODUCTION

Resin composites are widely used in restorative dentistry, and they can provide good clinical longevity.[1] The light output from curing lights is greater now than in the past, and this may be the reason why the patient experiences some postoperative pain. This may be related to the thermal, osmotic, and mechanical stimuli that cause rapid movement of fluid in dentinal tubules.[2,3] Several other factors can also affect pulp health, such as the presence of caries, chemical trauma, or thermal changes.[4] Excessive heating of the pulp is a concern in dental treatment because it can cause an inflammatory reaction, histopathological changes, vascular damage, and even cell death.[5]

Heat can be generated or transferred to the dentin-pulp complex during tooth preparation, when light curing, when polishing the restoration, or during light-activated bleaching.[6,7] The resulting rise in pulpal temperature is dependent on the duration of the light exposure[8]; the radiant power and energy from the light-curing unit (LCU); the amount of dentin thickness remaining[9]; the LCU[10]; the resin composite type, thickness, and shade; or the exothermic reaction as the resin polymerizes.[11-13] LCUs that deliver a high irradiance may produce a larger temperature rise,[10] and it is possible that a damaging temperature rise may occur during resin photopolymerization.[4,14]

The amount of heat generated when light curing resin-based composites depends on the curing light, type of composite, and the substrate used in the experiment.[15] Dark shades of resin composites tend to produce a lower initial temperature rise, but the temperature remains elevated for longer because the light penetration is reduced and polymerization occurs more slowly in the darker shades of composites.[11] Some bulk fill resin composites have been reported to cause greater temperature increases than when the composites are placed and light cured in increments.[16] Flowable composites tend to produce a greater temperature increase due to their greater resin content and lower filler load.[17] However, more studies are required using other bulk fill resin composites, especially those that have different viscosities.

When conducting laboratory tests, the *in vivo* conditions should be simulated as closely as possible. The movement of fluid in dentin tubules, or changes in pulp blood flow due to stimulation of the nervous system within the pulp, are both affected by different thermal stimuli *in vivo*.[18] The response can be increased by operative procedures,[6] or it can be less after delivery of a local anesthetic.[19] The intrapulpal blood circulation has been estimated to be 40 mL/min per 100 g of tissue,[20,21] and this fluid flow may be sufficient to dissipate some or all of the heat from external thermal stimuli to the dentin-pulpal complex.[18] Since it is considered that the absence of water and lack of fluid flow reduce the conduction of heat and the clinical relevance of a study,[7] some *in vitro* studies have used teeth positioned in a vessel containing water at 37°C, and have made some attempt to simulate the pulpal pressure.[8,22] Relatively few studies have measured the temperature rise in combination with a simulated pulpal micro-

Table 1: *Characteristics of the Dental Curing Lights Tested. Mean Values (Standard Deviations)*

LCU	VALO Cordless	Bluephase G2
Irradiance, mW/cm^2	1297.9 (3.3)	1393.8 (4.5)
Wavelength, nm	395-480	385-515
Manufacturer	Ultradent, South Jordan, UT, USA	Ivoclar Vivadent, Schaan, Liechtenstein

circulation (combined simulated pulpal fluid flow and pressure).[6,7]

The aim of this study was to evaluate the effect of simulated pulpal microcirculation using a novel device developed for this study to simulate both pulp fluid flow and pressure. The effect of the LCU on the temperature rise in the pulp chamber caused when light curing the adhesive system followed by light curing two different bulk fill composites in deep, flat cavities was examined. The null hypotheses were that 1) the simulated pulp fluid flow and light-curing unit would have no effect on the intrapulpal temperature rise, and 2) the different irradiances and radiant exposures from the two curing lights would have no effect on the rise in the intrapulpal temperature and on the degree of conversion of the bulk fill resin composites.

METHODS AND MATERIALS

Study Design

Two broad-spectrum multipeak LCUs, Bluephase G2 (Ivoclar Vivadent, Schaan, Liechtenstein) and VALO Cordless (Ultradent, South Jordan, UT, USA), and a flowable bulk fill composite, SDR, SureFil SDR flow (Dentsply, Konstanz, Germany) and a bulk fill paste composite, AURA, Aura Bulk Fill (SDI, Bayswater, Perth, Australia), were used. The characteristics of the LCUs are described in Table 1, and the composites and their composition are listed in Table 2. The irradiance, emission spectrum, and radiant exposure from the LCUs were characterized using a MARC resin calibrator (BlueLight Analytics Inc, Halifax, NS, Canada). The degrees of conversion (DCs) at the top and bottom of the resin composite samples were assessed using Fourier-Transform mid–Infrared Spectroscopy (FT-midIR; Vertex 70, Bruker Optik GmbH, Ettlingen, Germany). Forty extracted human maxillary molars (Ethics Committee in Human Research of Federal University of Uberlandia approval No. 1.451.872) received standardized 5×5-mm occlusal cavity preparations that were 4 mm deep, leaving 2.0 mm of dentin over the

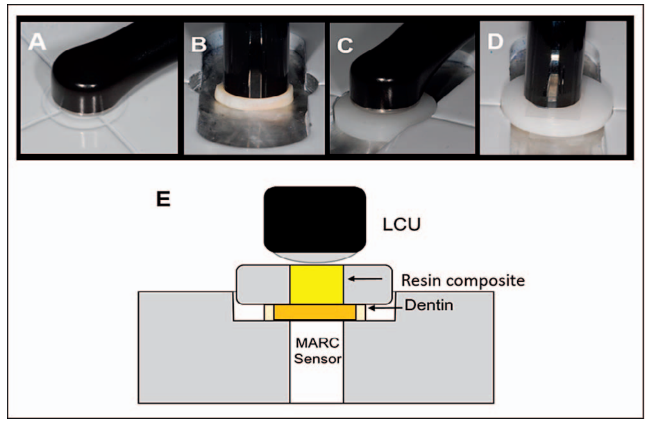

Figure 1. *Illustration of how the irradiance (mW/cm^2) and emission spectrum ($mW/cm^2/nm$) of LCU were measured: (A) VALO Cordless over the MARC-RC top sensor; (B) Bluephase G2 over 2.0-mm thickness of dentin on MARC-RC bottom sensor; (C) VALO Cordless over the 4.0 mm of bulk fill resin composite; (D) Bluephase G2 over the 4.0 mm of bulk fill resin composite plus 2.0 mm of dentin on MARC-RC bottom sensor; (E) Schematic of the specimen and LCU position in the MARC-RC system.*

pulp. Following the manufacturers' instructions, a self-etching adhesive system (Clearfil SE Bond, Kuraray, Tokyo, Japan) was applied to the dentin. The pulp temperature was measured both during light curing of the adhesive system and of the resin composite using J-type thermocouple (Ecil Produtos, SP, Brazil) inserted into the pulp chamber. The temperature was measured both with and without a simulated pulpal microcirculation of 1.0-1.4 mL/min through the pulp chamber and the temperature was recorded at the rate of 1Hz. The thermocouple was connected to a data acquisition device (ADS2000IP; Lynx Technology, São Paulo, SP, Brazil) to measure the exothermic reaction.

Irradiance, Emission Spectrum, and Radiant Exposure

The irradiance (mW/cm^2), emission spectrum ($mW/cm^2/nm$), and radiant exposure (J/cm^2) delivered by each LCU operating in the standard mode to the resin composites were measured using a MARC resin calibrator (RC). The measurements were recorded five times under different conditions: control–top; through 2.0 mm of dentin; through 4.0 mm of each resin composite; and through 4.0 mm of each resin composite over 2.0 mm of dentin.

Control–Top—The irradiance at the tip of each LCU was determined by placing the tip directly over and at a distance of 0 mm from the MARC-RC top sensor (Figure 1A). The Bluephase G2 delivered 27.7 J/cm^2 and the VALO Cordless delivered 25.7 J/cm^2, when used for 20 seconds. When used for 40 seconds,

Table 2: *Dental Composites Tested in the Study (Information Provided by the Manufacturers)*

Composite	Wt%	Vol%	Filler Type	Matrix	Manufacturer Resins
AURA	81	65	Silica, barium alumino-borosilicate glass	Bis-EMA, UDMA, TEGDMA	SDI (Bayswater, Perth, Australia)
SDR	68	44	Barium and strontium alumino-fluoro-silicate glasses	Modified UDMA, dimethacrylate and difunctional diluents	Dentsply (Konstanz, BW, Germany)

Abbreviations: Bis-EMA, bisphenol-A hexaethoxylated dimethacrylate; TEGDMA, triethylene glycol dimethacrylate; UDMA, urethane dimethacrylate.

the Bluephase G2 delivered 49.7 J/cm^2 and the VALO Cordless 49.4 J/cm^2.

Through 2.0 mm of Dentin—To estimate the irradiance, emission spectrum, and radiant exposure through dentin (Figure 1B), one human upper molar was sectioned using a low-speed diamond saw (Isomet, Buehler, Lake Bluff, IL, USA) using copious water cooling to obtain one slice of 2.0-mm-thick pulpal dentin. This 2.0-mm-thick dentin sample was placed directly on the surface of the MARC sensor, and the LCU was turned on. Before each measurement (n=5), the dentin slice was immersed in water for one minute so that it was hydrated.

Through 4.0 mm of Bulk Fill Resin Composite—To estimate the irradiance, emission spectrum, and radiant exposure transmitted through each bulk fill resin composite during photocuring (Figure 1C), a plastic ring mold (Delrin Ring, DuPont, Mississauga, ON, Canada) with an internal aperture of 6-mm diameter and 4 mm height was filled with each resin composite. A Mylar strip (DuPont Teijin Films, Hopewell, VA, USA) was placed over the MARC bottom sensor, the ring matrix was centered over the sensor, and the LCUs were turned on for 20 seconds for SDR and for 40 seconds for AURA (n=5).

Through 4.0 mm of Bulk Fill Resin Composite and 2.0 mm of Dentin—To estimate the irradiance, emission spectrum, and radiant exposure transmitted through the resin composite and dentin (Figure 1D,E), the slice of 2.0-mm dentin sample was placed directly on the surface of the MARC bottom sensor, a Mylar strip was placed over the dentin, and the Delrin ring filled with each uncured resin composite was placed over the dentin slice. The LCU was then turned on (according to the manufacturers' instructions) for 20 seconds for SDR and for 40 seconds for AURA (n=5).

The same trained operator conducted all of the light exposures. The tip of the LCU was fixed as close as possible to the surface of the resin with a rigid clamp. The MARC software displayed the maximum irradiance (mW/cm^2), radiant exposure (J/cm^2), and the emission spectrum (mW/cm^2/nm) received by the sensor.

DC of Resin Composites

The DCs at the top and bottom of the bulk fill resin composite samples (n=5) were assessed after 24 hours. The samples were prepared in a dark room with yellow light so that the room light did not impact the resin polymerization. After light curing with the LCU, the samples were then stored dry at 37°C, protected from light. The DCs were assessed using FT-midIR (Vertex 70, Bruker Optik GmbH) with attenuated total reflectance (ATR crystal) sampling, mid-infrared (MIR) and deuterated triglycine sulfate (DTGS) detector elements (Bruker Optik GmbH). The spectra were obtained between internal standard aromatic C=C bonds (1608 cm^{-1}) and aliphatic C=C bond (1638 cm^{-1}), at a resolution of 4 cm^{-1}, and 32 scans were averaged. All analyses were performed under controlled temperature (25°C±1°C) and humidity (60%±5%) conditions. DC was calculated from the equivalent aliphatic (1638 cm^{-1}) and aromatic (1608 cm^{-1}) ratios of cured (C) and uncured (U) resin composite specimens. The formula used to calculate the degree of conversion was $DC\ (\%) = (1 - C/U) \times 100$.

Tooth Preparation and Dentin Thickness Measurement

The temperature inside the pulp was measured using custom-made microcirculation equipment (Figure 2A) that was developed by the authors in partnership with ODEME (Luzerna, SC, Brazil). This equipment is currently under patent review (Protocol INPI No. BR 10 2016 016624 1). Forty extracted, intact, caries-free human maxillary third molars of young patients (18-20-year age range) were used in this study (Ethics Committee in Human Research of Federal University of Uberlandia approval No. 1.451.872). The inclusion criteria required the molars to have wide pulp chambers, two separate roots, and open apices. The apices of the roots were sectioned 5.0 mm from the furcation to expose the root canals. After cleaning the root canals, 1.2-mm-diameter metal tubes (40 × 1.2 18G1 irrigation needles; Embramac, Campinas, SP, Brazil) were inserted 2 mm into the root canal

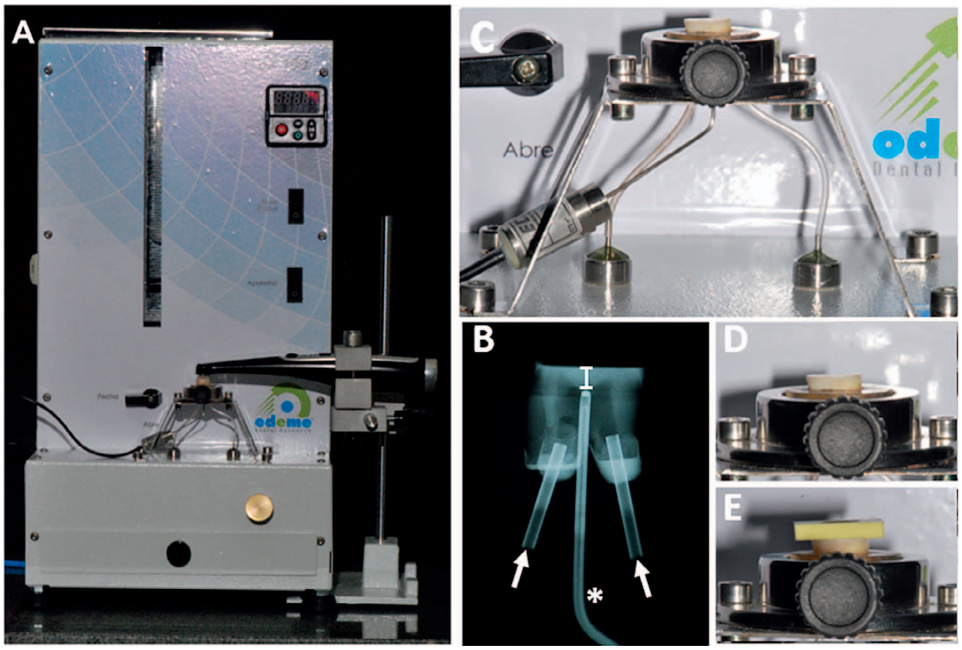

Figure 2. *Temperature measurement: (A) Equipment to simulate pulpal microcirculation, temperature measurement, and the LCU support; (B) Tooth, plastic tubes carrying the water connected to the sample, and thermocouple inserted into the pulp chamber; (C) X-ray of tooth sample with two metallic tubes and the thermocouple in contact with the top of dentin pulp floor where it is ~2 mm thick (region above the thermocouple); the arrows indicate the needles and the asterisk indicates the thermocouple; (D) Light curing the adhesive system; (E) Light curing the bulk fill using a silicon matrix to position the light in the same position each time.*

orifices, one in the palatal root and the other in the buccal root, while keeping 5 mm of the metal tubes exposed outside the tooth. The tubes were fixed using resin composite (Z250, 3M-ESPE, St Paul, MN, USA). The third root was sealed with the same resin composite. The teeth to be tested without any simulated pulpal microcirculation had their roots sealed with resin composite. The roots of the teeth were embedded in 10 mm of polystyrene resin (Cristal, Piracicaba, SP, Brazil), to a level just below the cemento-enamel junction. The pulp chamber was accessed through the furcation using a diamond bur (No. 1016 HL KG Sorensen, Barueri, SP, Brazil) in a high-speed handpiece with copious air-water spray to prevent damage to the pulp-dentin at the top of the pulp chamber. A radiograph (Kodak Dental Systems, Carestream Health, Rochester, NY, USA) was taken for each tooth to confirm the crown dimension and pulp chamber location so that the flat cavities (5 × 5 × 4 mm deep) were made to be approximately 2 mm above the pulp chamber. After preparation, another radiograph was taken to confirm the thickness of dentin remaining (in millimeters) and the position of the thermocouple. Figure 2B illustrates how the pulp-dentin remaining thickness was measured using ImageJ software (National Institutes of Health, Bethesda, MD, USA).

Temperature Rise Measurement

A J-type thermocouple with a 10-Hz response time (Ecil Produtos e Sistemas para Medição e Controle Ltda, Piedade, SP, Brazil) was inserted into the pulp chamber through the access hole in the furcation so that it contacted the pulp dentin floor at the top of the pulp chamber. This thermocouple was used to measure the temperature change produced inside the pulp chamber when light curing the self-etching adhesive system alone and then when light curing the bulk fill resin composites. This J-type thermocouple can measure temperature variations ranging from 0°C to 480°C at a rate of 10 Hz. The thermocouple was also connected to the simulated pulpal microcirculation equipment. The temperatures recorded were transferred to a computer using a dedicated software interface. The real-time data were recorded at 1 Hz and expressed both graphically and as an exportable data file.

The custom-designed pulpal microcirculation device has a peristaltic pump and reservoir with both an adjustable thermal and pressure control. The hydrostatic pulp pressure was adjusted to 20 cm H_2O.[22,23] The pulpal temperature was maintained at 37°C,[6,7] and distilled water was pumped through the pulp at a rate of 1.0-1.4 mL/min.[6,7] Two polyethylene tubes, one for water inflow and one for water outflow, were connected to the metal tubes in the tooth roots (Figure 2C).

The teeth were divided into eight groups (n=5) that were defined by three study factors: simulated pulpal microcirculation, no pulpal microcirculation; Bluephase G2 or VALO Cordless LCUs; and the bulk fill resin composites, SDR or AURA. The self-etching adhesive system (Clearfil SE Bond, Kuraray) was used according to the manufacturer's instructions. The primer was actively applied over the flat tooth surface for 10 seconds and dried using a gentle air flow; the adhesive was then applied, the excess was removed with a microbrush (KG Sorensen), and light cured for 20 seconds with the tip positioned close to, but not touching, the dentin (Figure 2D). The restoration was made over the flat dentin surface using a standardized polyvinyl siloxane impression matrix (Express XT, 3M-ESPE) that was 5 × 5 mm wide and 4 mm deep (Figure 2E). The matrix was centered over the flat tooth surface and carefully filled in bulk, avoiding the incorporation of any air bubbles. The resin composite was light cured for 20 seconds (SDR) and for 40 seconds (AURA). The temperature was recorded during the restorative process, and the peak maximum temperature was calculated at two timepoints: when light curing the adhesive system and when light curing the resin composite.

Exotherm of Materials

A second J-type thermocouple (5TC-TT-J-40-36; Alutal Siebeck Sensors, São Paulo, SP, Brazil) was used to measure the exothermic reaction of the light curing of materials used. This thermocouple was connected to the data acquisition device (AD-S2000IP; Lynx Technology, São Paulo, SP, Brazil). The data were transferred to a computer using specific acquisition signal transformation by data analysis software (AqDados 7.02 and AqAnalisys; Lynx). To measure the exothermic reaction of bulk fill resin composites, it was placed in one 4.0-mm increment (n=10). To measure the exothermic reaction of the adhesive, it was placed in a thin layer on the thermocouple tip (n=10). The LCUs were then positioned at 1.0 mm above the material, which were then light cured according to manufacturers' instructions: SDR and the adhesive both for 20 seconds, whereas the AURA was exposed for 40 seconds. The samples were prepared in a dark room with yellow light. The temperature was recorded before start of light curing. After the first light exposure, the samples were exposed three more times, after two, four, and six minutes. The mean of these three re-irradiations was calculated and represented that the temperature rise during the final postcure was due to the curing light and had no resin exotherm. To determine the contribution of the exothermic reaction to the temperature rise, the mean of the postcure temperature profile was subtracted from the temperature profile obtained during the first light exposure.[15,24]

Statistical Analysis

The dentin thickness (mm), maximum irradiance (mW/cm^2), DC of resin composite (%), temperature change (°C), and exothermic reaction (°C) data were tested for a normal distribution (Shapiro-Wilk, $p>0.05$) and equality of variances (Levene test), followed by parametric statistical tests. The Student *t*-test was used to compare the dentin thickness (mm). Two-way analysis of variance (ANOVA) was used to compare the effect of the resin composite, LCU, and their interaction for irradiance and radiant exposure data. Three-way ANOVA was used to compare the effect of the resin composite, LCU, and sample area on the DC data. Two-way ANOVA was used to compare the effect of the LCU and simulated pulpal microcirculation on the temperature rise when light curing the adhesive system. Three-way ANOVA was used to compare effect of the resin composite, LCU, and the effect of simulated pulpal microcirculation on the temperature rise data when light curing the resin composite. A paired Student *t*-test was used to compare the temperature rise when light activating the adhesive system and the resin composite, for all experimental conditions. Two-way ANOVA was used to compare the effect of material, LCU, and their interaction for exothermic reaction. All tests used an $\alpha = 0.05$ significance level, and all analyses were carried out using Sigma Plot version 13.1 (Systat Software Inc, San Jose, CA, USA). The light emission spectra were analyzed qualitatively.

RESULTS

Dentin Remaining Thickness (mm)

Based on the measurements taken from the radiographs, the thickness of the pulp floor dentin of the teeth randomly allocated to the AURA group was 1.89 ± 0.42 mm. This was statistically similar ($p=0.596$) to the measurement for the teeth allocated to the SDR group (1.99±0.43 mm).

Irradiance and Emission Spectrum Emitted by LCUs

The maximum irradiance (mW/cm^2), emission spectrum ($mW/cm^2/nm$), and radiant exposure (J/cm^2) emitted by the two LCUs at different positions simulating the experimental conditions are reported in Table 3 and Figure 3, respectively.

Two-way ANOVA showed that a significant interaction effect was observed between light-curing units and how the irradiance delivered to the resin composites by LCUs was measured ($p<0.001$). As

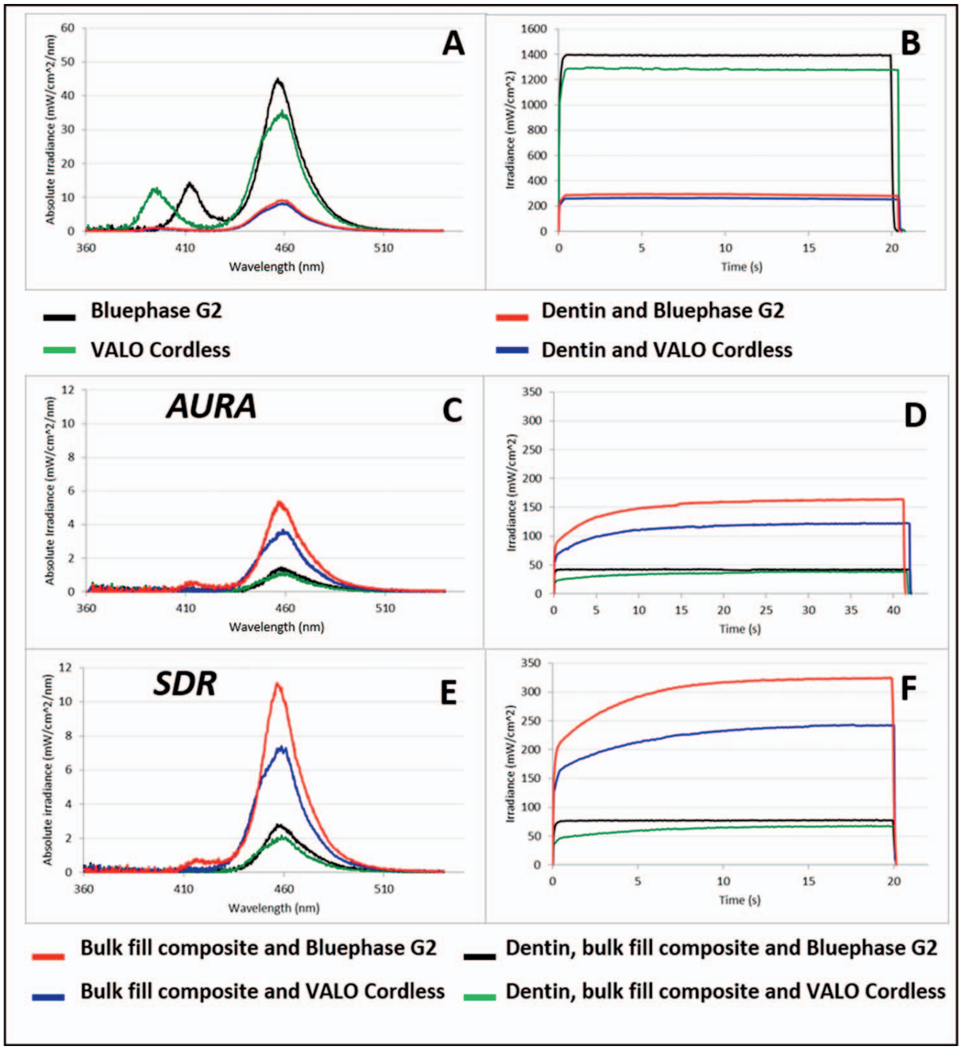

Figure 3. *Emission spectrum (mW/cm^2/nm) and irradiance (mW/cm^2) from the LCUs: (A) Emission spectrum of LCUs over the top sensor and through dentin on MARC bottom sensor; (B) Irradiance of LCUs over the top sensor and through dentin on bottom sensor; (C) Emission spectrum through AURA and 2.0-mm-thick dentin; (D) Irradiance through AURA and 2.0-mm-thick dentin; (E) Emission spectrum through SDR and 2.0-mm-thick dentin; (F) Irradiance through SDR and 2.0-mm-thick dentin. Note the irradiance scales are different in A compared to C and E. The scales are also different in B compared to D and F.*

expected, the irradiance emitted by LCUs was significantly greater when closer to the top sensor, and this effect was reduced by as much as 97.2% when measured through the 4.0 mm of AURA resin composite over 2.0 mm of dentin. The Bluephase G2 delivered a higher irradiance than did the VALO Cordless when measured at the top ($p<0.001$). However, no significant difference was found between both LCUs when measured through 2.0 mm of dentin plus 4.0 mm of AURA ($p=0.794$) or through 2.0 mm of dentin plus 4.0 mm of SDR ($p=0.480$).

DC (%) of Resin Composites

The means and standard deviations of the DC values for SDR and AURA at the top and bottom when light cured using Bluephase and VALO Cordless lights are shown in Table 4. Three-way ANOVA showed that only resin composite ($p<0.001$), LCU ($p<0.001$), and the region ($p<0.001$) significantly influenced the DC. Even though it was only exposed for 20 seconds, SDR had significantly higher DC than did AURA, regardless of the LCU used and the region measured. Despite delivering a lower irradiance, using the VALO Cordless produced a higher DC than did the Bluephase G2, regardless of the resin composite or the region measured. The top of the specimens achieved a higher DC than did the bottom, regardless of the resin composites or the LCU used.

Temperature Rise Measurement

The means and standard deviations of the maximum temperature change at the roof of the pulp chamber measured when light curing the adhesive system are shown in Figure 4. Two-way ANOVA showed that there was a significant interaction effect when the microcirculation through the pulp was simulated and on the LCUs that were used when light curing the adhesive system ($p<0.001$). When light curing

Table 3: *Irradiance (mW/cm²) Delivered by the Dental Curing Lights Under Different Conditions and Percent of Light Attenuation in Relation to the Control. (Control–Top: the Tip Irradiance of the Light-curing Units [LCUs] Was Determined by Placing the Light Tip Directly Over and at a Distance of 0 mm From the MARC-RC Sensor)[a] (ext.)*

LCUs	Control–Top	Through 2.0 mm of Dentin	Through 4.0 mm of AURA
VALO Cordless	1297.9 (3.3) Ab	237.6 (3.0) Bb 81.7%	124.2 (3.2) Cb 90.4%
Bluephase G2	1393.8 (4.5) Aa	290.6 (9.8) Ba 79.2%	166.0 (7.5) Ca 88.1%

[a] *Different letters indicate a significant difference: uppercase letters are used for comparing the condition of measurement, and lowercase letters are used for comparing the LCU (*$p<0.05$*).*

the adhesive system, the lack of any pulpal microcirculation resulted in a greater temperature change than was noted when pulpal microcirculation was simulated, regardless of the light-curing unit used ($p<0.001$). The VALO Cordless (dose delivered: 25.7 J/cm²) produced a smaller temperature increase (4°C) compared to the Bluephase G2 (dose delivered: 27.7 J/cm²), which produced a 6°C increase when light curing the adhesive system when no pulpal microcirculation was present. (Figure 4; $p<0.001$).

The means and standard deviations of the maximum temperature change at the roof of the pulp chamber measured during light curing of the bulk fill resin composites are shown in Table 5. The three-way ANOVA only revealed a significant effect when the pulpal microcirculation was simulated ($p<0.001$). The temperature change was significantly greater without a simulated pulpal microcirculation than when the pulpal microcirculation was simulated, regardless of choice of light-curing unit and bulk fill resin composites. No significant difference was observed between VALO Cordless and Bluephase G2 ($p=0.974$) and also between AURA and SDR ($p=0.340$), between interaction of two factors—LCUs and resin composite ($p=0.564$); LCUs and simulated pulpal microcirculation ($p=0.438$), resin composite, and simulated pulpal microcirculation ($p=0.284$); and also for interaction among three study factors—simulated pulpal microcirculation, LCUs, and resin composite ($p=0.857$).

The temperature changes produced by light activation of the adhesive system and resin composite with and without the simulated pulpal microcirculation are shown in Figure 4. The paired Student *t*-test showed that the temperature changes were significantly higher when light curing the adhesive system compared to when the resin composite was light cured (temperature difference of 3°C) for all combinations where the pulpal microcirculation was not simulated. However, no difference was found for any combination where the pulpal microcirculation was simulated.

Exothermic Reaction Measurement

The means and standard deviations of exothermic reaction for the adhesive system, SDR and AURA, when light cured using Bluephase G2 and VALO Cordless lights are shown in Table 6. Two-way ANOVA showed significant difference between materials ($p<0.001$). The exotherm was significantly higher for the 4.0-mm increment of SDR (7.7°C, Bluephase G2; 8°C, VALO Cordless) than for the 4.0-mm increment of AURA (4.7°C, Bluephase G2; 4.5°C, VALO Cordless). No significant difference was observed between VALO Cordless and Bluephase G2 ($p=0.528$) and also between the interaction of two factors—LCUs and material ($p=0.753$).

DISCUSSION

The use of simulated pulpal microcirculation, intrapulpal pressure, and the choice of LCU influenced the temperature rise in the pulp chamber when light curing the two resin-based composites used in this study. Furthermore, the irradiance from the two LCUs was significantly different through the dentin,

Table 4: *Mean (Standard Deviation) Degree of Conversion (%) of the Resin Composites at the Top and Bottom After Light Curing and the Percent of Light Attenuation[a]*

Resin Composites	Bluephase G2			VALO Cordless		
	Top	Bottom	Difference: Bottom to Top DC	Top	Bottom	Difference: Bottom to Top DC
AURA	65.6 (5.4) Bb	61.9 (4.5) Bb	5.6%	76.4 (3.2) Aa	66.6 (6.3) Bb	12.8%
SDR	76.4 (3.2) Aa	64.6 (2.7) Aa	15.5%	79.7 (3.3) Aa	75.6 (4.7) Aa	5.2%

[a] *Different letters indicate a significant difference: uppercase letters are used for comparing the composite resins, and lowercase letters are used for comparing light curing units (*$p<0.05$*).*

Table 3: *Extended.*

LCUs	Through 4.0 mm of SDR	Through SDR 4.0 mm + Dentin 2.0 mm	Through AURA 4.0 mm + Dentin 2.0 mm
VALO Cordless	237.2 (13.5) Da 81.7%	67.2 (9.6) Ea 94.8%	37.0 (1.6) Fa 97.2%
Bluephase G2	324.2 (21.7) Db 76.7%	71.3 (6.1) Ea 94.9%	38.5 (4.2) Fa 97.2%

and the bulk fill resin composites. Therefore, the null hypotheses were rejected.

To achieve the ideal mechanical properties the resin composites must receive sufficient energy at the appropriate wavelengths.[25] Although there was a difference between the two resin composites, both produced a high DC, confirming that sufficient light was able to reach to the bottom of 4 mm of the composite when the exposure times recommended by the manufacturers were used. For 20 s, the dose delivered at the top of the SDR samples from Bluephase G2 was 27.7 J/cm^2, and the dose was 25.7 J/cm^2 from VALO Cordless; at the bottom, 5.5 J/cm^2 and 3.9 J/cm^2 were received from Bluephase G2 and VALO Cordless, respectively. On the other

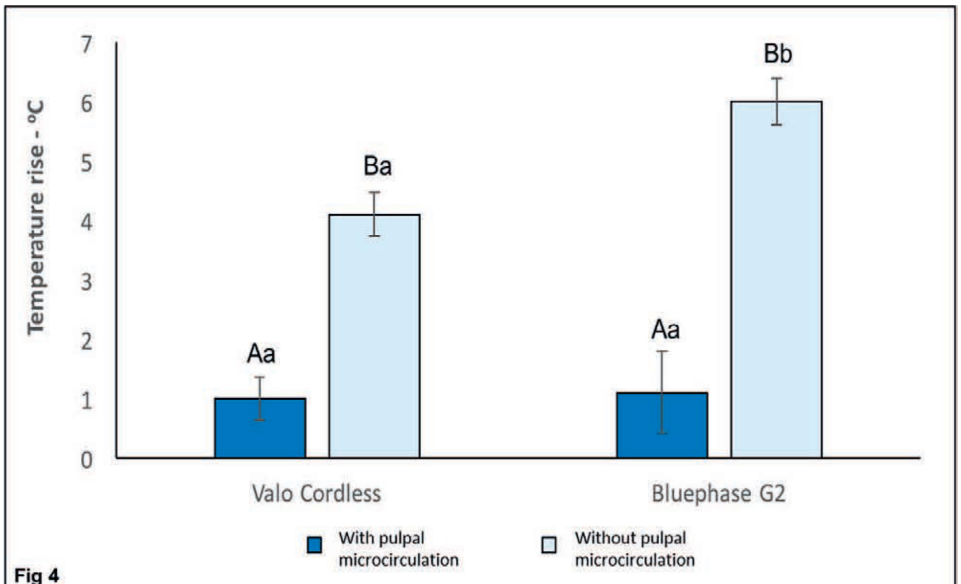

Figure 4. *Means and standard deviations of maximum temperature rise (°C) when light curing the adhesive system with and without microcirculation through the pulp (n=10). Different letters indicate a significant difference: uppercase letters used for comparing the simulated pulpal microcirculation and lowercase letters for comparing the results obtained using the two LCUs (*$p<0.05$*).*

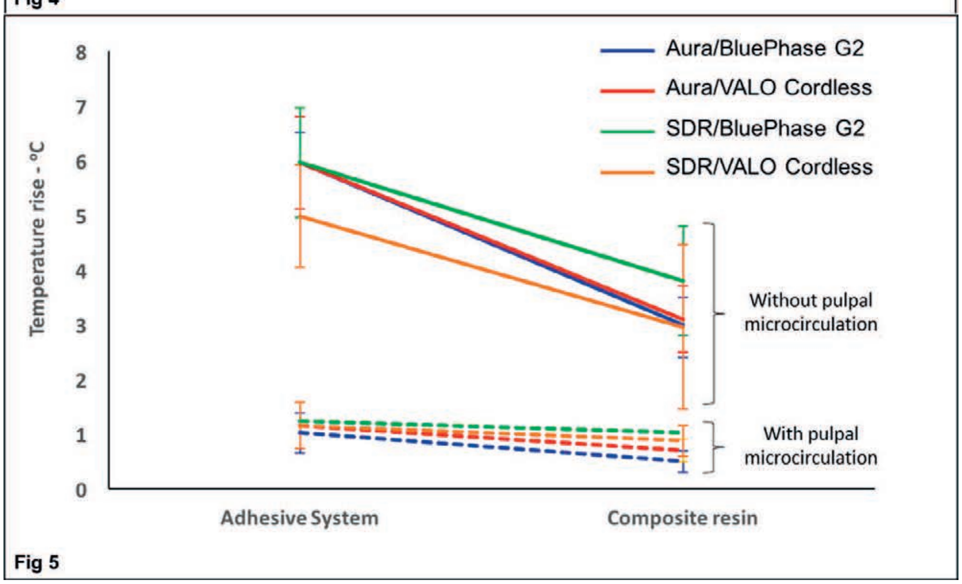

Figure 5. *Effect of pulpal microcirculation on the maximum temperature rise (means and standard deviations in °C) when light curing the adhesive system and the resin composite (n=5).*

Table 5: *Mean (Standard Deviation) Maximum Temperature Rise (°C) for Resin Composites When Light Cured With and Without Pulpal Microcirculation (n=5)[a]*

Composites	Bluephase G2		VALO Cordless	
	With Pulpal Microcirculation	Without Pulpal Microcirculation	With Pulpal Microcirculation	Without Pulpal Microcirculation
AURA	0.6 (0.2) Aa	3.0 (0.7) Ab	0.7 (0.2) Aa	3.1 (0.6) Ab
SDR	1.0 (0.4) Aa	3.1 (0.7) Ab	0.9 (0.3) Aa	2.9 (0.8) Ab

[a] *Different letters indicate a significant difference: uppercase letters used for comparing the resin composites and lowercase letters are used for comparing the simulated pulpal microcirculation ($p<0.05$).*

hand, for 40 s, the dose delivered at the top of AURA samples was 49.7 J/cm^2 from the Bluephase G2 and 49.4 J/cm^2 from the VALO Cordless, while at the bottom, only 5.3 J/cm^2 and 5.2 J/cm^2, were received for Bluephase G2 and VALO Cordless, respectively. Therefore, despite using twice the exposure time and delivering more energy, less energy reached the bottom of the AURA samples because there was greater light transmission through SDR.[26] This may explain why the SDR reached a higher DC at the bottom than did AURA, regardless of which LCU was used. Although Bluephase G2 delivered a higher irradiance and more energy than the VALO, using the VALO Cordless resulted in higher DC at the bottom of the samples. This may be because the VALO Cordless delivers a broader spectrum of light with three wavelength peaks (blue, mid-blue, and violet), while the Bluephase G2 had two peaks (violet and blue).[27] Although there was a difference between the two resin composites, both produced a high DC, confirming that sufficient light was able to reach the deep area close to the pulp dentin floor when the exposure times recommended by the manufacturers were used.

The influence of thermal stimulus on pulp temperature depends on the cavity depth and the remaining dentin thickness.[9] Enamel and dentin have a low thermal conductivity[28] and diffusivity, thus helping to protect the pulp from noxious thermal stimuli.[29] When preparing a cavity, the thickness of the remaining dentin is reduced, and the dentin tubule surface area is increased.[28] This likely explains why a larger temperature rise was observed when light curing the adhesive system and why the potential to damage the pulp is greater. Additionally, the resin composite can partially block and consume part of the emitted energy delivered by the LCU,[30] explaining the smaller temperature rise when the resin composite is light cured compared to when light curing the adhesive alone. Of note, Figure 3 shows that most of the lower wavelengths of violet light do not reach the bottom of 2 mm of dentin or 4 mm of composite.

The photons of light emitted from LCUs contain energy, and this energy can be a concern to the vitality of the pulpal tissues.[31] The heat generated depends on the irradiance delivered, the wavelength and frequency of each photon, the amount of resin composite,[25] the thickness, and the thermal conductivity of dentin.[32] Thus, it is relevant to measure the irradiance and emission spectrum delivered to the specimens and to estimate how much light reaches the pulp chamber through different materials and the remaining dentin. In this study, the emission spectrum from the LCU was recorded using a laboratory-grade spectrometer-based system. This showed that although the LCUs in this study delivered slightly different spectral emissions,[27] this small difference was unlikely to cause a difference in the temperature rise when the bulk fill composite was light cured. Flowable resin composite has a greater resin content compared to paste-like composites, and this results in a greater temperature rise from the exothermic reaction.[17,33] However, in this study no difference was observed in the temperature rise inside the pulp for both resin composites. However, there was a difference in the exothermic

Table 6: *Mean (Standard Deviation) Exothermic Reaction (°C) of the Composites When Photocured by the Light Curing Lights (LCUs)[a]*

LCUs	AURA	Clearfil	SDR
Bluephase G2	4.7 (1.3) Aa	4.7 (1.4) Aa	7.7 (0.8) Ba
VALO Cordless	4.5 (0.7) Aa	5.2 (2.1) Aa	8.0 (0.5) Ba

[a] *Different letters indicate a significant difference: uppercase letters are used for comparing the material, and lowercase letters are used for comparing the LCU ($p<0.05$).*

temperature increase produced by the two resin composites: SDR produced more heat than did AURA (temperature difference of 3°C from the Bluephase G2 and 3.5°C from the VALO Cordless). Another important aspect is that the SDR (20 seconds) received only half of the energy (27.7 J/cm^2 from the Bluephase G2 and 25.7 J/cm^2 from the VALO Cordless) compared to AURA (40 seconds) (49.7 J/cm^2 from the Bluephase G2 and 49.4 J/cm^2 from the VALO Cordless). This factor may explain the higher temperature rise for AURA than for SDR when no simulated pulpal microcirculation was used.

The temperature increase depends on many factors, such as the type of stimulus, the thickness of the dental tissues, the pulpal microcirculation,[7] and the substrate used in the experiment.[15] The lower temperature rise observed when pulpal microcirculation was simulated is most likely due to the simulated blood flow that removed some of the heat generated by the LCU.[7,31] A lack of microcirculation may overestimate values in studies that assess changes in intrapulpal temperature.[34] The blood flow in the pulp of healthy teeth has been reported to be 40 mL/min per 100 g of tissue.[20,21] To better simulate body temperature, the pulp chamber of the teeth tested is usually kept at a temperature of 37°C.[6,7] However, in a recent study it was discovered that *in vivo* the coronal human pulp is closer to 35°C.[35] In other laboratory studies, the pulp flow inside the pulp chamber was achieved by flowing distilled water at 37°C through a needle at a flow rate of 1 mL/min.[6,7] Using the equipment described in this study, it is possible to adjust both the temperature and pressure, thereby simulating different clinical conditions: for example, in simulating the increased blood flow when the dentin-pulp complex is stimulated by operative procedures,[6] or simulating the decreased pulpal blood flow (by approximately 43%) that occurs some six minutes after mandibular block anesthesia using 2% lidocaine with epinephrine 1:100,000.[19]

A previous study has reported that an increase of 5.5°C within the pulp chamber caused irreversible damage in 15% of healthy rhesus monkey teeth.[4] Below this value, the pulp can recover, but there are some small histological damages. In an *in vitro* study, LCUs that were analyzed in the presence of simulated pulpal fluid flow did not produce a temperature rise within the pulp chamber above the critical point of 6°C.[7] Similar results have been shown in other studies using different LCUs with different light-curing modes.[10,34] As in the present study, as a result of the effect of the water flow in the interior of the chamber, the two LCUs tested proved to be safe to use. However, in the absence of pulpal microcirculation, the temperature increase within the pulp could be harmful to the pulp,[7] especially when the LCU delivered an irradiance above 1000 mW/cm^2.[36] In a previous study, without microcirculation a thin layer of the adhesive system was unable to block the heating produced by LCU and produced a temperature increase that was above the critical point.[24] The present study confirmed that without a simulated pulpal microcirculation, when the adhesive system was light cured with Bluephase G2 for 20 seconds, the temperature rise could become critical.

Although studies have evaluated the effect of the restorative procedures on changes in the pulp temperature,[15,36] few studies have simulated the microcirculation when collecting these values.[6,7,34] The presence of pulpal microcirculation and pressure in the teeth tested better simulates the real clinical condition.[7] However, *in vitro* experimental studies always have limitations, and further studies are necessary to determine the effect of a simulated microcirculation in the pulp on the thermal control of the oral environment. Another limitation of this study is that the dentin thickness was only estimated from two-dimensional radiographs; the remaining dentin thickness could be better evaluated using three-dimensional methods.

To the knowledge of the authors, there is no other equipment available on the commercial market that combines the three factors of flow, pressure, and temperature all in the same apparatus. This combination allows clinical conditions to be better studied under *in vivo* conditions in the laboratory, and it could also be used in other biomechanical tests, such as measuring the shrinkage strain or bond strength testing.

CONCLUSIONS

Within the limitations of this study, we conclude that simulating microcirculation in the pulp can help to dissipate the heat generated when light curing resins, resulting in a lower temperature increase. The temperature rise was greatest when the adhesive system was light cured for 20 s (4 to 6°C without any microcirculation) and lower when the 4-mm-thick bulk fill resin composites were photocured for 20 or 40 s which produced a temperature increase of approximately 3°C when there was no microcirculation present.

The flowable bulk fill resin (SDR) used in this study produced a greater exothermic reaction, allowed more light transmission (18.3% for VALO Cordless and 23.3% for Bluephase G2), and achieved a higher DC at the bottom of 4 mm compared to the AURA composite. Although the Bluephase G2 always delivered a higher irradiance, the VALO Cordless produced a higher DC at the bottom surface of the two resin composites tested.

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Regulatory Statement

This study was conducted in accordance with all the provisions of the local human subjects oversight committee guidelines and policies of approval of the Ethics Committee in Human Research of Federal University of Uberlandia. The approval code for this study is: 1.451.872.

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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Resin-Based Materials Protect Against Erosion/Abrasion—a Prolonged *In Situ* Study

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Clinical Relevance

The application of resin-based materials, including resin infiltrants, on previously eroded enamel subjected to prolonged *in situ* erosive and abrasive challenges, was able to arrest enamel loss. This is a promising finding to support conducting clinical trials testing resin infiltration.

SUMMARY

While patient compliance is key to preventive measures related to dental erosion, the application of resin-based materials could serve as an additional treatment to inhibit erosion progression. This *in situ* study evaluated the effect of applying resin-based materials, including resin infiltrant, on previously eroded enamel subjected to prolonged erosive and abrasive challenges. The factors under study were types of treatment (infiltrant [Icon], sealant [Helioseal Clear], adhesive [Adper Scotchbond Multi-Purpose Plus], and control [no treatment]); wear conditions (erosion [ERO] and erosion + abrasion [ERO + ABR]) and challenge time (5 and 20 days) in a single-phase study. The blocks were prepared from bovine enamel, eroded (0.01 M HCl, pH 2.3 for

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30 seconds) and randomized among treatments, wear conditions, and volunteers. The application of resin-based materials followed the manufacturers' recommendations. Twenty-one volunteers wore the palatal intraoral device, in which one row corresponded to ERO and the other to ERO + ABR. In each row, all treatments were represented (2 blocks per treatment). For 20 days, the erosive challenge was performed 4 times/day (immersion in 0.01 M HCl, pH 2.3, for 2 minutes) for the ERO condition. For the ERO + ABR condition, two of the erosive challenges were followed by abrasion for 15 seconds with fluoride dentifrice slurry. Enamel and/or material loss was measured using profilometry (initial, after treatment, and after the end of the fifth and 20th days of *in situ* erosive challenge) and analyzed by ANOVA models and Tukey's test (α=0.05). The results showed that the application of resin-based materials did not cause superficial enamel loss. The infiltrant group showed a thicker layer of material above the enamel compared with the other materials (*p*=0.001). After the erosive challenge, there was no difference between the conditions ERO and ERO + ABR (*p*=0.869). All materials protected the enamel against erosion progression compared with the control group (*p*=0.001). Based on these results, we conclude that the application of resin-based materials results in protection of previously eroded enamel subjected to *in situ* erosive and abrasive challenge for 20 days.

INTRODUCTION

Over recent decades, there has been increased concern regarding erosive tooth wear (ETW).[1,2] Ideal preventive measures might act on ETW etiological factors[3]; however, specific protective products or materials can be applied to erosive lesions to increase treatment effectiveness.[4,5] The application of resin sealant and bonding materials over enamel has been shown to form a physical barrier, preventing contact of the erosive agent with the tooth surface, reducing ETW progression.[5-17]

Another resin-based material that was tested for erosion inhibition is resin infiltrant,[13-15,17] which was originally developed for initial dental caries arrest.[18,19] The infiltrant consists of a special low-viscosity resin that penetrates into the porous body of carious white spot lesions, blocking the diffusion of acids. Results on the effectiveness of resin infiltration on dental erosion are controversial.[13-15,17] In the study of Zhao and others (2017),[17] the use of 15% HCl on enamel for 2 minutes before applying the infiltrant promoted about 15 μm of enamel loss, and no protection against erosion associated with abrasion was observed. In contrast, other studies showed the formation of a 100-μm thickness of infiltrant coating over enamel when similar enamel conditioning was applied.[13,15] Moreover, after the erosive challenge, no enamel was lost.[13,15] Probably the mode of application of the material influences its thickness and its ability to prevent erosion. In addition, it was previously demonstrated that the presence of the resin infiltrant only inside the eroded surface does not inhibit erosion progression, that is, the material must remain on the enamel surface.[15]

There is no method available to measure the ETW lesion clinically, and most of the studies have not been conducted *in vivo*.[20] *In vitro* studies allow researchers to control the experiment and use precise measuring methods, but provide a low level of scientific evidence. Alternatively, *in situ* studies are an intermediate protocol between *in vivo* and *in vitro* that permit exposing the tooth specimens to the oral environment with all its biological variations and contact with saliva.[21] It is known that saliva is the predominant biological factor influencing the development and progression of ETW.[22,23] Taking into account that ETW is a chemical-mechanical process of dental hard tissue loss, with acid as the main cause,[2] the association between chemical and physical insults better resembles the clinical situation. In addition, it is important to clarify the property of a thick layer of infiltrant coating to resist erosion associated with abrasion *in situ*. Therefore, the present *in situ* study evaluated the effects of applying resin-based materials, including resin infiltrant, on previously eroded enamel subjected to prolonged erosive and abrasive challenges. The hypothesis of this study was that the tested infiltrant, sealant, and adhesive materials would protect eroded enamel against ETW (a chemical-mechanical process).

METHODS AND MATERIALS

Experimental Design

This study had a single-blind, single-phase randomized *in situ* design. The factors under study were types of treatment (infiltrant [Icon], sealant [Helioseal Clear], adhesive [Adper Scotchbond Multi-Purpose Plus], and control [no treatment]), wear conditions (erosion [ERO], erosion + abrasion [ERO + ABR]), and challenge time (5 and 20 days). Sample size calculation was based on a pilot *in situ* study with four volunteers. A sample size of 20 volunteers was estimated based on a type I error (α) of 5%, type II error (β) of 20%, 3.8 μm of enamel and/or material loss as the minimum detectable difference in means, and 3.5 μm of enamel and/or material loss as the estimated standard deviation. Considering a possible dropout, 21 subjects were selected. Bovine enamel blocks (n=430) were eroded (HCl for 30 seconds), selected by their hardness (n=336), and randomized among treatments, wear conditions, and volunteers. Each volunteer (n=21) wore an acrylic palatal device with two rows, each containing eight bovine enamel blocks, one row corresponding to ERO and the other to ERO + ABR. In each row, all treatments and control were represented (two blocks per treatment). The erosive cycling procedure consisted of immersing the palatal device extraorally in 0.01 M HCl, pH 2.3, for 2 minutes, four times per day for 20 weekdays. On weekends, the devices were maintained immersed in artificial saliva. On the ERO + ABR condition, the first and third erosive challenges were followed by abrasion for 15 seconds with fluoride dentifrice slurry. The response variable was tissue loss, determined profilometrically after the fifth and twentieth weekday challenges.

Enamel Block Preparation

Four hundred thirty bovine enamel blocks ($4 \times 4 \times 3$ mm) were prepared from freshly extracted bovine incisors. The enamel blocks were cut using a cutting machine (Isomet low-speed saw, Buehler Ltd, Lake Bluff, IL, USA) and two diamond disks (Extec Corp, Enfield, CT, USA), which were separated by a 4-mm thick spacer. The block's surface was ground flat with water-cooled silicon carbide discs (320, 600, and 1200 grades of Al_2O_3 papers - Buehler) and polished with felt paper wetted by 1-μm diamond spray (Buehler). The blocks were ultrasonicated in deionized water for 10 minutes (T7 Thornton, Unique Ltda, São Paulo, SP, Brazil) between polishing steps.

The enamel blocks were then marked with a scalpel blade (Embramac, Itapira, SP, Brazil) to define the reference areas at 1.0 mm (border) and the test area at 2.0 mm (center) in width. The initial profile of the blocks was evaluated using a profilometer (Marh; MarSurf GD 25, Göttingen, Germany) and contour software (MarSurf XCR 20). The blocks were fixed to a special holder to standardize their positions. Their locations were recorded to allow their replacement after material application and the *in situ* phase. In each block, five readings were made of the relative position of the block on the *y*-axis at the following distances: 2.25, 2.0, 1.75, 1.5, and 1.25 μm. The profile of each reading was saved individually. Any block that did not present an adequate flat surface was discarded.

Surface hardness was determined by performing five indentations at distances of 100 μm from each other on the test area of the blocks (Knoop diamond, 25 g, 10 seconds, hardness tester from Buehler). The initial mean hardness of the blocks (SHi) was 355 ± 11 KPa/mm^2. The erosion lesion was developed by immersing the blocks in 0.01 M HCl (pH 2.3) for 30 seconds (17.6 mL/block), resulting in surface softening without tissue loss.[24] The surface hardness determination was performed again (SHd) with 5 measurements at a distance of 100 μm in relation to the initial indentations (SHi). Then 336 eroded enamel blocks with Knoop hardness numbers (KHNs) between 205 and 234 (mean surface hardness, 220±11 KPa/mm^2) were selected.

The enamel blocks were sterilized by ethylene oxide gas exposure. The reference areas of the blocks (2/3) were protected by cosmetic nail varnish (Maybelline Colorama, Cosbra Cosmetics Ltda, São Paulo, SP, Brazil).

Materials Application

The resin-based materials were applied on the middle third of the enamel surface, following the manufacturers' instructions (Table 1). Afterward, the nail varnish was removed from the reference areas of the enamel surface. The blocks were repositioned on the special holder on the table of the profilometer according to their position in the baseline measurements. Five readings were performed using the same software (XCR 20, MarSurf GD 25, Göttingen, Germany) and the same measurement parameters described above (initial profilometry). Then, after re-covering the marks and reference area with nail varnish, the samples were subjected to the *in situ* phase.

In Situ Phase

This study was approved by the Local Research Ethics Committee (protocol No. 556258) and conducted in full accordance with the Declaration of Helsinki. Informed consent was obtained from the subjects at the beginning of the study. Twenty-one healthy adult volunteers (aged 20-41 years) participated in this study after satisfying the following inclusion criteria: residing in the same fluoridated area (0.70 mg F/L), physiologically stimulated salivary flow rate >1 mL/min, and adequate oral

Table 1: *Materials, Composition, and Application Steps According to the Manufacturer's Instructions*

Material	Composition	Application Steps
Adper Scotchbond Multi-Purpose Plus Adhesive	Bis-GMA, HEMA (>99wt%)	Etch with 37% H_3PO_4 (30 s), rinse and air-dry, apply adhesive Adper Scotchbond (10 s), and polymerization
Helioseal Clear	Bis-GMA, TEGDMA (>99wt%)	Etch with 37% H_3PO_4 (30 s), rinse and air-dry, apply Helioseal Clear (15 s), and polymerization
Icon	Icon-etch: HCl, pyrogenic silicic acid, surface-active substances	Etch with 15% HCl (120 s), rinse and dry, 95% ethanol-and-air–dry, resin infiltration with a syringe (180 s), polymerization, and infiltrant reapplication (60 s), and polymerization
	Icon-dry: 99% ethanol;	
	Icon-infiltrant: methacrylate-based resin matrix, initiators, and additives	

Abbreviations: Bis-GMA, bisphenol A-diglycidyl ether dimethacrylate; HEMA, 2-hydroxyethyl methacrylate; TEGDMA, triethylene glycol dimethacrylate.

health with no caries, erosive lesions, or significant gingivitis or periodontitis. Exclusion criteria were systemic illness, pregnancy or breastfeeding, under orthodontic intervention, and use of fluoride compounds in the last 2 months.

The palatal appliances were made with acrylic resin on a plaster model. They had two columns, one on the right side and one on the left, with four cavities (10 × 10 × 3 mm) in each column. Two enamel blocks were affixed on each cavity. One column corresponded to ERO and the other to ERO + ABR. In each column, all treatments and the control group were represented (2 blocks per treatment). The enamel blocks were fixed on the appliances with wax. An orthodontic wire was attached to the ends of the cavities, passing over the blocks without touching them on the column corresponding to erosion (Figure 1). This procedure was performed in order to prevent abrasion of the blocks by the tongue. The position of the blocks corresponding to each group was represented in each row. The position of the groups in the rows was randomly determined for each volunteer to ensure that in the role experiment, each row of the appliance had different groups (Figure 1). The positions of the ERO and ERO + ABR columns alternated among participants.

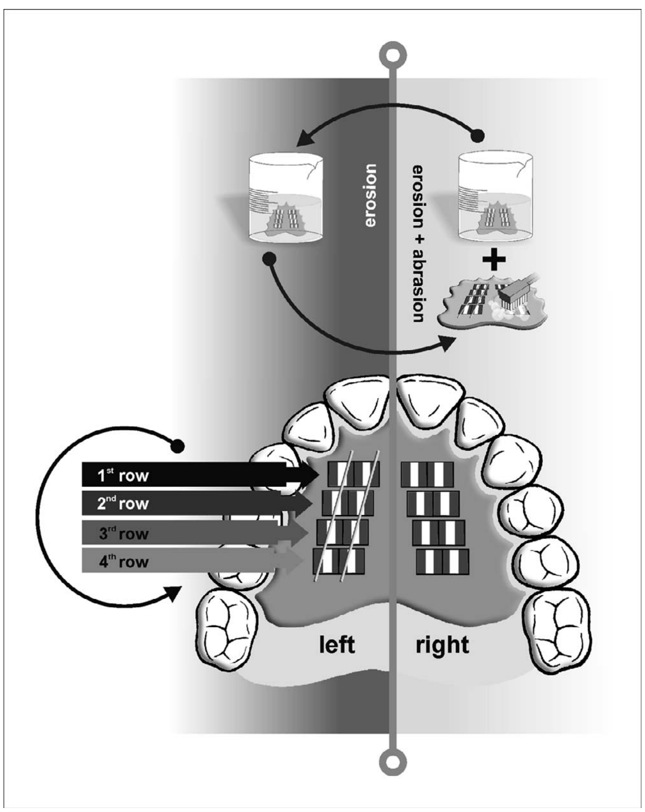

Figure 1. *Schematic illustration of the intraoral appliances.*

Seven days before and throughout the experimental phase, the volunteers brushed their teeth with a standardized toothbrush (Curaprox 5460 Ultrasoft, Curaden Swiss, Switzerland) and fluoride toothpaste (Triple Action, 1450 ppm F as sodium monofluorophosphate, Colgate, São Bernardo do Campo, SP, Brazil) after meals, without the appliances in the mouth. They were requested not to use any other fluoride product. The volunteers were trained to correctly follow the experimental *in situ* procedures. They also received written instructions and a form to register every step they followed in the *in situ* phase.

The subjects wore the intraoral appliance for 20 weekdays and business hours (7:30 AM to 6 PM ; total of 8 hours and 30 minutes of daily use), and removed it for 1 hour 45 minutes during meals[25] and on weekends. The time without the appliance provided for greater comfort of the volunteers. It was important to standardize the acid attack among the participants independently of their individual diet. When not in the mouth, the appliances were kept immersed in artificial saliva, whose composition was 0.33 g KH_2PO_4, 0.34 g Na_2HPO_4, 1.27 g KCl, 0.16 g NaSCN, 0.58 g NaCl, 0.17 g $CaCl_2$, 0.16 g NH_4Cl, 0.2

g urea, 0.03 g glucose, 0.002 g ascorbic acid, 2.7 g mucin, and 1000 mL distilled water at pH 7.0.[26] Tooth erosive challenge was simulated by immersing the appliances into 150 mL 0.01 M HCl, pH 2.3, at room temperature (37°C) for 2 minutes; this was done *ex vivo* to protect the volunteer's teeth from damage. The acid challenge was repeated four times daily at the following schedule: 8 AM, 10 AM, 2 PM, and 4 PM (whereas from 12 PM to 1:45 PM, the appliances remained outside the mouth). For the ERO + ABR condition, after the first and third acid immersion of the appliance, the volunteers applied one drop of fluoride dentifrice slurry 1:3 (Triple Action, 1.450 ppm F, Colgate Palmolive, São Paulo, Brazil) on each enamel block and only on the column corresponding to ERO + ABR, brushing each block for 15 seconds using an electric toothbrush (Oral-B Precision Clean, Procter & Gamble, Rio de Janeiro, Brazil) with a timer. The participants removed the appliances from their mouth to perform the erosive and erosive plus abrasive challenges.

Final Profilometry

At the end of the fifth and last day of the *in situ* phase, the enamel blocks were removed from the appliance and the cosmetic nail varnish was removed from the reference areas. The blocks were repositioned on the special holder on the profilometer table and profilometric analysis (five readings) was performed again at the same sites as the baseline measurements (initial profilometry).

Since the enamel specimens could be precisely repositioned in the profilometer, it was possible to match the baseline with the other profiles.[13] The graphs were superimposed and analyzed using a specific software program (MarSurf XCR 20, Göttingen, Germany). The resin-based material thickness after application and material and/or enamel loss after erosive cycling were quantitatively determined by calculating the average thickness of the materials and the depth of the eroded surface relative to the baseline surface profiles, respectively. The block enamel loss was expressed as the mean of five graphs.

Statistical Analysis

Statistical analysis was performed with SigmaPlot version 12.3 (2011 Systat Software, Erkrath, Germany). For the thickness of the coating layer after placement, two-way repeated measure ANOVA was applied. Three-way repeated measure ANOVA was applied to analyze the thickness of the coating layer and the enamel loss after the *in situ* phase, considering the three factors under study (type of treatment, wear condition, and times of challenge, the last being the repeated measure). The *post hoc* test used was Tukey's. For all cases, the level of significance was set at 5%.

RESULTS

The thickness of the coating layer of the studied materials after application is provided in Table 2, column "After treatment." There was a statistically significant difference among materials ($p<0.001$). Resin infiltrant showed the thickest layer, followed by sealant, which was followed by adhesive. There was no difference between blocks to be eroded vs abraded ($p>0.05$).

After the *in situ* phase, there was a statistically significant difference among the materials ($p<0.001$), between periods of challenge ($p<0.001$), and interaction between these criteria ($p<0.001$) (Table 2). Erosion resulted in a similar alteration of enamel and resin-based materials compared with the erosion associated with abrasion ($p>0.001$). For each material, there was no significant difference in thickness of the coating layer between 5 and 20 days of challenge. All the studied materials provided enamel protection against erosion whether associated or not with abrasion after 5 and 20 days because they differed from the control group. Enamel loss of the control group subjected to 20 days of erosion and/or abrasion was statistically significantly higher than 5 days.

Table 3 shows data on material loss (thickness after treatment minus thickness after *in situ* challenge) compared with enamel loss. There was a statistically significant difference among the materials ($p<0.001$), between challenge periods ($p<0.001$), and interaction between these criteria ($p<0.001$), but no difference was found between wear conditions ($p>0.001$). After 5 days of challenge, loss of material and enamel were statistically similar, while after 20 days, all materials were more resistant than enamel. Considering each material separately, there was no statistically significant difference of material loss between the fifth and twentieth days of challenge. The loss of enamel on the twentieth day of challenge was higher than that on the fifth day.

DISCUSSION

The results of the present study indicate that the application of resin-based materials, including infiltrant, was able to arrest enamel loss when chemical

Table 2: *Mean Material Thickness and/or Enamel Loss (μm±SD) After Treatments and Following In Situ Challenges (Erosion and Erosion Associated with Abrasion) of 5 and 20 Days*[a]

Wear Condition	Type of Treatment	After Treatment	5 Days of Challenge	20 Days of Challenge
Erosion	Adhesive	55.82 ± 26.59 A	53.99 ± 24.56 ab	47.86 ± 27.39 a
	Sealant	92.03 ± 38.74 B	83.59 ± 36.46 bc	78.37 ± 37.62 c
	Infiltrant	110.78 ± 19.67 C	107.28 ± 20.00 d	99.77 ± 20.42 d
	Control	−0.09 ± 0.03	−6.39 ± 4.65 f	−29.28 ± 42.85 e
Erosion + abrasion	Adhesive	66.43 ± 34.09 A	62.68 ± 34.58 ab	56.08 ± 36.57 a
	Sealant	87.06 ± 33.88 B	79.00 ± 27.49 bc	73.99 ± 25.50 c
	Infiltrant	116.87 ± 28.07 C	111.58 ± 28.12 d	107.68 ± 28.50 d
	Control	−0.10 ± 0.04	−11.30 ± 6.26 f	−50.29 ± 53.03 e

[a] *For column "After Treatment," different uppercase letters denote statistically significant differences (two-way repeated measures ANOVA, Tukey's test;* $p<0.05$*), the control group was not considered in this analysis. For columns "5 (20) Days of Challenge" and the lines "Erosion" and "Erosion + Abrasion," different lowercase letters denote statistically significant differences (3-way repeated measures ANOVA, Tukey's test;* $p<0.05$*). Positive and negative values correspond to enamel loss and presence of materials above enamel, respectively.*

and mechanical insults were applied. The mechanism of action of the professional application of resin-based materials on eroded enamel is the formation of a protective coating that inhibits contact of the acids with enamel,[5,27] depending on the coating's duration. Therefore, the materials' resistance to the oral challenges, mainly hydrolysis, acids, and mechanical forces, is very important. The *in situ* protocol of prolonged erosive and abrasive challenge used in this study is closer to the *in vivo* condition than the *in vitro* ones.[21] However, there are limitations that must be taken into account when transposing the results to the clinical situation. The enamel blocks were worn inside intraoral appliances *in situ*, but were eroded and abraded by brushing outside the oral environment for the sake of standardization and minimal risk to the volunteers.[28] This approach cannot adequately simulate the biological factors, such as dilution of the erosive solution by saliva or protection from erosion and abrasion by the natural pellicle, producing a higher amount of wear than in the clinical situation.[28-30] In addition, the use of electric toothbrushes ensures a standardized movement of the brush over the sample surface but also has a higher potential to damage eroded teeth than do manual brushes with the same force.[31] Brushing forces were not controlled, but the volunteers were carefully trained and instructed to brush the blocks with minimal force.

It is difficult to convert experimental characteristics and parameters—even *in situ* studies—into real, everyday situations.[28] In this study, the parameters were chosen to exaggerate clinical conditions so as to test the ability of resin-based materials to protect against ETW in a worst-case scenario. Assuming that in the daily situation, the tooth may be subjected to a maximum of 3 minutes of erosive challenge and 5 seconds of brushing with an electrical toothbrush,[17,28] a total of 160 minutes of acid attack and 120 seconds of brushing *in situ* might represent about 4 months of erosion and abrasion. The studied resin-based materials showed minimal wear (7% to 15%) during this period, and the mechanical toothbrushing forces did not take them away of the enamel. In contrast, clinically measuring palatal tooth wear after coating the dentin with

Table 3: *Mean Material Thickness Loss (Thickness After Treatment Minus Thickness After* In Situ *Challenge) and Enamel Loss (μm±SD) Following* In Situ *Challenges (Erosion and Erosion Associated With Abrasion) of 5 and 20 Days*[a]

Wear Condition	Type of Treatment	5 Days Challenge	20 Days Challenge
Erosion	Adhesive	1.83 ± 17.94 a	7.96 ± 24.79 ab
	Sealant	8.44 ± 8.34 ab	13.65 ± 12.65 b
	Infiltrant	3.50 ± 4.02 a	11.01 ± 9.53 ab
	Control	6.29 ± 4.65 ab	29.19 ± 42.85 c
Erosion + Abrasion	Adhesive	3.75 ± 4.82 a	10.34 ± 9.11 ab
	Sealant	8.06 ± 16.69 ab	13.06 ± 18.51 b
	Infiltrant	5.28 ± 6.32 a	9.18 ± 7.25 ab
	Control	11.20 ± 6.26 ab	50.19 ± 53.03 c

[a] *Different lowercase letters denote statistically significant differences (three-way repeated measures ANOVA, Tukey's test,* $p<0.05$*).*

resin-based materials showed that the preventive effect of the bonding agent lasted only 3 months.[9,10] On the other hand, a fissure sealant had lasted 9 months.[9,10] Not only the resin material's wear resistance can protect the enamel coating, but also retention of the material is of major importance for the acid-protective effect.[13,14] For resin materials' retention, the micromechanical interlocking of tiny polymerized resin tags within porosities of the acid-etched enamel surface provides the main achievable bond mechanism for the dental substrates.[32] The mechanism in dentin is more complex and less predictable because of the intrinsically hydrophilic characteristics associated with the organic matrix and its components.[32] Therefore, better results are expected for the application of acid protective layers on enamel. The differences between dentin and enamel and among commercial brands tested might explain the variation of results.

The measured mean layer of resin material formed on the enamel surface ranged from 57.86 μm (adhesive) to 107.68 μm (infiltrant). There was a great variation among the blocks for each studied material and among different materials. The application of materials was conducted by a single trained dentist (G.C.O.) and, even considering that the application was standardized, variation in *in vitro* thickness was observed. Therefore, this procedure might be subject to much more variation *in vivo*. Despite this variation in adhesive and sealant thickness among the different studies,[13,15-17,33] these materials formed a resin coating over the enamel. However, there is no consensus regarding the coating formation after the application of resin infiltrant.[13,15,17]

Zhao and others found enamel loss after treating enamel previously eroded by 15% hydrochloric acid (HCl) with resin infiltrant, while the formation of a material layer of approximately 4.5 μm was noticed when the enamel was not etched. The application of HCl was intended to remove the superficial, hypermineralized layer of the carious lesion,[34] resulting in tissue loss of approximately 15 μm when used on sound enamel.[34] Considering that eroded lesions have a lower mineral content and a mechanically less stable surface, it is likely that the softened layer of the initial erosive lesion might be removed by HCl. This is a probable side effect of resin infiltration that can be offset by resin coverage. Taking into account the fragility of the enamel etched by HCl, the infiltrant was applied with caution, gently positioning the brush onto the enamel without pressure. This procedure might be the reason for the formation of a thick layer of material in contrast to the occurrence of enamel loss in another study.[17] An alternative for the deleterious effect of HCl is the use of resin infiltration without previous enamel conditioning, which was shown to be sufficient to promote enamel coating against erosion.[15] However, this procedure resulted in less penetration on eroded enamel.[15,16] Another intermediate option that might be tested for eroded enamel is the use of H_3PO_4, which is capable of creating a microretentive surface for successful capillary diffusion and penetration of the infiltrant on sound enamel.[35,36]

There is *in vitro* evidence that eroded enamel is more susceptible to toothbrush abrasion, resulting in higher enamel loss than erosion alone.[37-40] Also for composite resins, erosion associated with abrasion resulted in higher material loss *in vitro*.[41] However, in the present study, no statistically significant difference was observed between erosion and erosion plus abrasion for enamel and the tested resin-based materials. It is hypothesized that in an *in situ* situation, there are biological factors that vary among subjects and influence the degree of wear.[1] Especially on the twentieth day of challenge, the standard deviation indicated a greater variation in enamel loss. At first, it was thought that this variation was due to the absence of brushing force standardization, but when the enamel was subjected only to erosion, a similar variation was observed. Regarding the resin-based materials, the high standard deviation had already been observed after their application.

It is expected that the resistance of the coating materials to the oral environment ensures their acid or mechanical protective effect over time.[42] Overall results of the present study indicate a similar amount of material loss over time, from the fifth to the twentieth day of assessment, with no difference among the materials. Although it was observed that at the end of 5 days of challenge, material and enamel loss were statistically similar; after 20 days, the loss of material was less than that of enamel. The higher enamel loss compared with resin-based materials is in accordance with previous studies.[43,44] This performance is mainly attributed to the composition of the materials. Even considering that the acid attack particularly compromises the polymerized net of the organic portion of materials, their overall resistance to erosion is greater than that of hydroxyapatite.

The susceptibility of resin-based materials to chemical and mechanical challenges is influenced by the type of monomer and filler content. In this case, all tested materials were filler-free, which diminishes their resistance.[45] The composition of infiltrant is based on methacrylate monomers, mainly triethylene glycol dimethacrylate (TEGDMA), that shows a higher penetration coefficient than do resins containing large amounts of bisphenol A-diglycidyl ether dimethacrylate (Bis-GMA) or urethane dimethacrylate.[18] On the other hand, TEGDMA molecules have a greater affinity to water molecules compared with Bis-GMA, which increases the presence of water uptake and the likelihood of hydrolysis.[46,47]

Helioseal Clear (Ivoclar Vivadent, Valencia, CA, USA), as a hydrophobic material based on a combination of Bis-GMA and TEGDMA, is less susceptible to water degradation than is the infiltrant. The bonding agent tested (Adper Scotchbond Multi-Purpose Bond, 3M, St Paul, MN, USA) is composed basically of Bis-GMA and hydroxyethylmethacrylate (HEMA). As it was developed to penetrate a previously etched surface, HEMA was introduced to optimize the wetness to the dental substrate to improve its penetrability. Therefore, its resistance was not expected. Likely, its performance demonstrating less loss might be due to its proper penetration into enamel, resulting in the formation of an initially thin layer on the surface that was resistant over time. Between the weekdays of erosive challenges, the studied blocks were immersed in artificial saliva, which ensures the simulation of hydrolysis challenge.[46,47] However, all studied materials succeeded in preventing enamel wear under the erosive and abrasive protocol compared with the group without protection. In addition, the thicknesses of material loss among the studied resin-based materials, including resin infiltration, were similar.

CONCLUSION

All of the studied resin-based materials can be considered promising in arresting erosive tooth wear, but clinical trials are necessary to confirm this promise.

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Regulatory Statement

This study was conducted in accordance with all the provisions of the local human subjects oversight committee guidelines and policies of the Bauru Dental School. The approval code for this study is 556.258 approval 2/26/2014.

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, or company presented in this article.

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Structural Integrity Evaluation of Large MOD Restorations Fabricated With a Bulk-Fill and a CAD/CAM Resin Composite Material

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Clinical Relevance

Both bulk-fill and CAD/CAM resin composite materials can be used to restore teeth with extensive cavity designs but with the CAD/CAM material potentially providing more increase in their structural integrity.

SUMMARY

Aims: To evaluate the effect of two composite restorative techniques (direct bulk fill vs indirect CAD/CAM) on the fracture resistance and mode of fracture of extended mesio-occlusal-distal (MOD) cavity preparations.

Methods: Fifty-one sound human mandibular third molars were divided into three groups (n=17). Extended bucco-lingual MOD cavities were prepared. Teeth in group 1 were restored with a bulk-fill resin composite (Filtek Bulk-Fill Posterior Restorative), teeth in group 2 were restored with composite computer-aided design/computer-aided manufacturing (CAD/CAM) inlays (Lava Ultimate), and teeth in group 3 served as control and remained intact. All specimens were submitted to thermocycling, and a fracture resistance test was performed using a Universal testing machine (0.5 mm/min). Mode of fracture was classified into five types. One-way analysis of variance and the Duncan test were used to analyze the fracture load data at a significance level of $\alpha = 0.05$. A chi-square test was used for the

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analysis of fracture mode between the restorative groups.

Results: Statistical analysis showed significant differences in fracture resistance among the experimental groups. The teeth restored with the bulk-fill composite exhibited lower fracture resistance (1285.3±655.0 N) when compared to the teeth restored with the composite CAD/CAM inlays (1869.8±529.4 N) ($p<0.05$). Mode of fracture showed the same distribution between the restorative groups.

Conclusions: Although both types of restorations failed at loads larger than those found in the oral cavity, the CAD/CAM composite inlays increased the fracture resistance of teeth with large MOD cavities when compared to direct bulk-fill composite restorations. The majority of fracture types were intraorally repairable for both restorative techniques.

INTRODUCTION

Contraction stresses that develop during placement of resin composite (RC) materials due to polymerization shrinkage are a major drawback in contemporary restorative dentistry.[1] Although RC restorative materials are commonly used in large and deep cavities, they often result in inconclusive success. Polymerization shrinkage of composite materials compromises the sustainability of the restoration since it may lead to decreased dentin bond strength, cuspal deflection, internal gap formation, and postoperative sensitivity.[1,2] As a matter of fact, incremental buildup of multiple thin layers is required mainly to ensure curing and to potentially reduce the consequences of shrinkage stress.

Incremental filling techniques are considered clinically sensitive and time-consuming procedures. Manufacturers have recently introduced a novel type of RC, namely, the bulk-fill composite. This type of RC is marketed in either high or low viscosity, and its main advantage is that it can be placed in 4- to 5-mm-thick increments, thus eliminating the time-consuming element of RC placement. Furthermore, bulk-fill RC exhibits lower volumetric shrinkage, resulting in lower contraction stresses.[3] In order to achieve sufficient polymerization depth, the fillers of bulk-fill composites were modified. In particular, there is an increase in filler size (>20 μm) and/or a reduction in filler load, mainly in the low viscosity bulk-fill resin-based composites.[4] Furthermore, novel photoinitiators (ie, Ivocerin for Tetric EvoCeram Bulk-Fill) and different combinations of high-molecular-weight monomers aim to contribute to a desirable polymerization reaction.[5]

With regard to their performance, research has shown that bulk-fill RCs present similar and sometimes superior properties compared to conventional RC materials.[3,6,7] As far as their clinical effectiveness is concerned, two randomized clinical studies showed that low-viscosity bulk-fill RC materials placed with a 4-mm bulk-fill technique presented good clinical effectiveness during a three- and a five-year follow-up, showing slightly better but not statistically significant durability compared to the conventional 2-mm layering technique.[8,9]

In an attempt to overcome the shortcomings of polymerization shrinkage and especially in large cavities, the use of indirect restorations is often recommended, where the contraction stresses are only limited in a small surface occupied by the luting cement between the tooth and the restoration.[10,11] Inlays/onlays can be either laboratory (indirect technique) or chairside fabricated using computer-aided design/computer-aided manufacturing (CAD/CAM) technology (semidirect technique).[12] The materials of choice for this type of restoration are either ceramic or RC. Recently, there has been an evolution of CAD/CAM resin-based materials. Various changes in their polymerization methods (high pressure, high temperature) as well as in their structure (glass ceramic networks) have improved their physical properties in comparison to their ceramic counterparts.[13,14] Due to the complexity of their structure, different names have been used for this group of materials by their manufacturers, such as resin nanoceramics, hybrid ceramics, ceramic resins, or glass ceramics in a resin interpenetrating matrix.[15]

Today, composite CAD/CAM materials appear with enhanced mechanical properties, elastic modulus near that of dentin, and optimal stress absorbance in comparison to their laboratory counterparts. Furthermore, CAD/CAM allows construction of materials with low brittleness, small marginal crack percentages, safe intraoral reparability, and potential thickness up to 0.2 mm.[16,17]

Resin-based CAD/CAM materials have been investigated mainly in the form of inlays, onlays, and crowns with tooth preparation designs according to textbook traditional designs.[18] It has been found that they present satisfactory behavior in terms of flexural strength and flexural modulus under occlusal stress conditions.[19] Batalha-Silva and others[20] concluded that CAD/CAM composite inlays increased the fatigue resistance and decreased the

Table 1: *Technical Characteristics of the Tested Materials of the Study According to Manufacturers*

Material	Classification	Organic Matrix	Fillers	Filler Content	Manufacturer	Flexural Strength (MPa)	Flexural Modulus (GPa)	Lot Number
Filtek Bulk-Fill Posterior Restorative (BF)	High-viscosity bulk-fill resin-based composite	AUDMA UDMA AFM DDDMA	SiO_2 (20 nm), ZrO_2 (4-11 nm), ZrO_2/SiO_2 nanoclusters YbF_3 (100 nm)	76.5 wt% 58.4 vol%	3M ESPE, (St Paul, MN, USA)	150	10.5	N706090
Lava Ultimate (LV)	Prepolymerized resin-based CAD/CAM block	Bis-GMA UDMA Bis-EMA TEGDMA	SiO_2 (20 nm), ZrO_2 (4-11 nm), ZrO_2/SiO_2 nanoclusters (0.6-10 μm)	80 wt%	3M ESPE	204	12.8	N721283

Abbreviations: AUDMA, aromatic urethane dimethacrylate; UDMA, urethane dimethacrylate; AFM, addition-fragmentation monomers; DDDMA, 1,12-dodecanediol dimethacrylate; Bis-GMA, bisphenol A-glycidyl methacrylate; Bis-EMA, bisphenol A-ethyl methacrylate; TEGDMA, triethylene glycol dimethacrylate.

crack propensity of large mesio-occlusal-distal (MOD) restorations when compared to direct restorations. Moreover, Ender and others[21] found that self-adhesive–luted CAD/CAM composite inlays showed similar marginal adaptation and fracture strength to glass-ceramic inlays.

There is limited literature regarding the properties of these two restorative modalities. Additionally, there is no evidence of their performance when a substantial amount of tooth structure is missing. It was therefore of interest to investigate the limitations of these materials when the size of the cavity is excessive. The purpose of this study was to evaluate the fracture resistance and mode of fracture of large MOD restorations using a highly viscous bulk-fill resin-based composite and a resin-based CAD/CAM material.

The null hypothesis was twofold. First, there will be no statistically significant difference between the experimental groups of the study regarding their fracture resistance. Second, there will be no statistically significant difference in the fracture mode between the two tested restorative techniques.

METHODS AND MATERIALS

Materials

A highly viscous bulk-fill resin-based composite (Filtek Bulk-Fill Posterior Restorative, 3M ESPE, St Paul, MN, USA) and a prepolymerized composite CAD/CAM material (Lava Ultimate, 3M ESPE) were investigated in this study. The shade of the composite materials was A3. The technical characteristics of the materials are presented in Table 1.

Preparation of Tooth Specimens

Fifty-one sound human third mandibular molars freshly extracted for orthodontic reasons were selected for this study. The teeth presented similar bucco-lingual and mesio-distal dimensions ($\leq$10% difference) and were randomly divided into three groups of 17 teeth each. The teeth were examined for cracks or other structural deficiencies under an optical microscope (20× magnification). Calculus deposits and soft tissues were removed with a hand scaler (13S/14S modified Gracey, Hu-Friedy Manufacturing Co, Chicago, IL, USA) and an ultrasonic scaler (EMS SA, Nyon, Switzerland). The teeth were stored in 0.2% thymol solution (renewed every five days) for no longer than three months before the onset of the experiment. Before the experiment, the teeth were mounted in acrylic bases, covering each root up to 3 mm below the cemento-enamel junction with acrylic resin (Palapress, Heraeus Kulzer GmbH, Dormagen, Germany).

Restorative Procedures

In group 1 (Bulk-Fill [BF]), MOD cavities were prepared utilizing a high-speed hand piece (Allegra TE-95, W&H GmbH, Bürmoos, Austria) under water cooling using diamond burs (959 KRD, 8959 KR Komet Dental, Gebr. Brasseler GmbH & Co, KG, Lemgo, Germany), which were replaced every five preparations. The hand piece was adapted to a parallelometer in order to ensure repeatability of preparations as far as the cavity dimensions were concerned. Slot-type MOD cavities were prepared with rounded internal angles, diverging buccal and lingual walls (5° to 10°), 5-mm bucco-lingual width, and 4-mm occlusal depth (Figure 1). Cavities were restored using Filtek Bulk-Fill Posterior Restorative (3M ESPE); etching of the cavity walls was performed for 30 seconds in enamel and 15 seconds in dentin with 35% phosphoric acid (Scotchbond Universal Etchant, 3M ESPE) and abundant rinsing and air-drying. Subsequently, the bonding

Figure 1. *Representative mesio-occlusal-distal cavity preparation ready for being restored.*

agent (Single Bond Universal Adhesive, 3M ESPE) was applied using an applicator tip and gentle implementation for 10 seconds. The bonding agent was then photopolymerized for 20 seconds using an LED light-curing unit (Elipar S10, 3M ESPE) at 1200 mW/cm^2 with standard curing mode, according to the manufacturer's instructions. The bulk-fill composite was placed into the cavities in one increment, and the occlusal surface was formed using prefabricated occlusal matrices (Occlu-Print, Hager & Werken GmbH & Co KG, Duisburg, Germany) in order to have a repeatable pattern and to prevent an oxygen inhibition layer during curing. Each surface (mesial, occlusal, and distal) of the restorations was light cured for 20 seconds according to the manufacturer's instructions. Finishing and polishing of the restorations was performed with a polishing disk system (Sof-Lex finishing and polishing disks, 3M ESPE).

In group 2 (Lava Ultimate [LV]), cavity preparations followed the same method as described above for group 1. The teeth were restored with inlay restorations that were fabricated using the Cerec 3 CAD/CAM system, CEREC 3D, version 3.85, Sirona Dental Systems, GmbH, Bensheim, Germany) with an average thickness of 3.5 mm at the central groove. A resin-based CAD/CAM material (Lava Ultimate Restorative for CEREC, 3M ESPE) was used for the preparation of the inlays. Restorations were mechanically polished using the same polishing disk system as in group 1. Internal surface treatment of the restorations included air abrasion (Aquacare Twin Dental air abrasion unit, Velopex Int, Medivance Instruments Ltd, London, UK) with 29-μm aluminum oxide particles at 0.2-MPa air pressure and was followed by 35% phosphoric acid cleaning. The internal surfaces were then rinsed for 30 seconds, air-dried, and silanated with Monobond S (Ivoclar Vivadent AG, Schaan, Liechtenstein) using a microbrush; allowed to react for 60 seconds, and dispersed with a strong stream of air. Tooth preparations were thoroughly cleaned and air-dried before cementation. The luting material was a self-adhesive resin cement (RelyX Unicem, 3M ESPE). Photopolymerization was performed initially for three seconds, and after careful removal of the cement excess, each surface was light cured for 20 seconds in accordance with the manufacturer's instructions. Finally, finishing and polishing of the restorations was performed with the polishing disk system (Sof-Lex finishing and polishing disks, 3M ESPE).

In group 3 (intact [INT]), which was the control group of the study, the teeth remained intact.

Artificial Aging

The specimens were submitted to thermal stress in a thermal cycling machine (10,000 cycles in a sequence of 37°C, 5°C, 37°C, and 55°C) with a dwell time of 10 seconds and a transport time of five seconds. Following thermocycling, all specimens were stored in distilled water at 37 ± 1°C for 24 hours before fracture testing.

Fracture Resistance Test and Fracture Mode Distribution

Each specimen was loaded axially on their occlusal surface at a crosshead speed of 0.5 mm/min in a universal testing machine (Testometric M350-10KN, Linkoln Close, Rochdale, UK). In order to keep the specimen firmly in place, a customized stainless-steel device was made and placed on the testing machine. A plunger with a steel ball (6-mm diameter) that made a tripod contact with the cusps was used to transmit the compressive force until fracture occurred (Figure 2).

The mode of fracture of the restorations was detected after failure using a classification previously described by Burke and others.[22] According to this classification, the specimens were assigned to the following categories based on the pattern of crown failure using standardized photography:

Type I - fractures involving minimal destruction of tooth structure
Type II - fractures involving one cusp and intact restoration

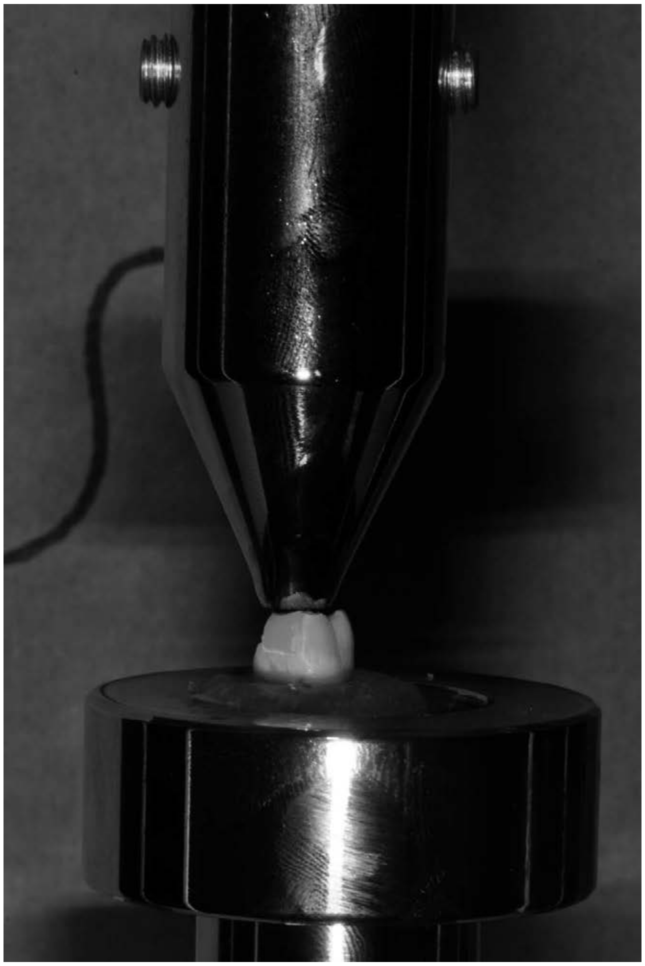


Figure 2. *Layout of the tooth specimen and stainless-steel device used for fracture resistance testing.*

Type III - fractures involving at least one cusp and up to one-half of restoration

Type IV - fractures involving at least one cusp and more than one-half of restoration

Type V - severe fractures involving tooth structure completely and/or longitudinal fracture that may require extraction of the tooth.

Statistical Analysis

The data were statistically analyzed using SPSS Statistics 20.0 software (IBM Corp, Chicago, IL, USA). Normality and homogeneity of the data were checked using the Kolmogorov-Smirnov test (p=0.937 for BF, p=0.967 for LV, and p=0.849 for INT) and the Levene test (p=0.311), respectively. One-way analysis of variance and the Duncan test were used to compare the mean fracture load among the experimental groups. The level of statistical significance was preset at $\alpha = 0.05$. In addition, a chi-square test was used for analysis of fracture mode between the restorative groups. The sample size (n=14) was calculated considering 80% power and a significance level of 5%.

RESULTS

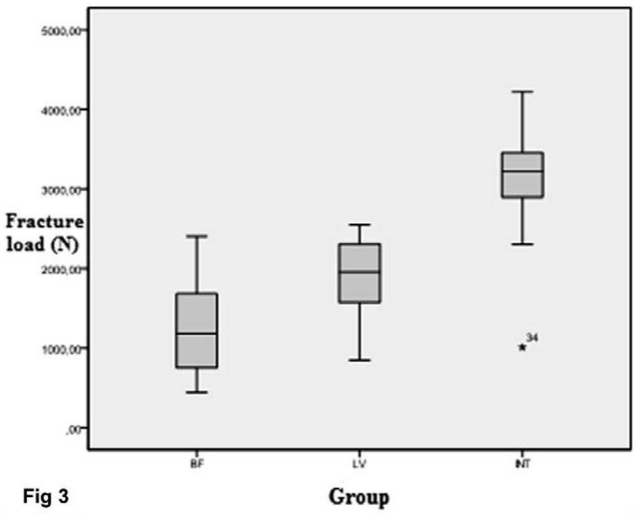
Three specimens (two from group 3 and one from group 2) were rejected due to wrong fixation in the acrylic resin bases. Further, the box-plot method revealed one outlier in the control group (Figure 3). Therefore, it was excluded from the analysis to avoid any erroneous results. Table 2 shows the frequency of the remaining specimens, which were ultimately used throughout the analysis. It must be noted that in determining the group sample sizes, a rule of thumb was followed that suggests that in experimental research with tight experimental controls, successful research is possible with samples as small as 10 to 20.[23] Further, according to the Levene test, these unequal sample sizes did not produce unequal variances. Therefore, SPSS was set up to deal with the problem of unequal sample sizes and unequal variances by using the Duncan *post hoc* test to compare the mean fracture load among the experimental groups.

Fracture Resistance Measurements

Mean values and standard deviations of fracture load (N) of the experimental groups of the study are illustrated in Figure 4. The bulk-fill composite restorations presented the lowest fracture resistance (1285.3±655.0 N) ($p<0.05$) followed by CAD/CAM composite restorations (1869.8±529.4 N), while the control group exhibited the highest fracture resistance (3198.0±490.7 N) ($p<0.05$). One-way analysis of variance and the Duncan test revealed that there was a statistically significant difference of the fracture resistance between the three groups ($p<0.001$). More specifically, there was a statistically significant difference between the restored groups (groups 1 and 2) as well as the restored and the intact teeth (group 3) ($p<0.05$).

Mode of Fracture Analysis

The mode of fracture of the specimens was reported immediately after the fracture resistance test, and the distribution is shown in Table 3. Representative photographs of each type of fracture are illustrated in Figure 5a-e. Application of the chi-square homogeneity test revealed that in all cases of fracture types, the distributions were the same between the two restorative groups.



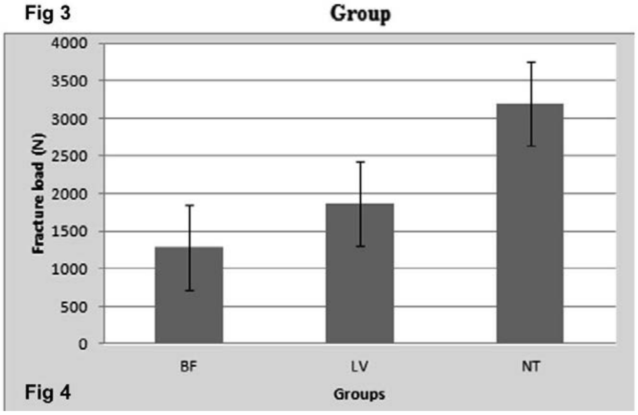


Figure 3. *Boxplot method, which reveals the outlier data.*

Figure 4. *Means and standard deviations of fracture resistance (N) of the experimental groups of the study.*

DISCUSSION

This study evaluated the fracture resistance and mode of fracture of posterior teeth with cavity preparation designs with an extensive isthmus restored with two restorative techniques—a direct RC and a chairside CAD/CAM—in an attempt to assess the most appropriate in terms of maximizing the structural integrity of the restored teeth. Many times, the clinician is faced with the dilemma of whether to restore a cavity with a wide isthmus with an intracoronal restoration or to proceed with traditional cusp protection protocols with partial or full-coverage crowns. The introduction of new materials and the evolution in adhesive technology can potentially give more conservative options for the restoration of these teeth. Two modern materials were tested—a direct bulk-fill composite and a hybrid RC CAD/CAM—following the respective adhesive/cementation protocols as suggested by the manufacturers. It was not the intention to assess the effect of different adhesive protocols in the fracture resistance of the restored teeth, only the effect of the two different restorative approaches to the restoration of teeth with extensive cavity designs.

In the current investigation, the restorations were subjected to a static loading test until failure occurred after artificially aged via thermocycling. The type of load exerted was in the form of a compressive force perpendicular to the occlusal surface of the restored teeth and parallel to their longitudinal axis. A tripodic contact with the buccal and lingual cusps was achieved through a 6-mm-diameter sphere made of stainless steel.[24-26] Regarding aging, the specimens were artificially aged via thermocycling and water storage. These procedures can compromise the mechanical properties of a material.[26] These changes are attributed to water sorption, polymer network expansion, and frictional reduction between polymer chains and may affect the clinical performance of the restoration.[28] Gale and Darvell[29] reported that a sequence of 35°C, 15°C, 35°C, and 45°C with 28, two, 28, and two seconds and 10,000 cycles is equivalent to one-year of oral function. In the present study, 10,000 cycles were performed, corresponding to approximately 12 months of oral function. Additionally, a sequence of 37°C, 5°C, 37°C, and 55°C was selected with a transfer time of five seconds and a dwell time of 10 seconds, which replicates the abrupt changes in temperature occurring in the oral cavity avoiding excessive forces due to long immersion (ie, 28 seconds).

In the oral environment, restorations may be loaded during their lifetime up to 10^7 cycles,[30] and during physiological function of the stomatognathic system, the stresses applied to posterior teeth may reach up to 300 N (usually 50 to 60 N) for a long duration of chewing cycles.[31] Furthermore, in terms of *in vivo* loading, the masticatory cycle consists of a combination of vertical and lateral forces, subjecting the restoration to a variety of off-axis loading forces.[32] In effect, dental restorations usually fail

Table 2: *Frequency of the Remaining Specimens That Were Ultimately Used Throughout the Analysis*

Group	Percentage (%)	Number of Specimens
Filtek Bulk-Fill Posterior Restorative (BF)	36.2	17
Lava Ultimate (LV)	34.0	16
Intact (INT)	29.8	14
Total	100	47

Table 3: *Mode of Fracture Distribution of the Two Restorative Groups According to Burke's Classification*

Mode of Fracture	Fracture (Yes/No)	Group 1 (BF)	Group 2 (LV)	Significance of χ^2 (*p*)
Type I	No	16 (94.1%)	15 (93.8%)	0.641
	Yes	1 (5.9%)	1 (6.2%)	
Type II	No	16 (94.1%)	15 (93.8%)	0.641
	Yes	1 (5.9%)	1 (6.2%)	
Type III	No	11 (64.7%)	10 (62.5%)	0.032
	Yes	6 (35.3%)	6 (37.5%)	
Type IV	No	12 (70.6%)	11 (68.8%)	0.222
	Yes	5 (29.4%)	5 (31.2%)	
Type V	No	13 (76.5%)	13 (81.2%)	0.302
	Yes	4 (23.5%)	3 (18.8%)	

Abbreviations: BF, Filtek Bulk-Fill Posterior Restorative; LV, Lava Ultimate.

as a result of many loading cycles or from an accumulation of damage from stress and water rather than during a single application of a high chewing load.[33] However, the intention of this investigation was to give a primary indication as to whether the proposed restorations would reinforce the structural integrity of the restored teeth.

In the present study, there was a significant difference in fracture resistance between the restorative groups (BF and LV). A possible explanation may be an increased crack formation in dental structures during the polymerization of direct restorations, which makes them more susceptible to fractures. Silva and others[20] reported that large direct conventional composite restorations exhibited significantly higher crack propensity (47%) as a result of polymerization shrinkage stresses compared to CAD/CAM composite inlays (7%). Furthermore, one important advantage of composite inlays is that the polymerization of the composite materials takes place before the clinical procedure, and as a result there are no consequences of polymerization shrinkage stresses on tooth structure. This may be the explanation of the higher fracture resistance of the LV group compared to the BF group in the current investigation. Increased fracture resistance of LV restorations may also be attributed to high content of fillers, standardized production conditions of CAD/CAM materials, and similar flexural modulus of the material and adhesive cement, meaning that an increased breaking force is needed to create cracks that could cause fractures.[34,35]

Additionally, physical and mechanical properties of restorative materials, such as fracture toughness, modulus of elasticity, creep, hardness, and polymerization shrinkage, are important for the fracture resistance of a restoration.[6] The modulus of elasticity of a material is one of the key factors determining the clinical performance of restorations in the testing of chewing forces. High-modulus materials tend to

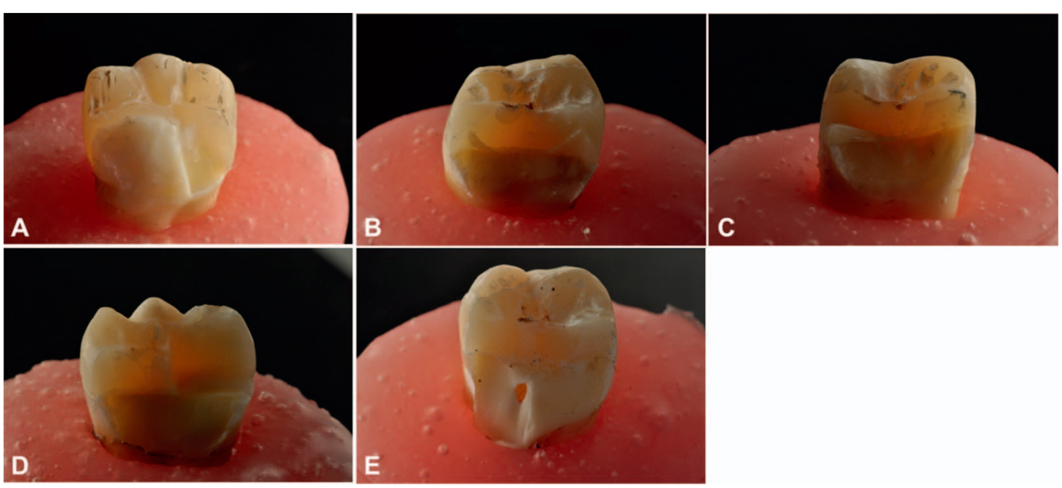


Figure 5. *(a-e): Representative images of the five types of fracture mode of restored teeth according to Burke's classification. (a): Type I. (b): Type II. (c): Type III. (d): Type IV. (e): Type V.*

accumulate stresses in their mass, while materials with low modulus of elasticity tend to absorb the forces transferring them to the surrounding dental structures.[36] When occlusal forces are applied to materials with high modulus of elasticity, tensile forces develop at the tooth/restoration interface just below the force application point.[37] The elastic moduli of dentin (E=17.6 GPa), bulk-fill composite (E=15.2 GPa), and CAD/CAM composite (E=14.5 GPa) used in this study were similar.[38] Consequently, the difference in the behavior of the materials in fracture resistance of the current study may be attributed to different parameters, such as the adhesive system or the photopolymerization shrinkage stresses. In the LV group, a self-adhesive resin cement (RelyX Unicem) was used for the adhesion of the composite inlays to tooth tissues, while in the BF group, an etch-and-rinse adhesive system (Single Bond Universal) was used. Both adhesive techniques were previously investigated and showed sufficient bond strength to dental tissues.[39,40]

Regarding the fracture mode distribution between the groups, the statistical analysis did not reveal any significant differences. The most common types of failures were found to be types III and IV, which were related to the tooth restoration interface as the fractures appeared in the buccal and lingual cavity walls and the axial-pulpal angle. These types could be repaired intraorally since the fracture line was located above the cemento-enamel junction (13 specimens of the BF group and 13 specimens of the LV group), while only seven (four specimens of the BF group and three specimens of the LV group) were considered impossible to be repaired. Factors that may affect the type of fracture could be the adhesive procedures, the fixation of the casts, the direction and angle of the force exerted, and the type of selected antagonist.[41]

Regardless of the fracture type, there are controversial views on the cusp protection in relation to the range of the occlusal isthmus. There are studies recommending cusp protection in order to have a sustainable restoration when the thickness of the remaining cavity walls reaches 2 mm or less.[24,42] On the other hand, Fonseca and others[26] reported that the cavity preparation and more particularly the width of the occlusal isthmus did not affect the fracture resistance of teeth bearing prepolymerized composite resin restorations, while Silva and others[20] claimed that extended dental preparations can be restored with prepolymerized composite resin restorations even in patients with a strong chewing activity. The results of this study indicated that cavities with a wall thickness of approximately 2 mm can be restored with RC CAD/CAM inlays, demonstrating a fracture strength that is higher than the stresses found in the oral cavity.

Within the limitations of this study, the first null hypothesis was rejected, as the results indicated that there was a significant difference of the fracture resistance between the experimental groups. The indirect CAD/CAM technique (LV group) presented significantly higher fracture resistance compared to that of the direct bulk-fill technique (BF group). The results are in agreement with previous studies comparing conventional direct composite restorations with indirect CAD/CAM composite restorations.[20,24] Nevertheless, the comparison between a bulk-fill and a CAD/CAM composite restoration has never been investigated before. As expected, intact teeth exhibited higher fracture resistance than the restored teeth, which is in accordance with previous studies evaluating various types of cavity preparations.[25,26] The second null hypothesis of the study was accepted, as it was found that there was no significant difference in the mode of fracture between the two experimental groups.

Although fatigue tests provide more accurate data for restored teeth failures, they present difficulties in repeatability and are more time consuming.[20,43] Fracture resistance tests, despite their limitations, provide valuable information on the ability of restored teeth to cope with specific clinical conditions.[26] One of the main disadvantages of fracture resistance tests compared to fatigue tests is that the fracture load of a specimen, which breaks under aggravating conditions, offers limited information on preexisting tooth cracks.[44] Therefore, before engaging any time-consuming durability tests, it was necessary first to establish that the structural integrity of the restored tooth had not been fatally compromised by the use of an untested design. This study has shown that this is not the case and that teeth restored with both restorative materials fail after application of a load that is a lot higher than the loads exerted in the oral cavity. As an indication, this is promising but requires further investigation with fatigue tests before suggesting the restoration of cavities with extensive occlusal isthmus with no cusp protection and with materials and techniques tested in this study as an option for the clinician.

CONCLUSIONS

Within the limitations of this *in vitro* study, it can be concluded that CAD/CAM RC inlays could be promising alternative restorative materials for improving the prognosis of large posterior tooth restorations with regard to their fracture resistance. Although the bulk-fill composite restorations presented lower fracture resistance when compared to CAD/CAM composite materials, they can be considered appropriate for use in large posterior restorations, as the restorations failed at loads a lot higher to those found in the oral cavity. The mode of fracture showed that the majority of failures reported for both direct and indirect restorations could be repaired intraorally. However, further clinical studies are necessary to confirm the significance of the results of the present investigation. Fatigue tests should also be useful to evaluate the mechanical properties of these types of restorations.

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Regulatory Statement

This study was conducted in accordance with all the provisions of the local human subjects oversight committee guidelines and policies of approval of the Ethics Committee, School of Dentistry, Faculty of Health and Sciences, Aristotle University of Thessaloniki. The approval code for this study is 04/11-10-2016.

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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Surface Sealant Effect on the Color Stability of a Composite Resin Following Ultraviolet Light Artificial Aging

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Clinical Relevance

Surface sealants may be effective in perceptibly extending the original color of the restoration, within a clinically acceptable range, for a protracted period of time; however, the material as well as the restorative (composite resin) should be evaluated during routine oral hygiene or examination appointments for color stability and/or surface defects.

SUMMARY

Objective: To examine how exposure to accelerated artificial aging (AAA) stimuli (ultraviolet [UV] light) affects the color stability of a composite resin following surface sealant (SS) application.

Methods and Materials: A total of 30 cylindrical composite resin (Esthet-X) discs were prepared using Teflon-coated rings. The treatment groups, defined by different SS (Seal-N-Sine, PermaSeal, OptiGuard, Biscover LV, and DuraFinish) use, were divided into five groups of six discs each. The discs were subjected to baseline color measurements followed by measurements after surface sealant application (specular included component [SCI] and specular excluded component [SCE]) using a spectrophotometer. Three measurements (SCI and SCE) were performed for a total of 18 readings (test surface) per specimen group. All specimens were then exposed to a UV light source for a total of 382 hours. Color readings of the specimens were again recorded for each group. Quantitative color measurements were executed using Commission Internationale de l'Eclairage L*a*b* calculations.

Results: Baseline color measurements of the composite resin discs, following the AAA exposure protocol, revealed no significant differences. A comparison of the composite resin

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discs before and after SS application (without UV light exposure) showed statistically significant differences using both SCI and SCE measurement criteria. Although significant differences were encountered between the ΔL*, Δa*, Δb*, and ΔE parameters, all specimens (groups) were within the clinically acceptable range ($1.0<\Delta E\leq 3.3$). Again, statistically significant differences were noted (ΔL*, Δa*, Δb*, and ΔE parameters) for all specimen groups receiving SS application, utilizing both SCI and SCE measurements, following exposure to UV light. All groups were within the clinically acceptable range ($1.0<\Delta E\leq 3.3$), except the Durafinish group. The Durafinish SS group experienced significantly greater ($p<0.001$) overall color change (SCI and SCE) following UV light exposure. An intergroup comparison following UV exposure revealed that the Permaseal, OptiGuard, and Seal-n-Shine SS groups displayed the least amount of color change statistically but not necessarily always perceptibly significant, while the Durafinish group exhibited the greatest color change statistically and perceptibly.

Conclusions: The color stability of a composite resin, including the addition of most SSs, was not affected perceptibly by UV light exposure.

INTRODUCTION

A direct correlation can exist between the final esthetic appearance of a dental restoration and the performance of the finishing and polishing procedures.[1-4] Application of specific formulation liquid polishing agents has been recommended supplementary to immediate insertion and finishing of direct placement resin-based restoratives. This treatment has been suggested to overcome possible deficiencies associated with physical properties of the materials and, perhaps, operator imprecision.[5,6] These post-restorative covering agents have been referred to as rebonding/glazing/liquid polishing agents or, more specifically, surface sealants (SSs).[5,6] Such sealants are applied to the restoration surface and surrounding tooth structure, seemingly promoting improved marginal sealing while also permeating surface microdefects and/or voids formed during material insertion and polymerization.[5,6]

Traditional dentin bonding agents and pit-and-fissure sealants have attempted to serve in this capacity in the past. However, clinical performance is directly related to the factors of viscosity and/or wettability (fluidity) of the individual formulations, and thus these materials were not necessarily viable alternatives.[7] Currently, SSs contain low-viscosity unfilled resins and other low-molecular-weight monomers as well as extremely efficient photoinitiators and modifiers.[5,6,8] For effective utilization and long-term success of these agents, the surface tension of the SS and the incumbent surfaces to be restored should be equivalent if adequate wetting and, in turn, adhesion are expected.[9]

Color instability of resin-based restoratives can also be affected by physicochemical material alterations from exposure to different aging stimuli.[8,10] Experimental accelerated artificial aging (AAA) protocols consist of submitting restorative materials to intervals of contact to ultraviolet (UV) irradiation, hygroscopic, and/or temperature extremes comparable to long-term exposure periods produced by natural external environments.[11-24] Therefore, *in vitro* AAA methods can predict *in vivo* modifications in dental resins (ie, color instability), conceivably foretelling clinical conditions.[11-24]

Quantitatively defining color change for a tooth-colored restoration has been directed by the Commission Internationale de l'Eclairage (CIE) L*a*b* three-dimensional color space measurement system in which the L* axis measures luminosity or lightness ranging from 0 (black) to 100 (white), the a* coordinate measures redness ($a>0$) or greenness ($a<0$), and the b* coordinate measures yellowness ($b>0$) or blueness ($b<0$).[25-27] Quantitative measurement of the total change in color (ΔE) incorporates a specific formula for qualitative application pertaining to perception and acceptance thresholds.[25-27]

This study evaluated the effects of a specific type of AAA protocol, UV light irradiation, reporting two specific light reflectance measurements—specular included component (SCI) and specular excluded component (SCE)—for the color stability of a composite resin before and after SS application. The hypothesis of the study was that significant change in color qualities of a composite resin, incorporating the tested SSs, occurs following exposure to the AAA protocol.

METHODS AND MATERIALS

Treatment Groups and Specimen Preparation

The experimental groups (Table 1) were defined by the different SS materials, including Seal-N-Sine (Pulpdent Co, Watertown, MA, USA), PermaSeal (Ultradent Products Inc, South Jordan, UT, USA), OptiGuard (Kerr Co, Orange, CA, USA), Biscover LV

Table 1: *Product (Group), Manufacturer, and Composition of Surface Sealants Used*

SS Group	Manufacturer	Composition
A: Seal-N-Sine	Pulpdent Co (Watertown, MA, USA)	Uncured acrylate ester monomers, silica
B: PermaSeal	Ultradent Products Inc (South Jordan, UT, USA)	Bis-GMA, TEGDMA, DMAEMA
C: OptiGuard	Kerr Co (Orange, CA, USA)	2,2′-ethylenedioxydiethyl dimethacrylate, TEGDMA, CQ
D: Biscover LV	BISCO Inc (Schaumburg, IL, USA)	Ethanol, PENTA
E: DuraFinish	Parkell Inc (Edgewood, NY, USA)	MMA, CQ

Abbreviations: Bis-GMA, bisphenol A glycidyl methacrylate; TEGDMA, triethylene glycol dimethacrylate; DMAEMA, 2-dimethylaminoethyl methacrylate; CQ, camphorquinone; PENTA, dipentaerythritol pentaacrylate; MMA, methyl methacrylate.

(BISCO Inc, Schaumburg, IL, USA), and DuraFinish (Parkell Inc, Edgewood, NY, USA).

Thirty cylindrical discs (10.0-mm inner diameter×1.0-mm thickness) were prepared from Teflon-coated rings using Esthet-X HD (Dentsply Caulk, Milford, DE, USA), shade A3 micromatrix composite resin. Each ring/material insertion was covered with transparent polyethylene terephthalate matrix strips (Mylar DuPont Teijin Films, Chester, VA, USA) on each side to ensure a uniform finish. The composite resin/matrices were compressed between two microscopic glass slides with pressure applied from a 10-pound stainless-steel weight in order to extrude any excess material. Each composite resin insertion was polymerized through the slides, from each side, for 40 seconds with a Valo (Ultradent) light-emitting diode curing light, thus yielding one disc. The light intensity (>800 mW/cm^2) was verified with a Coltolux Light Meter (Coltene, Inc, Mahwah, NJ, USA).

Color Measurement and Accelerated Artificial Aging Protocol

The composite resin discs were randomly divided into five treatment groups of six discs per group (groups A-E) based on the type of SS covering material. Both sides of each disc received an initial transparent matrix (Mylar) surface finish. Prior to SS application, baseline color measurements were performed for each composite resin disc, including a total of 18 measurements per group (one side served as a test surface, while the other side was assigned as an identification surface, appropriately marked). Each disc was measured for two separate color parameters: SCI and SCE against a black background using a Konica Minolta spectrophotometer CM-5 (Konica Minolta Sensing Americas, Inc, Ramsey, NJ, USA). Afterward, the test side of each disc was etched or "cleaned" using Ultra-Etch (Ultradent) 35% phosphoric acid solution, followed by coating with a respective SS, and light cured for 20 seconds. The specimens were wiped/buffed with a lint-free clean cloth to remove any oxygen-inhibited layer or other debris. The transparent matrix side (marked surface) remained undisturbed. Usage of all restorative materials strictly adhered to manufacturer directions regarding application, polymerization, and handling. Following application of SSs, color measurements were performed for the specimens. All specimens were immediately exposed to the AAA protocol, consisting of a UV light chamber ("mirrored" superior/inferior surfaces) containing four fluorescent bulbs (nine watts each) for a total of 382 hours. A custom-fabricated holder was used to support the specimen discs in a vertical orientation in order to receive appropriate light exposure (approximately 50 millimeters [mm] from the light source). The specimens were again measured for color, following identical procedures. Regarding the UV light exposure protocol of the different dental materials, the authors were attempting to simulate a clinical experience. During SS application of the composite resin disc, a covering agent or barrier (clear matrix, gel) was not utilized, and therefore creation of an oxygen-inhibited layer was probable.

The present study included exposure of the material specimens to 24 hours of UV light per day using artificially induced UV irradiation for a total of 382 hours of UV exposure.

All color measurements were analyzed using CIE L*a*b* system criteria. The mean L*a*b* values were calculated for each composite resin and SS group. The CIE 1976 Delta E formula[25-27] $\Delta E^*_{ab} = \left[(\Delta L^*_{ab})^2 + (\Delta a^*_{ab})^2 + (\Delta b^*_{ab})^2\right]^{1/2}$ for total color change was chosen rather than more current but increasingly complex versions (CIE1994, 2000). Measurements before and after application of the SSs and exposure to AAA were completed noting the following clinically applicable thresholds: $\Delta E_{ab} < 1.0$ = excellent match; $1.0 < \Delta E_{ab} \leq 3.3$ = acceptable; and $\Delta E_{ab} > 3.3$ = clinically unacceptable (mismatch) for color comparisons.[28]

Table 2: *ΔL*, Δa*, Δb*, and ΔE (means and standard deviations) of the specimen groups tested following addition of the surface sealants (specular included component [SCI] and specular excluded component[SCE]) (statistically significant intergroup differences also included)*[a]

	Sample Size	ΔL*	Δa*	Δb*	ΔE
Group (SCI)					
A	18	0.65 (0.4008) ABC	0.11 (0.0711) A	0.55 (0.6056) ABC	1.06 (0.3574) AB
B	18	1.06 (0.3885) B	0.15 (0.0695) A	0.78 (0.4079) AB	1.38 (0.3845) ACD
C	18	0.90 (1.2470) B	0.13 (0.2396) A	1.11 (2.0160) A	1.57 (0.3593) CD
D	18	0.35 (0.6735) A	0.18 (0.1230) A	−0.19 (1.1410) B	1.20 (0.6751) BC
E	18	0.22 (0.7094) C	0.55 (0.2535) B	−1.10 (1.3000) D	1.80 (0.6760) D
Group (SCE)					
A	18	0.05 (0.8226) AC	0.13 (0.1289) A	0.90 (0.2817) A	1.18 (0.3655) A
B	18	1.07 (0.8420) B	0.15 (0.0896) A	0.71 (0.7009) A	1.61 (0.5110) AB
C	18	1.81 (1.1750) B	−0.08 (0.7083) A	0.35 (1.1740) AB	2.06 (0.9929) B
D	18	0.90 (1.4520) BC	0.16 (0.1593) A	−0.60 (1.4020) B	2.05 (0.9468) B
E	18	0.69 (0.4402) AB	0.55 (0.2979) B	−1.64 (1.2500) C	2.08 (0.9721) B

[a] *Same letters in each column indicate no statistically significant differences.*

Statistical Analyses

Statistical analyses were conducted using parametric one-way analysis of variance and, if applicable, Tukey-Kramer multiple comparison tests to determine statistically significant differences in Δ (ΔL*, Δa*, Δb*, and ΔE) among the materials (groups) tested. All data were submitted for statistical analyses at the $\alpha = 0.05$ level of significance. The statistical calculations were performed using Instat (GraphPad Software, Inc, La Jolla, CA, USA).

RESULTS

Following exposure to UV light, the baseline color change or the overall ΔE of the composite resin discs (without SS application) revealed readings of 1.10 (SCI) and 1.13 (SCE). Although these measurements were numerically statistically significant from the original color of the discs, the readings were in the clinically acceptable range ($1.0<\Delta E_{ab}\leq 3.3$) for both the acceptance and the perceptibility thresholds. Table 2 shows the ΔL*, Δa*, Δb*, and ΔE mean scores (standard deviations) and statistically significant differences among specimen groups prior to and following SS application, considering both SCI and SCE measurements (prior to UV light exposure). Total overall numerical (statistical) differences, according to the ΔE CIE parameter, were apparent; however, clinically perceptible changes (ΔE) were not revealed for the specimens (all groups) following SS application. For intergroup comparisons, statistically significant differences were exhibited between specimen groups, with group E (Durafinish) having revealed the greatest overall numerical color change (ΔE: 2.08) before and after SS application but again not clinically perceptible. The mean overall color change scores (ΔE) comparing composite discs (groups) before and after SS covering revealed a progression (from least to greatest): A < D < B < C < E for the SCI measurements and A < B < D < C < E for the SCE measurements. Again, these specimen measurements were acquired prior to UV light exposure. Table 3 shows the ΔL*, Δa*, Δb*, and ΔE mean scores (standard deviations) and statistically significant differences between specimens following SS application and UV light exposure, considering both SCI and SCE measurements. Total overall numerical (statistical) color changes, according to the ΔE CIE parameter, were again apparent. Clinically perceptible changes (ΔE) were revealed only for group E (Durafinish), yielding a ΔE of 4.02 (SCI) and 4.49 (SCE). Statistically significant differences were exhibited between specimen groups. Groups A, B, and C (Seal-n-Shine, Permaseal, and OptiGuard) displayed the least amount of color change, including statistically significant ($p<0.05$) differences. Groups D and E showed the greatest color changes, with group E (Durafinish) having revealed statistically significant ($p<0.001$) as well as clinically perceptible differences following UV exposure. The mean group overall color change scores (ΔE) following SS application/UV exposure revealed a progression (from least to greatest): B < A < C < D < E for both SCI and SCE measurements.

DISCUSSION

The primary objective of the present study was to measure the color stability of a direct placement composite resin restorative before and after applica-

Table 3: *ΔL*, Δa*, Δb*, and ΔE (means and standard deviations) of the surface sealant specimen groups tested following UV light exposure (specular included component [SCI]and specular excluded component [SCE]) (statistically significant intergroup differences also included)*[a]

	Sample Size	ΔL*	Δa*	Δb*	ΔE
Group (SCI)					
A	18	0.75 (0.140) A	0.15 (0.206) A	−1.44 (0.362) AB	1.66 (0.322) AB
B	18	0.51 (0.137) B	0.14 (0.145) A	−1.16 (0.299) A	1.29 (0.308) A
C	18	0.64 (0.289) AB	0.14 (0.189) A	−1.56 (0.429) BC	1.71 (0.493) BC
D	18	0.73 (0.157) A	0.11 (0.248) A	−1.91 (0.438) C	2.08 (0.401) C
E	18	1.54 (1.538) C	−0.37 (0.359) B	−3.66 (0.529) D	4.02 (0.570) D
Group (SCE)					
A	18	0.54 (0.1643) A	0.15 (0.2144) A	−1.45 (0.4926) A	1.58 (0.503) AB
B	18	−1.26 (0.5986)	0.22 (0.1041) ABC	−0.13 (0.4884)	1.40 (0.553) AC
C	18	0.56 (0.2229) AB	0.16 (0.1926) ABD	−1.56 (0.3460) A	1.69 (0.351) BC
D	18	0.72 (0.2755) AB	0.12 (0.2658) ACD	−2.13 (0.5220)	2.28 (0.530) D
E	18	1.59 (0.3473)	−0.40 (0.3831)	−4.15 (0.6503)	4.49 (0.696) E

[a] *Same letters in each column indicate no statistically significant differences.*

tion of various SSs exposed to a specific AAA protocol (UV light) over a predetermined period of time (simulating long-term clinical conditions). The hypothesis of the study stating that UV light exposure would negatively affect the color qualities of the composite resin and all applicable SS coverings was partially rejected. All groups of composite resin discs (prior to SS application) were well within the clinically acceptable range ($1.0<\Delta E_{ab}\leq 3.3$) following exposure to the UV light. These results were somewhat contradictory with findings from a previous study[12] showing significant changes to direct placement composite resins (again, without the addition of a SS) following exposure to additional external stimuli. Specimens, including an SS covering, revealed statistically significant differences and, for one SS (Durafinish), clinically perceptible changes following UV light exposure. Specifically, following UV exposure, specimens (including SS application) from groups A-D (SCI and SCE) showed slight increases in luminosity or lightness (ΔL^*), redness (Δa^*), and blueness (Δb^*). Group E (Durafinish) specimens, revealed statistically and clinically significant ($p<0.001$) increases in lightness (ΔL^*), greenness (Δa^*), and blueness (Δb^*). According to these measurements, group E (SCI and SCE) was the only group to yield clinically (perceptible) unacceptable ($\Delta>3.3$) matches within the ΔL^*, Δb^*, and ΔE coordinates, given an acceptance threshold of 3.7 ΔE. No relevant studies could be located that employed similar experimental procedures utilizing a UV light exposure protocol and measuring the color stability of composite resins following SS application.

Two separate color (reflectance) measurements were performed for this research study: SCI and SCE. The SCI is considered the "true" color of an object and the measurement of a particular surface, including the reflection of specular and diffuse light, unaffected by the type of surface. The SCE measures the color appearance of an object and excludes any reflected light and thus is more sensitive to surface conditions.[29,30]

In the present study, each disc received a Mylar surface and visually was comparably smooth and glossy, although microvoids and blemishes were present under higher magnification. The decision was reached that the SCI readings would perhaps be more applicable (considering the imperfect surface conditions), although the results revealed similar color change data for specimens measuring both SCI and SCE parameters.

Technique and material improvements have been effective in changing the performance of esthetic restorative systems; however, numerous factors can induce color instability, including the specific components of the restorative (resin matrix, filler particles), which can affect the physical characteristics, that is, the modulus of elasticity and coefficient of thermal expansion, which can, in turn, alter the hardness and/or abrasion resistance, bond strengths, and the ability of the material to resist microleakage of contaminants at the tooth/material margin.[12,31-35] Additional material variables include the degree of conversion of carbon bonds and the influence of photoinitiators and modifiers.[12,31,36-38] Color change as a consequence of external influences includes postinsertion finishing/polishing procedures, oral habits, absorption and adsorption of extrinsic coloring agents (food colorants), dietary regimens (staining), polymerization light limitations (wavelength and intensity), fluctuations in temperature and hygroscopic absorption, and diverse ambient UV light sources.[1-4,12-27,39-48]

Fluorescent tubes used for illumination produce a spectrum of UV radiation (UVA) with wavelengths from 315 to 400 nm, with irradiance measured in milliwatts per centimeter squared (mW/cm^2).[49,50] The irradiation chamber utilized in the present study consisted of four nine-watt (36 watts total) fluorescent lamps with a peak wavelength of 365 nm, producing a UV index (UVI) of 1.5. The UVI measures the level of a source of radiation and is reported as "exposure category" (low to extreme) and corresponding "UVI range" (<2-11+).[51] Comparison to the sun's energy irradiance would be problematic and perhaps unattainable due to influential factors including elevation, cloud cover, ground reflection, ozone levels, latitude, and altitude.[51]

In vitro AAA methods have been used extensively, testing the physical properties of dental materials (composite resin) and thus presumably foretelling the long-term clinical effects from different stimuli, such as visible and UV light, humidity (water storage), and temperature (thermocycling).[8,10-24] The stresses placed on the composite resin constituents, specifically the organic matrix and inorganic filler particles, can presumably cause alterations in the mechanical and optical properties.[13] There appears to be very little standardization in the literature regarding different AAA exposure periods necessary for alteration of composite resin characteristics (color change). Studies conducted by Drubi-Filho and others[18] and Pires-de-Souza and others[19] have utilized combination exposure cycles of temperature and UV light for varying periods of time (384 vs 8 hours, respectively). A study conducted by Furuse and others[14] subjected composite resins to different "photoaging" periods of 0, 24, 72, 120, and 193 hours in order to detect color changes. Other studies testing different direct placement tooth-colored restoratives exposed specimens to 100% relative humidity (water bath at dissimilar temperatures) and visible/UV light irradiation for periods of up to 300 hours, which was equated to one year of clinical service.[12,24] Finally, a study protocol conducted by Heydecke and others[15] subjected porcelain veneers to 300 hours of AAA consisting of UV light and water spray from an apparatus referred to as a "Weather-O-Meter." The manufacturer of the Weather-O-Meter claimed that 300 hours of AAA exposure was equivalent to one year of clinical service. Although dental restorations are subjected to varying external stimuli, including combinations of different qualities and quantities of light, humidity, temperature, colorants, and foodstuffs during the life of the material, there is probably minimal evidence-based information supporting positive correlations between *in vivo* and *in vitro* conditions.

Several important factors must be noted regarding the quality of polymerization for a particular resin-based substance, including the material thickness and shade; light source, intensity, and wavelength spectrum generated; the time and distance of exposure; and the individual material photoinitiator's absorption target or peak wavelength (nm).[38,52,53] The light source includes the wattage or the amount of electrical power consumed. The strength or intensity refers to the measured output of light energy. Light is also measured according to the spectral output or wavelengths in nanometers and is revealed in a scale of visible and invisible energy.[49,50] The light intensity is an important component regarding polymerization of resin-based dental materials; however, the wavelength spectrum of light irradiation should closely match the absorption spectra of the photoinitiator incorporated in the material.[38,53] Peak activation of a resin-based material depends on the photoinitiator wavelength and the energy of the photons (wavelength) of the polymerization source. The photoinitiators contained in the material absorb the incoming energy from the light source and precipitate conversion of the polymer composition.[53]

Surface sealants have been advocated as adjuncts for completion of the restoration finishing and polishing procedures.[5,6] Potential benefits include increasing the seal at the tooth/restoration interface or margin, thereby preventing or decreasing the occurrence of microleakage. Surface sealants also serve to saturate the material surface, filling any defects, voids, and/or irregularities and increasing wear and stain resistance and thus enhancing esthetic qualities.[33-35,54-61] However, very limited research exists concerning the use of these materials and the extent to which they improve the longevity and appearance (color stability) of a composite resin restoration.[4]

Regarding the present study, an interesting, but not unexpected phenomenon occurred following the polymerization of SSs onto composite resin restoration surfaces. The formation of a sticky oxygen-inhibited layer following light polymerization having been exposed to ambient air was quite noticeable.

This surface layer of unreacted monomers was formed from the absence of the use of a clear matrix or layer of unreactive substance (eg, glycerin gel). Polymerization of the underlying material, which permeates into the surface irregularities and defects, was accomplished; however, the overlying surface film layer of the material was unreactive and uncured to varying degrees (ie, the formation of an oxygen-inhibited layer).[62] Although the initial appearance was a glossy surface, complete polymerization had not occurred. With the formation of the oxygen-inhibited layer, the SS addition could be considered a negative attribute. As this process can occur with regularity, some manufacturers tout their products as containing ingredients producing a very thin oxygen-inhibited layer or film thickness following polymerization. However, the routine usage by a dental professional of a covering barrier (matrix and/or gel) placed over the surface sealant prior to light polymerization is probably not a realistic expectation.

According to Ferracane and others,[20] the formation of an oxygen-inhibited layer in a polymerized material can precipitate into the eventual formation of yellow-colored peroxides, with a material that contains greater than 35% unconverted bonds. In the present study, although statistically significant differences were noted between several of the groups regarding the parameters of ΔL^*, Δa^*, Δb^*, and ΔE, most of the significant perceptible color changes involved Δb^* or increases in the blueness of a material following the AAA protocol.

CONCLUSIONS

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

1) Following the AAA exposure protocol, the composite resin discs, without the inclusion of SS application, revealed no statistically or perceptibly significant differences in overall color change or ΔE, considering both SCI and SCE color measurements.
2) Following application of surface sealants to the composite discs, statistically significant changes in color were exhibited; however, clinically perceptible changes were not evident. Intergroup comparisons following SS application revealed that the Durafinish group, although statistically but not clinically significant, had the greatest degree of color change.
3) Following exposure to the UV light protocol, using both SCI and SCE measurements, group E (Durafinish) experienced significantly greater ($p<0.001$) overall color change (ΔE) compared to the other groups. Also, group E (Durafinish) specimens, revealed statistically significant ($p<0.001$) increases in lightness (ΔL^*), greenness (Δa^*), and blueness (Δb^*) and was the only group to yield clinically (perceptible) unacceptable ($\Delta>3.3$) matches within the ΔL^*, Δb^*, and ΔE coordinates.
4) Following the AAA exposure protocol and measurement using both SCI and SCE parameters, groups A-C (Seal-n-Shine, Permaseal, and OptiGuard) displayed the least amount of overall color change (although not necessarily always statistically significant) compared to groups D and E. A statistically significant ($p<0.001$) difference was shown between specimen groups D and E.

The study hypothesis was partially rejected. Only one of the experimental groups revealed statistically and clinically perceptible color changes following UV light exposure, while no statistically significant or clinically perceptible differences were revealed by the composite discs alone following light exposure. For the majority of the groups tested, application of SSs as "polishing" adjuncts following insertion of composite resin restoratives and exposure to a specific AAA protocol provided long-term color stability—if perception and acceptance thresholds are considered as the key indicator instead of statistical significance before and after.

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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Effectiveness of Light Sources on In-Office Dental Bleaching: A Systematic Review and Meta-Analyses

JR SoutoMaior • SLD de Moraes • CAA Lemos • BC do E Vasconcelos • MAJR Montes • EP Pellizzer

Clinical Relevance: The use of in-office bleaching techniques with light sources is recommended to improve the performance of bleaching gels. The use of hydrogen peroxide alone, without light, is effective for achieving tooth color changes.

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Letter to the Editor re: Effectiveness of Light Sources on In-Office Dental Bleaching: A Systematic Review and Meta-Analyses

AL Faria-e-Silva

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Influence of Polishing Systems on Surface Roughness of Composite Resins: Polishability of Composite Resins

L St-Pierre • C Martel • H Cre'peau • MA Vargas

Clinical Relevance: Not all composite resins have the same polishability, nor do all polishers produce acceptable surface roughness.

https://doi.org/10.2341/17-140-L

The Influence of Distance on Radiant Exposure and Degree of Conversion Using Different Light-Emitting-Diode Curing Units

AO Al-Zain • GJ Eckert • JA Platt

Clinical Relevance: It may be necessary to double or triple exposure times when polymerizing at increasing clinically relevant distances from the base of the preparation.

https://doi.org/10.2341/18-004-L

Full-mouth Rehabilitation of Hypocalcified-type Amelogenesis Imperfecta With Chairside Computer-aided Design and Computer-aided Manufacturing: A Case Report

C Moussally • H Fron-Chabouis • A Charrière • L Maladry • E Dursun

Clinical Relevance: This case report describes the use of a few sessions of chairside computer-aided design and computer-aided manufacturing for esthetic restoration of dentition severely affected by amelogenesis imperfecta. We describe the successive treatment steps to help practitioners treat similar disorders.

https://doi.org/10.2341/17-241-T

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Effectiveness of Light Sources on In-Office Dental Bleaching: A Systematic Review and Meta-Analyses

JR SoutoMaior • SLD de Moraes • CAA Lemos
BC do E Vasconcelos • MAJR Montes • EP Pellizzer

Clinical Relevance

The use of in-office bleaching techniques with light sources is recommended to improve the performance of bleaching gels. The use of hydrogen peroxide alone, without light, is effective for achieving tooth color changes.

SUMMARY

Objective: A systematic review and meta-analyses were performed to evaluate the efficacy of tooth color change and sensitivity of teeth following in-office bleaching with and without light gel activation in adult patients.

Methods: This review was registered at PROSPERO (CRD 42017060574) and is based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA). Electronic systematic searches of PubMed/MEDLINE, Web of Science, and the Cochrane Library were conducted for published articles. Only randomized clinical trials among adults that compared in-office bleaching with and without light activation with the same bleaching gel concentrations were selected. The outcomes were tooth color change and tooth sensitivity prevalence and intensity.

Results: Twenty-three articles from 1054 data sources met the eligibility criteria. After title and abstract screening, 39 studies remained. Sixteen studies were further excluded. Twenty-three studies remained for qualitative

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analyses and 20 for meta-analyses of primary and secondary outcomes. No significant differences in tooth color change or tooth sensitivity incidence were found between the compared groups; however, tooth sensitivity intensity decreased when light sources were applied.

Conclusion: The use of light sources for in-office bleaching is not imperative to achieve esthetic clinical results.

INTRODUCTION

The effectiveness, minimally invasive procedure, and biological safety are some of the reasons for the frequent request for tooth bleaching treatment by patients with discolored teeth.[1] Although tooth bleaching is generally considered to be a safe and simple treatment, some studies suggest that in-office dental bleaching could result in side effects to dental and gingival tissues, mainly when higher concentrations of hydrogen peroxide are used.[2] Tooth sensitivity during and after treatment is the major side effect observed.[3]

The chemical reaction rates between bleaching gels and dental pigments are proportional to the effectiveness of the bleaching agent.[4] Methods that increase chemical reaction rates improve treatment efficiency and comfort. For example, bleaching with light sources is recommended for in-office bleaching treatments, to accelerate the action of bleaching gels.[5]

There are many types of light sources for bleaching activation, such as lasers, light-emitting diodes (LEDs), and plasma arc (PAC) and halogen lamps.[6] The purpose of using light units is to heat the hydrogen peroxide,[7] which increases the rate of oxygen decomposition to form oxygen free radicals, thereby enhancing the release of stain containing molecules.[8]

Despite many light activation systems being introduced into the dental market for accelerating in-office bleaching treatments,[5] it is important to analyze tooth surface color changes and sensitivity when performing in-office bleaching with light sources. Therefore, the aim of this systematic review with meta-analyses was to evaluate the effects of light activation on bleaching effectiveness and tooth sensitivity during in-office bleaching. The null hypothesis was that light does not influence tooth color change. The second hypothesis was that light influences tooth sensitivity.

METHODS AND MATERIALS

Registration Protocol

This systematic review is based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) checklist described by Moher and others.[9] The study was registered on the International Prospective Register of Systematic Reviews (PROSPERO; CRD 42017060574).

Eligibility Criteria

Studies were selected and included/excluded, based on the article title and abstract, by two researchers (J.R.S.M and C.A.A.L), working independently. Eligible studies included randomized controlled trials (RCTs) and studies that compared in-office light- vs non-light-activated bleaching systems, using the same bleaching gel concentration, with at least 10 participants, published in English. Exclusion criteria were prospective nonrandomized and retrospective studies, in vitro studies, animal studies, computer simulations, case reports, studies that evaluated associations with techniques, and published report reviews.

A specific question was formulated based on population, intervention, control, and outcome (PICO) criteria. The question was "Can light-activation of in-office whitening systems influence bleaching effectiveness and tooth sensitivity?" According to these criteria, the population was the participants who had their teeth bleached with an in-office whitening system, the intervention was in-office light-activated tooth bleaching, and the comparison was in-office non-light-activated tooth bleaching. The primary outcome was the effectiveness of dental bleaching, and the secondary outcome was tooth sensitivity.

Search Strategy and Information Sources

Two independent investigators (J.R.S.M and C.A.A.L) conducted an electronic search of PubMed/MEDLINE, Web of Science, and the Cochrane Library for articles published between January 2000 and May 2017, using the following search terms: "tooth bleaching and light"; "dental bleaching and light."

The same researchers manually searched for articles published in *Operative Dentistry, Journal of Dentistry, Journal of Dental Research, Journal of Esthetic and Restorative Dentistry,* and *Quintessence International*. All choice differences between the investigators were analyzed by a third investigator

(S.L.D.M), and consensus was reached through discussion.

Data Analysis

Data extracted from the articles were classified as quantitative or qualitative by one of the researchers and then checked by another. Any disagreements were resolved via discussion until consensus was reached.

Risk of Bias

Two investigators (J.R.S.M. and C.A.A.L) assessed the methodologic quality of the included studies, as well as the risk of bias based on the Cochrane collaboration criteria.[10]

Summary Measures

The meta-analysis was based on the Mantel-Haenzel (MH) and inverse variance (IV) methods. Data from eligible studies were either dichotomous (absolute risk of tooth sensitivity) or continuous (intensity of tooth sensitivity, subjective and objective color variation). Bleaching technique was considered a continuous outcome, evaluated by mean differences (MDs) and corresponding 95% confidence intervals (CIs). Tooth sensitivity was considered a dichotomous outcome, evaluated by risk ratio (RR). RR and MD values were considered significant when $p<0.05$. The software Reviewer Manager 5 (Cochrane Group) was used for the meta-analyses. Heterogeneity analyses evaluated the I^2 value (25% low, 50% moderate, and 75% high). The meta-analyses effects were based on the heterogeneity study. Where heterogeneity was statistically significant ($p<0.10$), random effects meta-analyses were conducted; otherwise, meta-analyses were performed from fixed effects.[11]

Additional Analysis

The κ score was used to calculate agreement between the researchers during the selection process. Any disagreements were resolved by discussion and the consensus of all authors.

RESULTS

Literature Search

The database search retrieved 1054 references, including 670 from PubMed/MEDLINE, 276 from Web of Science, and 108 from The Cochrane Library. After duplicate references were removed, a detailed review was carried out of the titles and abstracts of the selected comparative studies, and after applying the inclusion/ exclusion criteria, 39 full papers were selected for eligibility assessment (Figure 1). After reading the full texts of these articles, 23 studies were included in the final review.[5,6,12-25] Reasons for study exclusion are detailed in Figure 1.

Characteristics of the Included Studies

Detailed data of the 23 included studies are listed in Table 1. All selected studies were RCTs. Among these studies, 15 compared bleaching efficacy.[6,12,14,16,18,19,22-30] and 13 compared tooth sensitivity.[4,5,6,14,16,17,19-21,23-25,27]

A total of 925 patients were included in the 23 studies, and the sample size of each study ranged from 20 to 88 patients. In nine articles, most participants were females, whereas 14 studies did not report this information. Hydrogen peroxide (HP) was used as the agent for in-office bleaching in all studies. The HP percentages were 35% in 15 studies,[4,5,12,13,16-21,23,24,26,28,30] 38%[6,18,29] and 25%[14,15,22] in three studies, 20% in two studies,[24,25] and 15% in two studies.[27,31]

Thirteen studies used a shade guide for color evaluation.[6,12,16,19,22-30] Six of these added an objective instrument (spectrophotometer or colorimeter) for color assessment.[12,14,18,24,29,30] Three studies did not evaluate color. For pain evaluation, eight of the 13 studies used a 0-10 visual analog scale.[4,6,14,17,19-21,25]

Assessment of Methodologic Quality

Few of the selected studies provided details on all items of the Cochrane risk of bias tool. To request further information, e-mails were sent to 14 authors. Two authors replied with the requested information. Each trial was assessed for risk of bias; the scores are summarized in Figure 2.

In summary, the scores showed a higher number of studies remaining unclear for the random sequence generation and allocation concealment items. Apart from participant blinding, personnel and outcome assessment, incomplete outcome, and selective reporting items, a low risk of bias was observed.

Meta-Analysis

Bleaching Efficacy—Bleaching efficacy was observed by subjective (Vita Classical shade guide) and objective (spectrophotometer) tooth color change methods. For better comprehension, the color evaluations were divided into subgroups: immediate

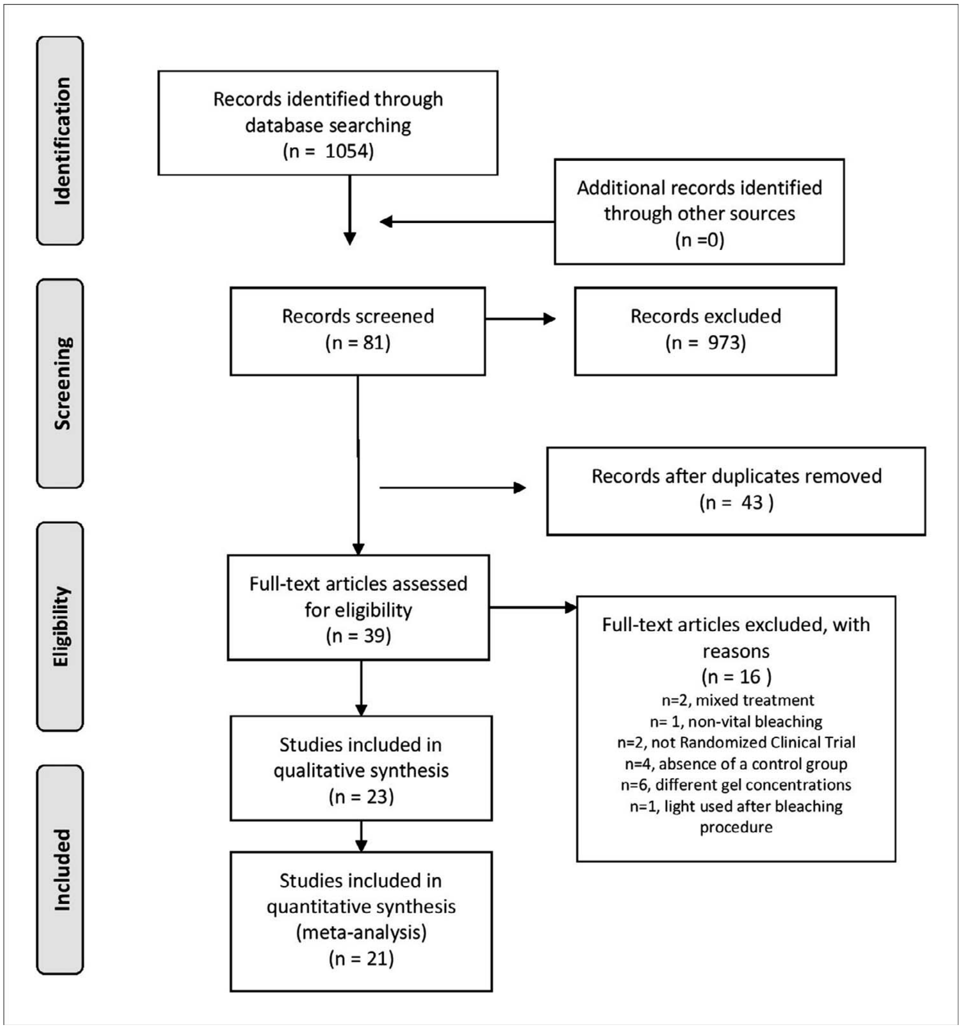

Figure 1. *Flowchart of the literature search.*

(within one day), short-term (one to four weeks), and medium-term (greater than four weeks) effects, depending on the time of evaluation.

Immediate Effect—Eight studies assessed immediate bleaching efficacy using visual measurements.[14,16,19,25-30] Random effects showed no significant differences between light and non-light bleaching (p=0.38; MD: −0.38; CI: −1.24 to 0.47). The data was heterogeneous (χ^2:178.87; I^2 = 94%; p<0.00001; Figure 3), and all studies included in the analysis did not share a common effect size. After a detailed analysis of the studies and even after excluding the study with the highest difference between the experimental and control groups,[29] the results remained the same, and the heterogeneity was unchanged. Lack of relevant studies prevented us from performing meta-regression or subgroup analysis.

Short-Term Effect (One to Four Weeks)—As shown in Figure 4, eight studies reported short-term bleaching efficacy assessed by visual measurements. In all studies, random effects showed no significant difference between light and non-light bleaching techniques (p=0.63; MD: 0.16; CI: −0.5 to 0.83) The data were heterogeneous (χ^2: 31.02; I^2 = 65%; p=0.001; Figure 4), and all studies included in the analysis did not share a common effect size. After a detailed analysis, it was not possible to identify any studies that were responsible for the high heterogeneity.

Medium-Term Effect (More Than 4 Weeks)—Four studies reported medium-term bleaching efficacy assessed by visual measurements. The results showed no difference between light and non-light bleaching techniques (p=0.60; MD: −0.23; CI: −1.07 to 0.62). The data were heterogeneous (χ^2: 24.76; I^2 = 84%; p<0.00001; Figure 5), and all studies included in the analysis did not share a common effect size. After a detailed analysis, it was not possible to

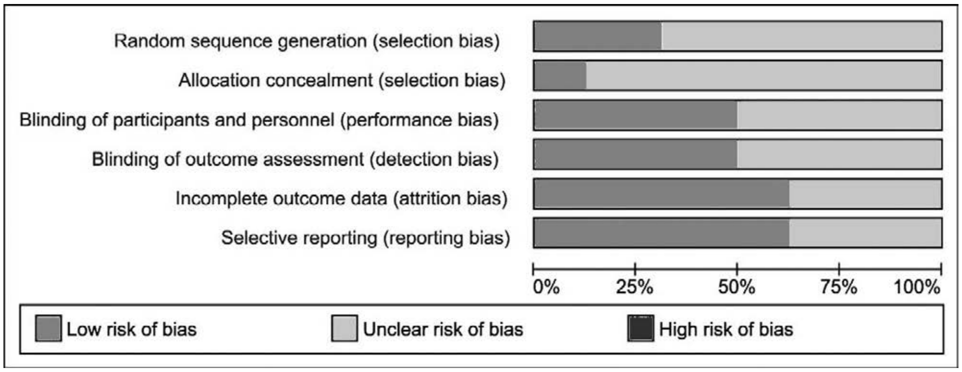

Figure 2. *Risk of bias graph.*

identify any studies that were responsible for the high heterogeneity.

Tooth Sensitivity—Tooth sensitivity was divided into two categories: incidence and intensity. The intensity was determined when the patient quantified his pain response on a visual analogue scale, while the incidence was evaluated by the number of sensitivity events.

Intensity of Tooth Sensitivity—To evaluate tooth sensitivity, six studies [4,6,14,17,19,20] were assessed by continuous outcome data via visual analogue scales. Random effects showed a significant difference in favor of light bleaching systems (p=0.01; MD: −2.19; CI: −3.85 to −0.53) Light systems demonstrated a significantly lower intensity of tooth sensitivity than non-light systems (Figure 6). However, data were heterogeneous (χ^2: 325.81; $I^2 = 98\%$; p<0.0001), and all studies included in the analysis did not share a common effect size. After a detailed analysis, the study of Bortolato and others[4] did have an impact on the high heterogeneity of this outcome. When this study was removed from the present meta-analysis, the heterogeneity was not significant, and the overall mean difference was shown as significant

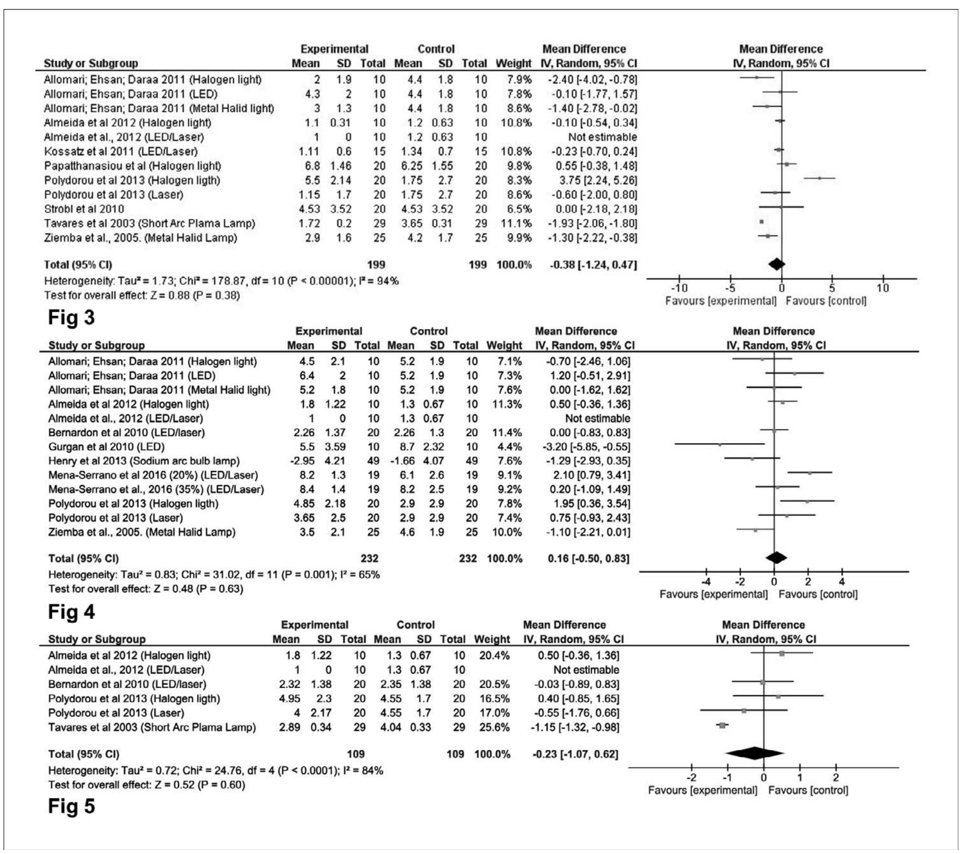

Figure 3. *Forest plot for the event "immediate color change."*

Figure 4. *Forest plot for the event "short-term effect color change."*

Figure 5. *Forest plot for the event "medium-term effect color change."*

Table 1: *Characteristics of the analyzed studies*

Author/Date	Study	Sample Size	Sex	Light Source (N)	Bleaching Agent
Papathanasiou and others, 2002[26]	RCT	20	NR	Without light (20) Halogen light (20)	35% HP
Tavares and others, 2003[27]	RCT	87	M: 38 (43.67%) F: 49 (56.33%)	Without light (29) Short arc plama lamp (29)	15% HP
Goodson and others, 2005[31]	RCT	NR	NR	Without light (NR) Short arc plasma lamp (NR)	15% HP
Ziemba and others, 2005[25]	RCT	50	NR	Without light (25) Metal halide lamp (25)	20% HP
Marson and others, 2008[5]	RCT	40	NR	Without light (10) Halogen light (10) LED (10) LED/laser (10)	35% HP
Ontiveros and others, 2009[14]	RCT	20	NR	Without light (20) Short-arc halide lamp(20)	25% HP
Kugel and others, 2009[15]	RCT	22	NR	Without light (11) LED (11)	25% HP
Allomari and others, 2010[19]	RCT	40	M: 12 (30%) F: 28 (70%)	Without light (10) Halogen light (10) LED (10) Metal halide light (10)	35% HP
Calatayud and others, 2010[13]	RCT	21	NR	Without light (21) LED (21)	35% HP
Bernardon and others, 2010[12]	RCT	20	NR	Without light (20) LED/laser (20)	35% HP
Strobl and others, 2010[30]	RCT	20	M:7 (35%) F:13 (65%)	Without light (20) Laser (20)	35% HP
Gurgan and others, 2010[6]	RCT	40	M: 11 (27.5%) F: 29(72,5%)	Without light (10) LED (10)	38% HP
Kossatz and others, 2011[16]	RCT	30	NR	Without light (15) LED/Laser (15)	35% HP
Almeida and others, 2012[17]	RCT	30	NR	Without light (10) Halogen light (10) LED/laser (10)	35% HP

Table 1: *Characteristics of the analyzed studies (ext.)*

Author/Date	Bleaching Time	Subjective Shade Evaluation	Objective Shade Evaluation	Tooth Sensitivity
Papathanasiou and others, 2002[26]	20′ × 1	IM: 6.25 ± 1.55	NR	NR
	20′ × 1	IM: 6.8 ± 1.46	NR	NR
Tavares and others, 2003[27]	20′ × 3	IM: 3.65 ± 0.31	NR	IM: 29 (29)
		MT: 4.04 ± 0.33		ST: 23 (39)
	20′ × 3	IM: 1.72 ± 020	NR	IM: 29 (29)
		MT: 2.89 ± 0.34		ST: 25 (29)
Goodson and others, 2005[31]	20′ × 3	NR	NR	NR
	20′ × 3			
Ziemba and others, 2005[25]	15′ × 3	IM: 4.2 ± 1.7	NR	IM:0.4 ± 0.9
		ST:4.6 ± 1.9		ST: 0.2 ± 0.4
	15′ × 3	IM:2.9 ± 1.6	NR	IM:0.7 ± 1.4
		ST: 3.5 ± 2.1		ST: 0.2 ± 0.4
Marson and others, 2008[5]	15′ × 3	NR	NR	ST: 6 (10)
	15′ × 3	NR	NR	ST: 5 (10)
	15′ × 3	NR	NR	ST: 8 (10)
	15′ × 3	NR	NR	ST: 6 (10)
Ontiveros and others, 2009[14]	15′ × 3	6.1 ± 3.1	ST: 2.8 ± 1.5	IM:1.4 ± 1.6
	15′ × 3	4.7 ± 2.2	ST: 3.8 ± 1.4	IM: 2.8 ± 3.0:
Kugel and others, 2009[15]	20′ × 3	NR	NR	IM:6 (10)
	20′ × 3 +20′ light	NR	NR	IM:10 (11)
Allomari and others, 2010[19]	20′ × 3	IM: 4.4 ± 1.8	NR	IM: 0.3 ± 0.5
		ST: 5.2 ± 1.9		
	20′ × 3	IM: 2.0 ± 1.9	NR	IM: 0.8 ± 0.4
		ST: 4.5 ± 2.1		
	20′ × 3	IM: 4.3 ± 2.0	NR	IM: 1.00 ± 0.0
		ST: 6.4 ± 2.0		
	20′ × 3	IM: 3.0 ± 1.3	NR	IM: 0.8 ± 0.4
		ST: 5.2 ± 1.8		
Calatayud and others, 2010[13]	10′ × 2	NR	NR	NR
	10′ × 2	NR	NR	NR
Bernardon and others, 2010[12]	15′ × 3	ST:2.26 ± 1.30	ST: 8.41 ± 3.14	NR
		MT:2.59 ± 1.45	MT: 8.03 ± 3.08	
	15′ × 3	ST:2.26 ± 1.37	ST: 8.76 ± 3.40	NR
		MT: 2.45 ± 1.34	MT: 8.37 ± 3.08	
Strobl and others, 2010[30]	1′45″ × 3	IM: 4.53 ± 3.52	IM:5.83 ± 3.17	NR
	1′45″ × 3	IM: 4.53 ± 3.52	IM:5.39 ± 3.0	NR
Gurgan and others, 2010[6]	15′ × 2	ST: 8.7 ± 2.32	5.54 ± 0.15	IM: 3.37 ± 1.94
	20′ × 2	ST: 8.5 ± 3.59	5.43 ± 0.20	IM: 2.9 ± 1.48
Kossatz and others, 2011[16]	15′ × 3	IM: 1.34 ± 0.7	NR	IM:13 (15)
	15′ × 3, 1′ light + 2′ without light 3 times	IM: 1.11 ± 0.6	NR	IM:15(15)
Almeida and others, 2012[17]	10′ × 3	NR	NR	IM: 2.8 ± 3.01
	10′ × 3, 3 × 20" light	NR	NR	IM: 2.8 ± 2.97
	10′ × 3 + 3 × 3′ light	NR	NR	IM: 2.2 ± 3.22

Table 1: *Characteristics of the analyzed studies (cont.)*

Author/Date	Study	Sample Size	Sex	Light Source (N)	BleachingAgent
Mondelli and others, 2012[18]	RCT	32	NR	Without light (16)	35% HP
				LED/laser (16)	
				Without light (16)	38% HP
				LED/laser (16)	
Almeida and others, 2012[28]	RCT	30	NR	Without light (10)	35% HP
				Halogen light (10)	
				LED/laser (10)	
Polydorou and others, 2013[29]	RCT	60	NR	Without light (20)	38% HP
				Halogen light (20)	
				Laser (20)	
Moncada and others, 2013[20]	RCT	87	M: 13 (27%) F: 64 (73%)	Without light (35)	35% HP
				LED/laser (27)	
Martin and others, 2013[21]	RCT	88	M: 23 (18,4%) F: 65 (81.6%)	Without light (NR)	35% HP
				LED/laser (NR)	
Henry and others, 2013[22]	RCT	49	M: 24 (48.9%) F: 25 (51.02%)	Without light (49)	25% HP
				Sodium arc bulb lamp (49)	
Bortolato and others, 2013[4]	RCT	40	NR	Without light (20)	35% HP
				LED/laser (20)	
Freitas and others, 2016[23]	RCT	22	M: 10 (45.4%) F: 12 (54.6%)	Without light (22)	35%HP
				LED/laser (22)	
Mena-Serrano and others, 2016[24]	RCT	77	M: 27 (35%)	Without light (19)	20%HP
				LED/laser (19)	
			F: 50 (65%)	Without light (19)	35% HP
				LED/laser (19)	

F, female; IM, immediate effect; M, male; MT, medium-term effect; NR, not related; ST, short-term effect.

Table 1: *Characteristics of the analyzed studies (ext.) (cont.)*

Author/Date	Bleaching Time	Subjective Shade Evaluation	Objective Shade Evaluation	Tooth Sensitivity
Mondelli and others, 2012[18]	15′ × 3	NR	IM: 7.8 ± 1.42	NR
			ST: 5.64 ± 1.45	
			MT: 4.49 ± 1.45	
	11 × 3 + 3 × 3′ light	NR	IM: 7.49 ± 1.45	NR
			ST:5.43 ± 1.47	
			MT: 4.33 ± 1.39	
	15′ × 3	NR	IM: 7.83 ± 1.39	NR
			ST: 5.78 ± 1.37	
			MT: 4.64 ± 1.26	
	11′ × 3 + 3 × 3′ light	NR	IM: 7.76 ± 1.5	NR
			ST: 5.64 ± 1.38	
			MT: 4.42 ± 1.47	
Almeida and others, 2012[28]	10′ × 3	IM: 1.2 ± 0.63	NR	NR
		ST: 1.3 ± 0.67		
		MT: 1.3 ± 0.67		
	10′ × 3, 3 × 20′′ light	IM: 1.1 ± 0.31	NR	NR
		ST: 1.8 ± 1.22		
		MT: 1.8 ± 1.22		
	10′ × 3, 3 × 3′ light	IM: 1.0 ± 0.00	NR	NR
		ST: 1.0 ± 0.0		
		MT: 1.0 ± 0.00		
Polydorou and others, 2013[29]	15′ × 4	IM: 1.75 ± 2.7	IM: 4.8 ± 3.7	NR
		ST: 2.9 ± 2.9	ST: 7.25 ± 2.9	
		MT: 4.55 ± 1.7	MT: 7.05 ± 2.3	
	15′ × 4 + 8′ light	IM: 5.5 ± 2.94	IM: 6.1 ± 1.9	NR
		ST: 4.85 ± 2.18	ST: 5.55 ± 2.2	
		MT: 4.95 ± 2.3	MT: 5.1 ± 2.1	
	15′ × 4 + 30” light	IM: 1.15 ± 1.7	IM: 2.15 ± 2.4	NR
		ST: 3.65 ± 2.5	ST: 6.75 ± 3.2	
		MT: 4 ± 2.17	MT: 6.7 ± 2.8	
Moncada and others, 2013[20]	45′	NR	NR	IM: 31.51 ± 29.34
				ST: 7.23 ± 9.2
	10′ × 3 + 6′ light × 3	NR	NR	IM: 42.40 ± 31.78
				ST: 8.68 ± 17.99
Martin and others, 2013[21]	45′	NR	NR	IM: 31.51 ± 29.34
				ST: 9.65 ± 12.78
	10′ × 3 + 5× light cycles, 1′30 “ each	NR	NR	IM: 42.41 ± 31.78
				ST: 10.24 ± 18.56
Henry and others, 2013[22]	15′ × 3	ST: −1.66 ± 4.07	NR	NR
	15′ × 3	ST: −2.95 ± 4.21	NR	NR
Bortolato and others, 2013[4]	15′ × 3	NR	NR	IM: 37.6 ± 5.9
	8′ × 3 + 4× light cycles, 1′ each hemiarc	NR	NR	IM: 11.1 ± 3.3
Freitas and others, 2016[23]	15′ × 3	ST: 3.3	NR	IM: 10 (22)
	8′ × 3 + 3× light cycles, 1′ each hemiarc	ST: 3.8	NR	IM: 8 (22)
Mena-Serrano and others, 2016[24]	15′ × 3	ST: 6.1 ± 2.6	ST: 13.2 ± 4.1	IM: 12 (19)
	15′ × 3 + 1′ light+ 2′ without light × 3	ST: 8.2 ± 1.3	ST: 11.8 ± 4.0	IM: 14 (19)
	15′ × 3	ST: 8.2 ± 2.5	ST: 12.4 ± 3.7	IM: 15 (19)
	15′ × 3 + 1′ light+ 2′ without light × 3	ST: 8.4 ± 1.4	ST: 14.1 ± 2.9	IM: 16 (19)

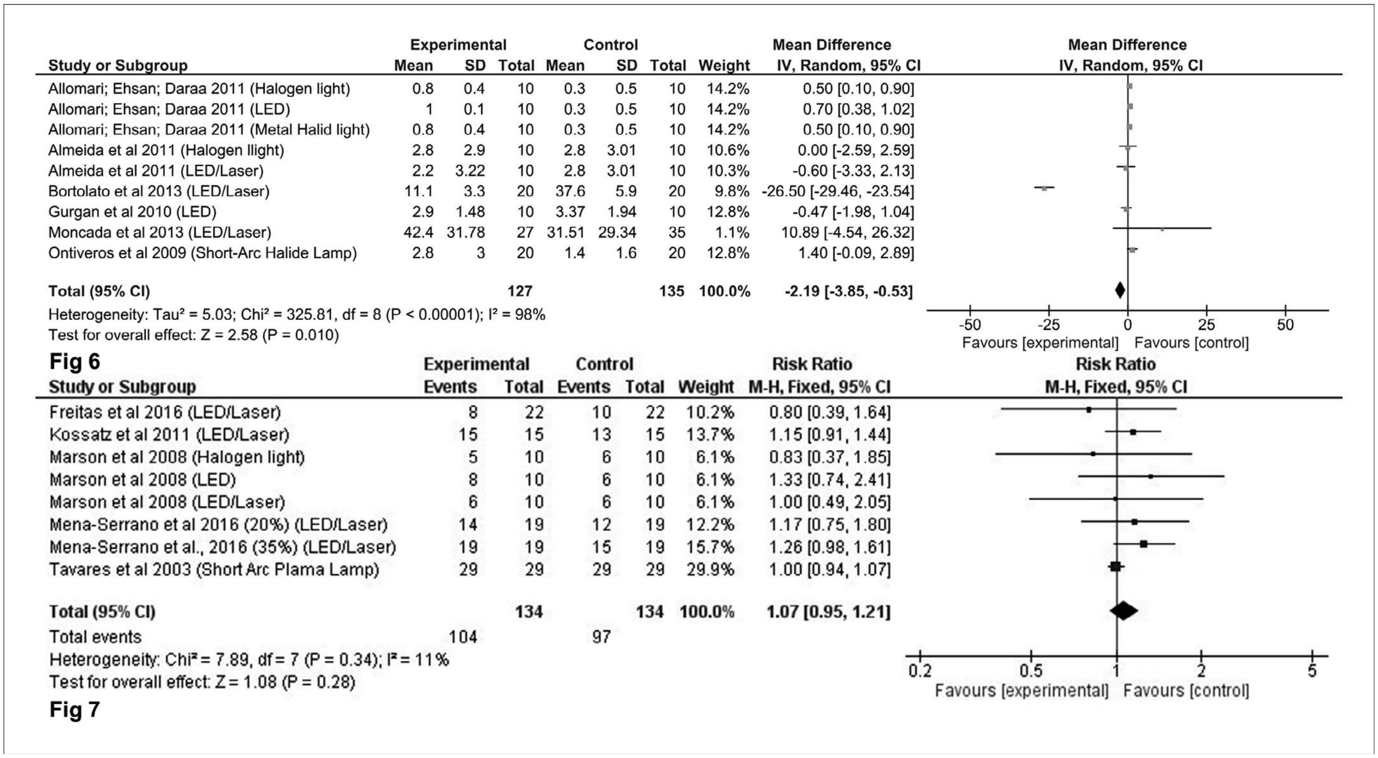

Figure 6. *Forest plot for the event "immediate sensitivity intensity."*
Figure 7. *Forest plot for the event "immediate sensitivity incidence."*

with a lower chance of tooth sensitivity for the non-light bleaching procedure (data not shown).

Incidence of Tooth Sensitivity—The incidence of tooth sensitivity between light and non-light bleaching systems according to visual analogue scale scores was assessed in four studies.[5,16,23,27] RRs showed that there were no differences between light- and non-light-activated bleaching systems (p=0.28; MD: 1.07; CI: 0.95 to 1.21). Heterogeneity was not significant (χ^2: 7.89; I^2 = 11%; p=0.33; Figure 7), and all studies included in the analysis did share a common effect size, suggesting that there are no differences in the incidences of tooth sensitivity between the two bleaching protocols (Figure 7).

DISCUSSION

In the present study, no significant differences were observed in bleaching efficacy, as measured by color change, between light- and non-light-activated bleaching systems, independent of time (immediate, short term, or medium term). Thus, we can accept the first null hypothesis. These results were corroborated with other published studies.[12,14,23,28] However, there have been other studies that observed better results when light was used with hydrogen peroxide.[14,15,25,27]

The use of hydrogen peroxide alone, without light, is effective for improving tooth color changes.[13] These results could be justified because high-concentration (25%-35%)[32] hydrogen peroxide already contains sufficient amounts of radicals to produce bleaching by chemical degradation only, without the use of light.[32] The light source could improve the tooth color change, when applied to low-concentration (15%-20%)[32] in-office hydrogen peroxide gel.[24] This is probably because the light improves the quantity of hydroxyl radicals available to compensate for the gel concentration.[16]

In some studies, the light had no influence on tooth color change,[12,16,18] whereas in others, light accelerated tooth bleaching in short-term evaluation.[15,19,22,29] This acceleration could be explained by tooth dehydration,[6] when light and heat are applied to the tooth surface.[13] However, in this systematic review, although a favorable trend was observed with the use of light-activated bleaching, no significant difference was observed compared with non-light-activated bleaching in the immediate, short-term, and medium-term effect. Even with this subgroup analysis, the results showed heterogeneity. The main reason for this effect could be different bleaching protocols, concentrations of the bleaching products and the type of light used.

Most of the studies analyzed immediate tooth color changes, whereas only four studies followed up after more than 4 weeks. Considering that ADA guidelines stipulate that at least 50% of patients followed up for 3-6 months after treatment should maintain perceptible color changes,[33] more studies are required to evaluate tooth color bleaching stability in the medium term.

It is important to emphasize that this study only included RCTs. However, even if these are controlled clinical studies, which are the best scientific evidence for a systematic review, it is important to note a limitation due to high heterogeneity attributed to the different in-office bleaching procedures. According to Kossatz and others,[16] it is difficult to compare color change following in-office bleaching due of the different measurement methods (subjective and objective) and units (CIE-Lab system and shade guide scales), material concentrations, and techniques used.

Many studies use the Vita Classic Guide (subjective method) to measure color[23] or an objective method such as spectrophotometric guides;[5,27] both techniques are considered acceptable.[5,13] All included studies that evaluated tooth color changes used a subjective method, whereas only four studies used an objective method. This could be due to the wide use of the Vita Classical in clinical dental practice[12,13] and is the reason subjective measurements were used for color change meta-analyses.

One of the most commonly reported side effects of tooth bleaching is tooth sensitivity[6,20] and was therefore one of the outcomes evaluated in this study. Tooth sensitivity after in-office light bleaching procedures may occur as light absorbed by the bleaching gel and the resultant energy produces heat.[16] The tooth sensitivity outcome was evaluated after bleaching treatment for all the included studies through a visual analogue scale.

Regarding incidence of sensitivity, there were no differences observed between the groups analyzed. This suggests that sensitivity is not related to the light source but rather the bleaching gel concentration,[20] considering that bleaching gel increases enamel and dentin permeability and enhances the ability to achieve the pulp chamber[34] causing significant cell damage.[35]

Hydrogen peroxide gel concentration could have a significant role in tooth sensitivity. Agents with low concentrations are more tolerable by patients.[21] Apparently, with low concentration gel, light does not influence the sensitivity.[24,25,27] In the high-concentration gel, some studies have verified that the LED/laser systems can favor the reduction of sensitivity[4,6,]; on the other hand, some studies reported that light influence was worse [16,17,19] or did not influence.[5,20,21,23,24] Only one study compared the influence of different gel concentrations and the use of light and did not verify any differences between different gel concentrations on sensitivity.[24] However, this study focused on the influence of light sources during in-office tooth bleaching. Subgroup analyses were not carried out, given the small number of studies compared. Studies comparing bleaching gel concentrations should be developed and analyzed.

The second null hypothesis was accepted, because it was observed that light activation bleaching decreases sensitivity compared with non-light activation bleaching techniques. However, it was observed that a high heterogeneity and a single study had a great influence on the result.[4] Two facts can affect this result: the light used and the time of exposure to bleaching gel. The light source used was a LED/laser unit and the result can be explained by analgesic[37] and anti-inflammatory effect of this hybrid light. The infrared laser wavelength can promote a high polarization of the nervous membrane, minimizing incidence and the intensity of the sensitivity.[37] However for Farhat and others,[38] the LED-laser source did not prevent or reduce sensitivity. Another reason for this result was the reduction of the bleaching gel contact time with the dental structure with the light bleaching group. For all studies analyzed, the time of bleaching gel tooth surface contact was the same or very close. However, for this study, the time of bleaching gel contact, for the light group, was one half that of the non-light group. Trindade and others[35] affirm that the degree of damage is higher when increasing concentration and application time of the bleaching agent.

The dental literature is very contradictory concerning incidence of tooth sensitivity. Many studies showed a high sensitivity intensity when the light was used.[14,19] This can be explained by the high concentration of peroxide penetrating the tooth structure, which causes direct activation of a pulp neuronal receptor[22] and, along with the power intensity of the light source used,[17,21] may increase tooth temperature.[23] A temperature increase of 5.55°C compromises tooth vitality in 15% of dental pulps.[39] The use of a light source should not be considered when higher concentrations of hydrogen peroxide are used and not be justified due to the risks involved.[40]

Sensitivity analyses were always performed with short-term follow-up. Only three studies evaluated sensitivity after one week, and only one study evaluated sensitivity over 30 days. This suggests that the greatest pain intensity occurs within the first hours of bleaching.[20,23]

Due to the risk of bias analyses, it is important to emphasize that fewer studies had complete information about sequence generation and allocation concealment. It is important that randomized controlled trials present methodologies explicitly so that data can be extracted and interpreted clearly. Another limitation of this study was the differences in bleaching protocols (number of bleaching sessions, number of gel applications per sessions). Thus, it is recommended that studies are developed with convergent methodologies.

CONCLUSION

In our meta-analyses, bleaching with light and non-light activation showed no differences in tooth color changes or tooth sensitivity incidence. However, light activation bleaching decreased the intensity of tooth sensitivity. Thus, the use of lights for in-office bleaching is not imperative in achieving the desired esthetic clinical results.

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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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Influence of Polishing Systems on Surface Roughness of Composite Resins: Polishability of Composite Resins

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Clinical Relevance

Not all composite resins have the same polishability, nor do all polishers produce acceptable surface roughness.

SUMMARY

Objectives: The objective of this *in vitro* study was to compare, with a threshold value of 200 nm, the surface roughness obtained when using 12 different polishing systems on four different composite resins (microfill, nanofill, and two nanohybrids).

Methods and Materials: A total of 384 convex specimens were made using Durafill VS, Filtek Supreme Ultra, Grandio SO, and Venus Pearl. After sandblasting and finishing with a medium-grit finishing disc, initial surface roughness was measured using a surface roughness tester. Specimens were polished using 12 different polishing systems: Astropol, HiLuster Plus, D♦Fine, Diacomp, ET Illustra, Sof-Lex Wheels, Sof-Lex XT discs, Super-Snap, Enhance/Pogo, Optrapol, OneGloss and ComposiPro Brush (n=8). The final surface roughness was measured, and data were analyzed using two-way analysis of variance. Pairwise comparisons were made using protected Fisher least significant difference.

Results: There were statistical differences in the final surface roughness between polishing systems and between composite resins ($p<0.05$). The highest surface roughness was observed for all composite resins polished with OneGloss and ComposiPro Brush. Enhance/Pogo and Sof-Lex Wheels produced a mean surface roughness greater than the 200-nm threshold on Filtek Supreme Ultra, Grandio SO, and Venus Pearl. Data showed that there was an interaction between the composite resins and the polishing systems.

Conclusions: A single polishing system does not perform equally with all composite resins. Except for Optrapol, multi-step polishing systems performed generally better than one-step

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systems. Excluding Enhance/Pogo, diamond-impregnated polishers led to lower surface roughness. Durafill VS, a microfill composite resin, may be polished more predictably with different polishers.

INTRODUCTION

Composite resin is extensively used as a dental restorative material, as it is very conservative and has high esthetic potential. Although composite resin is used frequently, it remains a challenge to identify appropriate polishing systems to obtain high surface gloss. A smooth surface is important to prevent discoloration and plaque accumulation, which can increase caries risk and gingival inflammation.[1,2] A surface roughness value of 200 nm has been established as the threshold under which bacterial adhesion could be prevented.[3] Long-term success and the esthetics of composite resin restorations may be improved through proper polishing, which prevents marginal staining and discoloration.[4-8] Moreover, proper polishing may preserve high surface quality and gloss over time.[9]

The surface quality of composite resin is influenced by several factors, including filler particle size, filler loading and resin content, type of filler, and particle morphology.[10-13] Polishing success is reported to be increased when smaller particles are included in composite resin materials.[14] Microfilled composite resins are known to obtain the highest gloss and surface quality because of their small particles and high resin content. However, microfilled composite resins have lower mechanical properties than universal composite resins, such as nanohybrid and nanofill composite resins.[12]

Several systems are available to finish and polish composite resin materials. These systems require one or multiple steps, and they differ greatly in their composition, presentation, type and hardness of abrasive particles. These differences significantly influence the surface gloss and roughness of composite resin materials.[8,9,15-19] Considering that simplified systems are less time-consuming, it is important for dental practitioners to know what systems offer adequate surface quality to improve both esthetics and longevity of composite resin restorations.

Several studies[9,16-25] have assessed different finishing and polishing systems using various types of composite resins. However, many of these studies limit the number of finishing/polishing systems evaluated and use discs of composite resin presenting flat surfaces. To the knowledge of the authors, there is currently no study comparing the surface roughness obtained when using several different polishing systems on convex composite resin surfaces, as is normally the case in clinical situations.

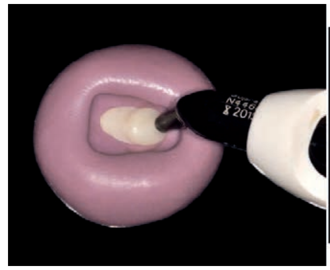


Figure 1. *Impression of a Vita Shade guide in which composite resin was inserted in one increment.*

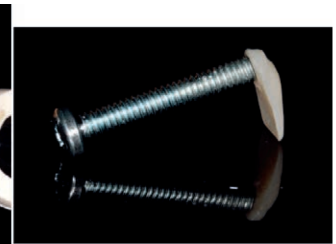


Figure 2. *A flat-end screw was inserted in the back of the specimen in its cervical portion to a depth of approximately 1.5 mm for handling purposes.*

The purpose of this study was to compare the surface roughness obtained when using 12 different polishing systems commonly used in private dental practice on four different composite resin specimens with a convex surface. The main null hypothesis was that there is no difference in surface roughness between the different polishing systems tested for each composite resin. Secondary null hypotheses were that there are no differences in the surface roughness between the four composite resins tested for each polishing system and that there is no interaction among the two variables: polishing system and composite resin.

METHODS AND MATERIALS

Impressions of a VITA shade tab (VITA North America, Yorba Linda, CA, USA) were made using polyvinyl siloxane putty material (Extrude XP, Kerr Corporation, Orange, CA, USA) Specimens of each composite resin were made by placing composite resin in one increment into the mold (Figure 1). A total of 384 specimens were fabricated: 96 specimens were made from a nanofill composite resin (Filtek Supreme Ultra), 96 from a nanohybrid composite resin (GrandioSO), 96 using a second nanohybrid composite resin (Venus Pearl), and 96 from a microfilled composite resin (Durafill VS). Composite resin specifications are listed in Table 1.

To improve handling during finishing and polishing procedures, a lubricated flat-end screw was inserted in the back of the specimen in its cervical portion to a depth of approximately 1.5 mm (Figure 2) before polymerization. The composite resin was

Table 1: *Specifications of Composite Resin Tested*

Composite Resin	Manufacturer	Shade	Type	Organic Matrix	Abrasive Particles and Particles Size	% Filler Content (% wt)	Batch Number
Durafill VS	Heraeus Kulzer, Hanau, Germany	A2	Microfill	BisGMA UDMA TEGDMA	Silicon dioxide (20-70 nm) Prepolymer (<20 nm)	50.5[26]	010222
Filtek Supreme Ultra	3M, St Paul, MN, USA	A2	Nanofill	BisGMA UDMA TEGDMA PEGDMA BisEMA	Silica (20 nm), zirconia (4-11 nm), zirconia-silica nanoclusters	78.5	N495465
GrandioSO	Voco America Inc, Indian Land, SC, USA	A2	Nanohybrid	BisGMA BisEMA TEGDMA	Glass ceramic (average 1 um) Silicon dioxide (20-40 nm) Pigments: iron oxide, titanium dioxide	89	1512206
Venus Pearl	Heraeus Kulzer Hanau, Germany	A2	Nanohybrid	Patented monomer (TCD-DI-HEA)	5 nm to 5 μm and prepolymerized filler	80	010028

Abbreviations: BisEMA, ethoxylated bisphenol A dimethacrylate; BisGMA, bisphenol A diglycidyl ether dimethacryalate; PEGDMA, polyethylene glycol dimethacrylate; TEGDMA, triethylene glycol dimethacrylate; UDMA, urethane dimethacrylate.

subsequently light-cured for 40 seconds (Optilux 501, Demetron, Kerr, Danbury, CT, USA). After the first polymerization cycle, the screw was removed, and the specimens were light-cured for an additional 40 seconds. The specimen was then removed from the putty material, and the unexposed surface was light-cured for an additional 40 seconds. The intensity of the curing light was verified periodically (after curing five specimens) using the radiometer on the unit to ensure that at least 600 mW/cm^2 was delivered to the material.

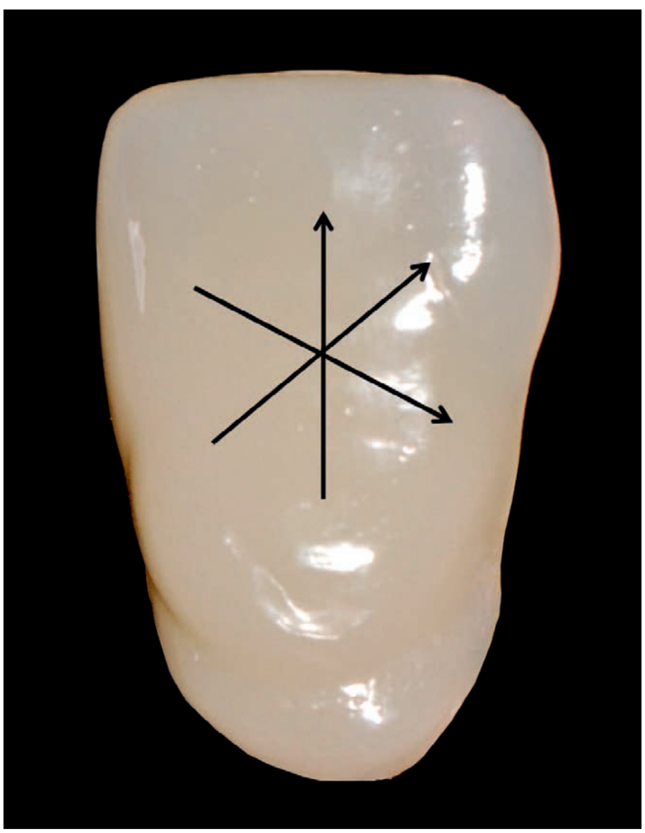


Figure 3. *Three surface roughness measurements were taken by rotating the specimen at an angle of 60°.*

To ensure uniform initial roughness, the composite resin surface was first sandblasted with 50-μm aluminum oxide particles until the surface layer appeared uniformly rough (Microetcher II, Danville, San Ramon, CA, USA). Specimens were then cleaned in 70% ethanol in an ultrasonic bath (Ultrasonic 08849-00, Cole-Parmer, Vernon Hills, IL, USA) for 2 minutes, rinsed, and dried. Finishing was simulated using a medium-grit Sof-Lex XT disc with an electric handpiece (ForZaElm, Brasseler, Savannah, GA, USA). Next, specimens were rinsed with combined air and water spray and air-dried to remove excess moisture. To further remove surface debris, impressions using a low-viscosity polyvinyl siloxane (Aquasil XLV Ultra, fast set, Dentsply Caulk, Milford, DE, USA) were taken and allowed to set for 5 minutes. These impressions were discarded.

The initial surface roughness (Ra) of each specimen was then measured with a surface roughness tester (Surftest 402, Mitutoyo, Kanagawa, Japan) using a tracing length of 3 mm and a cutoff λC of 0.25 mm. Three measurements were taken of each specimen by rotating the specimen 60°, and the average was calculated for statistical analysis (Figure 3).

Table 2: *Finishing and Polishing Systems Evaluated*

Polishing System	Manufacturer	Type	Abrasive Particle	Particle Size	Batch Number
Astropol	Ivoclar Vivadent Inc, Amherst, NY, USA	Three-step rubber polishing system	Diamond	36.5 μm (F)[16] 12.8 μm (P)[16] 3.5 μm (HP)[16]	RL0751
HiLuster Plus	Kerr Corporation, Orange, CA, USA	Two-step rubber polishing system	Aluminum oxide, diamond	—	5462546
D♦Fine	Clinician's Choice, New Milford, CT, USA	Two-step rubber polishing system	Diamond	45 μm [7] 5 μm[27]	—
Diacomp	Brasseler Savannah, GA, USA	Two-step rubber polishing system	Diamond	40-60 μm[27] 1-3 μm[27]	KR6FF KR8MZ
ET Illustra	Brasseler Savannah, GA, USA	Two-step rubber polishing system	"Proprieraty abrasive particles," manufacturer's information	—	KB7EM
Sof-Lex Spiral Wheels	3M, St Paul, MN, USA	Two-step rubber wheel polishing system	Aluminum oxide	—	N511340
Sof-Lex XT Discs	3M St Paul, MN, USA	Four-step rubber polishing discs	Aluminum oxide	Coarse: 60 μm[28] Medium (29 μm)[16,19] Fine (14 μm)[16,19] Extra fine (5μm)[16,19]	
Super-Snap	Shofu, San Marcos, CA, USA	Four-step rubber polishing discs	Silicon carbide, aluminum oxide	Black: 60 μm[28] Violet: 30 μm[28] Green: 20 μm[28] Red: 7 μm[28]	0312012
Enhance-Pogo	Dentsply Milford, DE, USA	Two-step rubber finishing and polishing (single polishing step)	Aluminum oxide, diamond	Enhance: 40 μm[16,19] Pogo: 7 μm[16,29]	120609
Optrapol	Ivoclar Vivadent	One-step rubber finishing and polishing system	Diamond	12 μm	PL1811
OneGloss	Shofu, San Marcos, CA, USA	One-step rubber finishing and polishing system	Aluminum oxide	80 μm[27]	0112918
Composipro Brush	Brasseler Savannah, GA, USA	One-step polishing system	Silicon carbide	N/A	—

Specimens of each composite resin type were then randomly and equally divided into 12 groups according to the finishing and polishing system used, as listed in Table 2 (n=8).

Specimens were polished by a single operator according to the polisher manufacturer's instructions regarding the speed, pressure, and need for water during the procedure (Table 3). Specimens were thoroughly rinsed with water between each polishing step. An electric handpiece was used to standardize the polishing speed, and a chronometer (Traceable timer, Control Company, Webster, TX, USA) was used to control the polishing time. The operator rehearsed and tested the protocol until the highest gloss was achieved for each polisher using extra specimens of Filtek Supreme Ultra that were discarded.

To minimize the variable of operator improvement throughout the experiment, a list of specimens placed in random group order was established using a random-sequence generator (Random.org, Dr. Mads Haahr, School of Computer Science and Statistics, Trinity College, Dublin, Ireland). The goal was to randomly polish one specimen in each group before moving forward to the second specimen.

Surface roughness was then measured with the same surface roughness tester (Surftest 402, Mitutoyo) using the same protocol as for the initial surface roughness measurements.

Statistical analysis was conducted using SAS for Windows (version 9.4, 2015, SAS Institute Inc, Cary, NC, USA). A two-way analysis of variance (ANOVA) model was used to study the effect of polishing system and composite resin on surface roughness. The model was adjusted for the roughness measurements before and after polishing. Pairwise comparisons were made using protected Fisher least significant difference. A p-value of less than 0.05 was used as a criterion for statistical significance. Residual analysis was performed to verify the

Table 3: *Polishing Protocol Followed*

Polishing System	Abrasive	Speed, RPM	Duration, s	Pressure	Water Coolant
Astropol	1. Grey	10,000	60	Moderate	Yes
	2. Green	10,000	60	Moderate	Yes
	3. Pink	10,000	60	Moderate	Yes
		10,000	30	Low	Yes
HiLuster Plus	1. Blue	10,000	60	Moderate	Yes
	2. Gray	10,000	60	Moderate	No
		10,000	30	Low	No
D♦FINE	1. Gray	10,000	60	Moderate	Yes
	2. Pink	10,000	60	Moderate	Yes
		10,000	30	Low	Yes
Diacomp	1. Green	15,000	60	Moderate	Yes
	2. Gray	15,000	60	Moderate	No
		6000	30	Moderate	No
ET Illstra	1. Purple	12,000	60	Moderate	No
	2. Gray	7000	60	Moderate	No
		7000	30	Low	No
Sof-Lex Wheels	1. Yellow	10,000	60	Low	No
	2. White	10,000	90	Low	No
Sof-Lex Discs	1. Light orange	10,000	60	Low	No
	2. Yellow	10,000	90	Low	No
Super-Snap	1. Purple	10,000	30	Low	No
	2. Green	10,000	60	Low	No
	3. Pink	10,000	60	Low	No
Enhance/Pogo	1. Brown	10,000	60	Moderate	No
	2. Gray	10,000	60	Moderate	No
		10,000	30	Low	No
OptraPol	1	8000	60	Moderate	Yes
		8000	60	Low	Yes
OneGloss	1	5000	60	High	Yes
		5000	60	Low	No
ComposiPro Brush	1	5000	60	High	No
		5000	60	Low	No

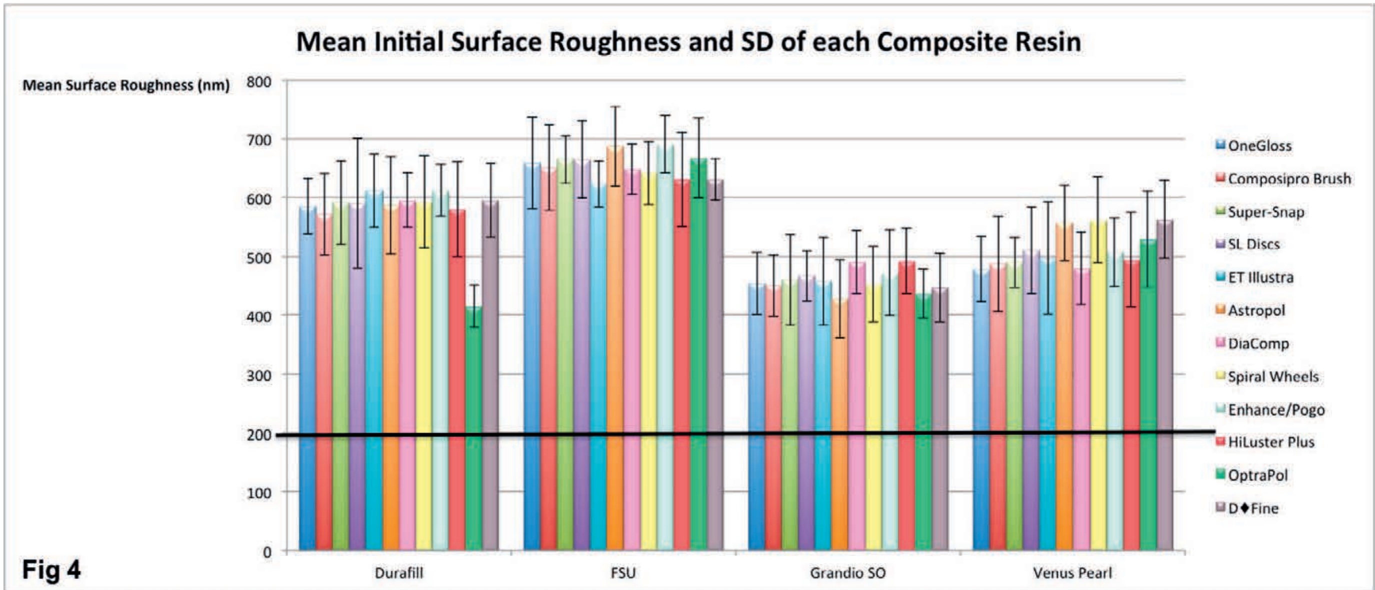
normality and the homogeneity of the variance assumptions.

RESULTS

Descriptive statistics for initial surface roughness and final surface roughness measurements are presented in Figures 4 and 5. Figure 4 shows that the initial surface roughness is greater than the 200-nm threshold for all composite resins tested and that Grandio SO and Venus Pearl have an overall lower surface roughness value. Figure 5 depicts that the highest final surface roughness for each composite resin was observed with OneGloss and ComposiPro Brush. Enhance/Pogo and Sof-Lex Wheels produce a surface roughness below the 200-nm threshold on Durafill VS, whereas the surface roughness was above the threshold on Filtek Supreme Ultra, Grandio SO, and Venus Pearl.

Results of the two-way ANOVA are presented in Table 4. For initial surface roughness, only the main effect of composite resins was significant ($p<0.0001$), meaning that the mean initial surface roughness measurements between the composite resins tested were statistically different. Furthermore, differences observed between composite resins were the same for all polishing systems, since the interaction term was not significant ($p=0.34$). Pairwise comparisons of composite resins are presented in Table 5, which shows that Filtek Supreme Ultra had the highest initial surface roughness and Grandio SO the lowest.

Regarding the final surface roughness, results of the two-way ANOVA revealed that the interaction



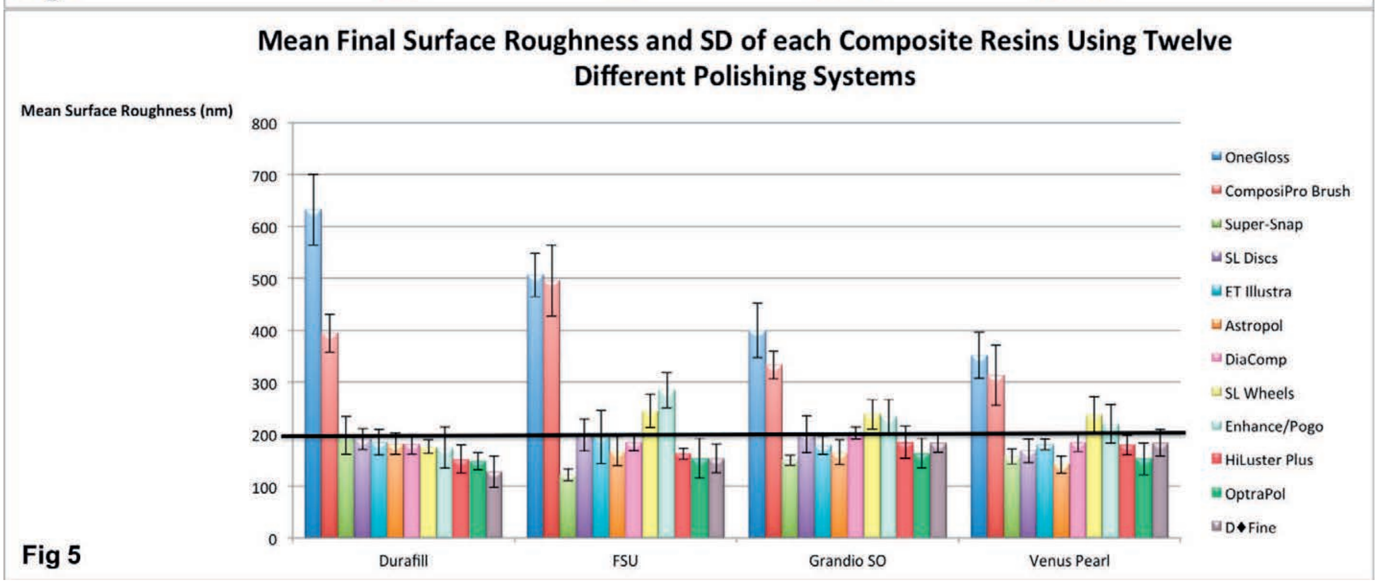


Figure 4. *Initial surface roughness measurements after sandblasting procedures and medium grit Sof-Lex XT disc.*

Figure 5. *Comparison of composite resin final surface roughness measurements after polishing with different systems.*

between composite resins and polishing systems was statistically significant ($p<0.0001$). This indicated that the final surface roughness obtained with different polishing systems was not the same for each composite resin tested. Table 6 illustrates the pairwise comparisons of different polishing systems for each composite resin as well as the pairwise comparisons of different composite resins for each polishing system. It may be concluded from this table that the polishing systems leaving the smoothest

Table 4: *Results of the Analysis of Variance for Both Initial and Final Surface Roughness Measurements*

Effect	Num *df*	Den *df*	Initial Measurement		Final Measurement	
			F Value	*p* Value	*F* Value	*p* Value
Composite resin	3	336	168.01	<0.0001	18.57	<0.0001
Polishing system	11	336	0.61	0.8188	310.86	<0.0001
Composite × polishing	33	336	1.09	0.3432	17.78	<0.0001

Table 5: *Initial Surface Roughness (nm) Difference Between Composite Resins*[a]

Composite Resin	Mean Surface Roughness, nm	Standard Deviation	Group Comparison
Filtek Supreme Ultra	655.0	6.63	A
Durafill VS	589.6	6.63	B
Venus Pearl	513.0	6.63	C
Grandio SO	459.0	6.63	D

[a] *Different letters indicate statistical differences between groups (p<0.05).*

surfaces for each composite resin are not the same. Durafill VS, D♦Fine, Optrapol, and HiLuster Plus produced the lowest surface roughness. However, except for OneGloss and Composipro Brush, most systems reached a mean surface roughness below the 200-nm threshold, although some standard deviations were slightly higher. For Filtek Supreme Ultra, Super-Snap achieved the smoothest surface, but Astropol, HiLuster Plus, D♦Fine, Diacomp, and OptraPol also obtained mean surface roughness value less than 200 nm. For Grandio SO and Venus Pearl, the lowest surface roughness was obtained when using Super-Snap, OptraPol, and Astropol adding ET Illustra for Grandio SO and Sof-Lex discs for Venus Pearl.

DISCUSSION

Composite resin surface quality is important to optimize esthetics and longevity of restorations. The best surface quality with the lowest surface roughness has often been obtained with a composite resin cured against a Mylar strip.[17-19,26,30,31] However, this surface has a resin-rich layer and presents a lower hardness. To prevent wear and discoloration, it is suggested to finish and polish this surface.[32] This study evaluated the effect of different commercially available polishing systems on the surface roughness of composite resins.

The results of the present study suggest that a single polishing system does not produce the same surface quality for all composite resins. This may not be entirely attributed to the quality of the polishers but to the interaction between the polisher and the composite resin. This is in accordance with the findings of previous studies.[9,16,19] Several factors have been proposed to affect the polishability of composite resin, including the polishing system, the composite resin used, and variables associated with the operator.

Traditionally, ideal polishing protocols have been explained as a selective wear process using a sequence of abrasive particles from coarse grit gradually decreasing toward fine grit.[5,15] Currently, a variety of polishing systems are commercially available. Some systems require multiple steps, whereas others are simplified and require only one grit used with gradually decreasing pressure. The hardness of the backing or rubber media into which the abrasive particles are embedded influences the surface quality.[15] The hardness of the abrasive particles vary and may be classified as follows according to the Mohs's hardness scale: diamond >

Table 6: *Comparison of Mean Final Surface Roughness (nm) and Standard Deviation for Composite Resins and Polishing Systems*[a]

Polishing System	Composite Resin			
	Durafill VS	Filtek Supreme Ultra	Grandio SO	Venus Pearl
Astropol	181.4 ± 32.3 A, cd	167.5 ± 37.2 AB, de	164.5 ± 56.1 AB, ef	141.5 ± 28.8 B, f
HiLuster Plus	152.0 ± 38.8 B, def	162.3 ± 25.4 AB, e	184.0 ± 34.3 A, de	179.0± 26.9 AB, de
D♦FINE	127.7 ± 48.4 B, f	153.5 ± 46.5 AB, e	182.2 ± 30.8 A, de	183.1 ± 40.3 A, de
Diacomp	180.5 ± 36.3 A, cd	184.4 ± 26.1 A, de	201.4 ± 37.5 A, d	184.5 ± 34.0 A, d
ET Illustra	184.2 ± 36.8 A, c	194.7 ± 60.7 A, d	178.1 ± 37.1 A, def	179.9 ± 21.9 A, de
Sof-Lex Wheels	175.2 ± 35.8 B, cde	245.0 ± 42.4 A, c	237.6 ± 34.9 A, c	236.4 ± 50.3 A, c
Sof-Lex Discs	190.8 ± 51.5 A, c	198.3 ± 37.0 A, d	199.0 ± 41.2 A, d	167.8 ± 31.7 A, def
Super-Snap	197.5 ± 45.8 A, c	121.3 ± 22.7 C, f	149.4 ± 20.1 BC, f	156.7 ± 29.2 B, def
Enhance/Pogo	173.7 ± 65.3 C, cde	284.8 ± 64.6 A, b	233.4 ± 72.3 B, c	219.3 ± 79.5 B, c
OptraPol	147.8 ± 28.3 A, ef	153.5 ± 42.0 A, e	162.8 ± 35.0 A, ef	152.3 ± 38.2 A, ef
OneGloss	632.3 ± 95.8 A, a	506.8 ± 89.6 B, a	400.0 ± 78.4 C, a	352.0 ± 58.3 D, a
ComposiPro Brush	394.4 ± 85.9 B, b	495.8 ± 83.4 A, a	332.5 ± 38.3 C, b	313.5 ± 68.7 C, b

[a] *Capital letters represent statistical differences among composite resins (within the row), and lowercase letters represent statistical differences among polishing systems (within the column). Different letters indicate statistical differences between groups (p<0.05).*

silicon carbide > tungsten carbide > aluminum oxide > zirconium silicate.[15] The hardness and the size of abrasive particles are very important. First, the abrasive particles must be harder than the filler particles present in the composite resin to avoid abrading only the resin matrix and leaving the filler particles protruding. Second, the abrasive particles must be small to prevent scratches on the composite resin. Multi-step systems use smaller particles for each step to remove scratches from the previous polisher until a highly shined surface is obtained. For one-step systems, the grit size is important because it may leave scratches on the composite resin. Some studies reported that multi-step polishers perform better than one-step polishers.[9,16] Indeed, in the literature, it may be found that Sof-Lex discs produced higher gloss along with Astropol,[8,9,16] whereas brushes produced high surface roughness.[16] On the contrary, some studies reported that the Pogo system, used as a one-step or a two-step system, showed the highest gloss, whereas aluminum oxide discs produced a poorer surface finish.[16-19] In the present study, data showed that following final polishing, most polishing systems obtained a clinically adequate surface roughness of less than 200 nm. However, OneGloss and CompoSiPro Brush, two simplified one-step polishing systems, were unable to reach an acceptable surface roughness and left roughness significantly above the threshold for all the composite resins tested. The final surface roughness obtained with OneGloss was even higher than before polishing procedures. Of the one-step systems, only Optrapol had a surface of less than 200 nm. Therefore, multi-step systems generally provided a better surface finish, a finding that is in partial agreement with the current literature. Although the Enhance/Pogo system showed good results in a previous study, the present data revealed that it left surface roughness above the 200-nm threshold on Filtek Supreme Ultra, Grandio SO, and Venus Pearl. Therefore, except for the Enhance/Pogo system, polishing systems containing diamond particles produced, in general, a superior surface finish, which is consistent with previous studies.[15,16] Super-Snap, which contains silicon carbide and aluminum oxide particles, also left an excellent surface roughness, especially with Filtek Supreme Ultra. The Sof-Lex Wheels left a surface roughness greater than 200 nm on Filtek Supreme Ultra, Grandio SO, and Venus Pearl. The Sof-Lex Wheels used in the present study contained only aluminum oxide particles. Since the study was performed, the manufacturer modified the composition of the final polisher by replacing aluminum oxide with diamond particles. This would have probably altered the efficacy of this system.

Factors related to the composite resin also influence surface quality. These include the resin matrix content and formulation, the filler particle characteristics (type, hardness compared with the abrasiveness of the polishers, size, and shape), the composite resin filler load, the quality of the silane coupling agent, and the degree of conversion after light curing.[33-36] The matrix and filler particles have different hardness, which may influence the polishability of the composite resins. Insufficient abrasiveness of the polisher particles compared with the composite resin fillers will mostly abrade the matrix, leaving the filler particles in protrusion. In addition, insufficiently bonded fillers may debond and dislodge, leaving a dull surface. Therefore, the results suggest that the combination of composite resin and polisher has an influence on the result, with some polishers leaving an excellent finish on some composite resins but a less optimal finish on others. It is well known that smaller particles reduce the surface roughness after polishing procedures.[34] It has also been reported that spherical particles allow for a better light reflection than irregular particles.[36] It has been suggested that composite resin should be polished with the polishing system of the same manufacturer,[37] an assertion that could not be confirmed in the present study. The result of the present study reveals that, although not statistically different for all polishing systems used, Durafill VS, a microfill composite resin containing small particles and high resin content, showed less variability among the polishing systems. Filtek Supreme Ultra, a nanofilled composite resin, was reported by the manufacturer to have a unique formulation, in which nanosized particles were individually silanized[38] and agglomerations or nanoclusters that seem to resist particle loss during the polishing procedure, leaving a more uniform surface with less roughness.[33] The results of this study generally confirm this, except when using some polishers (Enhance/Pogo and Sof-Lex Wheels).

A high surface roughness has been found with Grandio in some studies.[8,9] However, compared with the other composite resins tested in the present study, this high surface roughness was not observed. Although the mean surface roughness was close to the threshold for some polishers (Sof-Lex discs and Diacomp) or above the threshold for some others (Enhance/Pogo, Sof-Lex Wheels, OneGloss, and ComposiPro Brush), many polishing systems left a mean surface roughness less than 200 nm. This may be due to the recent improvement in the Grandio SO formulation to obtain a better surface finish. Venus Pearl also seemed to adequately polish, with most polishers tested except with Sof-Lex Wheels and Enhance/Pogo.

An interaction was found in the present study, meaning that the surface roughness depends on the combination of polishing system used and composite resin. This is in accordance with the results of previous studies comparing polishing systems and composite resins.[18,26]

Possible bias may be attributed to operator variables such as the polishing time, the speed of the handpiece, the pressure applied to the composite resin, the hand skill improvement, and the experience of the operator. Heintze and others reported that surface roughness and gloss are time dependant, with the greatest improvement after five seconds and continued improvement for up to 30 seconds for each of the steps of the Astropol system (three-step polishing system).[39] In the present study, the operator, in accordance with the manufacturer's instructions, established the best polishing protocol (pressure, speed, and time) for all polishers to obtain the highest surface quality possible. These specimens were not included in the study. In the present study, specimens were polished for a minimum of 30 seconds for each step controlled with a chronometer (Table 3). Establishing this protocol also allowed the operator to rehearse prior to the study to obtain a standardized pressure while polishing the composite resin specimens. The speed of the handpiece was standardized using an electric handpiece. All steps were performed by the same rehearsed operator, who was a trained second-year dental student. According to Zimmerli and others, the age and experience of the operator do not seem to influence the surface quality of the composite resin after polishing procedures.[40] However, to control for the variability of improvement in hand skills throughout the study, specimens were polished in random order.

Previous studies evaluating the efficacy of polishing protocols in terms of surface roughness and gloss are mostly performed on discs of composite resin.[8,9,18,26,29,41,42] However, in clinical situations, composite resin is often placed in convex morphology, which may influence the result of polishing procedures, and this is the reason why convex specimens were used in the present study. Although disks allow gloss measurements, only surface roughness was measured in the present study because it was impossible to obtain reproducible gloss values due to specimens' convexity.

To establish an initial roughness for all the composite resins tested, specimens were first roughened using the same sequence of sandblasting (50 μm aluminum oxide particle) followed by a medium-grit Sof-Lex XT disk indicated for excess composite resin removal and recontouring before polishing. Although the same procedure was applied to all specimens, the initial roughness varied among the four composite resins tested. However, these differences did not seem to influence the final surface roughness results.

Many different factors may affect polish retention over time. It has been shown that the surface may be altered by bacterial biodegradation.[43] Surface quality may also be influenced by alcohol and acidic solution exposure.[44-49]

The results of the present study should be interpreted with caution and may not apply to other composite resins, polishing instruments, or polishing techniques. Clinical studies evaluating the effect of polishing quality on the longevity of composite resin restorations would be relevant.

CONCLUSION

The null hypotheses were rejected, since surface roughness was influenced by the polishing system and the composite resin tested. In addition, there was an interaction between the polishing systems and the composite resins. Indeed, a given polishing system does not perform equally with all composite resins. The results of the present study suggest that, except for Optrapol, multi-step polishing systems performed generally better than one-step systems. Moreover, excluding Enhance/Pogo, diamond-impregnated polishers allowed for lower surface roughness. In addition, Durafill VS, a microfill composite resin, may be polished more predictably with different polishers.

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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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The Influence of Distance on Radiant Exposure and Degree of Conversion Using Different Light-Emitting-Diode Curing Units

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Clinical Relevance

It may be necessary to double or triple exposure times when polymerizing at increasing clinically relevant distances from the base of the preparation.

SUMMARY

Objectives: To investigate the influence of curing distance on the degree of conversion (DC) of a resin-based composite (RBC) when similar radiant exposure was achieved using six different light-curing units (LCUs) and to explore the correlation among irradiance, radiant exposure, and DC.

Methods and Materials: A managing accurate resin curing-resin calibrator system was used to collect irradiance data for both top and bottom specimen surfaces with a curing distance of 2 mm and 8 mm while targeting a consistent top surface radiant exposure. Square nanohybrid-dual-photoinitiator RBC specimens ($5 \times 5 \times 2$ mm) were cured at each distance (n=6/LCU/distance). Irradiance and DC (micro-Raman spectroscopy) were determined for the top and bottom surfaces. The effect of distance and LCU on irradiance, radiant exposure, and DC as well as their linear associations were analyzed using analysis of variance and Pearson correlation coefficients, respectively (α=0.05).

Results: While maintaining a similar radiant exposure, each LCU exhibited distinctive patterns in decreased irradiance and increased curing time. No significant differences in DC values (63.21%-70.28%) were observed between the 2- and 8-mm distances, except for a multiple-emission peak LCU. Significant differences in DC were detected among the LCUs. As expected, irradiance and radiant exposure were significantly lower on the bottom surfaces. However, a strong correlation between irradiance and radiant exposure did not necessarily result in a strong correlation with DC.

Conclusions: The RBC exhibited DC values >63% when the top surface radiant exposure was maintained, although the same values

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were not reached for all lights. A moderate-strong correlation existed among irradiance, radiant exposure, and DC.

INTRODUCTION

The polymerization effectiveness of light-cured resin-based composite (RBC) depends on its composition and the light's spectral characteristics.[1,2] An RBC should receive the necessary power at the appropriate wavelengths for a sufficient amount of time to effectively activate polymerization.[1-5] The amount of energy needed varies according to the RBC's composition, shade, and translucency.[1-5]

Manufacturers do not typically disclose all of their product components and concentrations. The manufacturer-recommended RBC curing time is typically based on testing the material in ideal laboratory conditions, in which a light-curing unit (LCU) guide tip is positioned as close as possible to the specimen, commonly at a distance of 0 mm.[5] However, in a clinical setting, a 0-mm distance between the light guide and the restoration surface or cavity floor is not often attained. For example, the distance between the light guide tip and the cervical floor of a class II proximal box can reach up to 8 mm.[3] Increasing distance decreases the amount of irradiance (irradiance [mW/cm^2] = power/surface area)[1-6] and radiant exposure (radiant exposure [J/cm^2] = irradiance × time)[1,2,5,6] received by an RBC. Consequently, using the same curing time as instructed by the manufacturer when the distance is increased can result in a lower radiant exposure than required for sufficient photoinitiator activation.[3,7,8] This can lead to formation of a polymer network with less than ideal properties.[2-4,9,10] In addition to decreased properties, insufficient polymerization can result in leaching of unreacted monomers into the oral environment and compromised restoration longevity.[3,11-13] Therefore, increasing curing time may be needed as the curing distance increases from the RBC.

When maintaining radiant exposure, some RBCs exhibit similar properties,[2,14,15] but others may not.[9,16,17] Musanje and Darvell[9] reported that calculations using radiant exposure delivered to a restoration are based on the law of reciprocity, and the calculations do not recognize product behavior. Although this may be true, clinicians need usable guidelines when curing RBCs. A recent study showed that a better depth-of-cure comparison was achieved when a similar radiant exposure was delivered.[18] In addition, most studies evaluating RBC polymerization used different irradiance and curing time combinations and different light sources at one curing distance.[2,9,14-18] Determining curing protocols remains complicated because of variations in RBCs and the complexities of polymerization kinetics. The literature recommends that manufacturers provide curing protocols identifying the required energy for each RBC.[9,14] Unfortunately, detailed curing protocols at clinically relevant distances to effectively activate polymerization are rarely provided, and clinicians are left to subjectively determine appropriate exposure times. Determining the curing effectiveness for different distances based on radiant exposure calculations from the irradiance and curing time provided by the manufacturer was worth investigating.

The aims of this study were 1) to investigate the influence of distance on the degree of conversion (DC) of an RBC when similar radiant exposure is achieved using multiple light-emitting-diode (LED) curing units and 2) to explore the correlation among irradiance, radiant exposure, and DC for multiple LED units at two clinically relevant distances.

METHODS AND MATERIALS

Light Characterization

Six LCUs were explored in this study (Table 1). The irradiance and spectral irradiance for each curing unit were measured using a managing accurate resin curing-resin calibrator (MARC-RC) system (BlueLight Analytics, Halifax, Canada). The system had custom-designed top and bottom 4-mm cosine corrector sensors designed to collect the light output at 180° to eliminate any optical interference issues associated with the light-collection sampling geometry.[19] The measurements collected from the top sensor represented the irradiance and radiant exposure received on the top RBC surface. The bottom sensor measurements obtained under an RBC increment in real time represented the irradiance and radiant exposure received on the bottom surfaces.[8,20-23]

The irradiance measurements and specimen preparation were performed in a constant-temperature room (21°C) with 380- to 520-nm ambient light filtered from the environment. On the top sensor, each curing unit position was standardized using a mechanical arm, with the guide tip centered over the sensor. Each unit was positioned at 0, 2, 4, 6, and 8 mm between the guide tip and the top sensor to collect the irradiance and spectral emission (n=6/LCU/distance). The collected irradiance was used to adjust the curing times for each tested distance to

Table 1: *Light-Curing Units (LCUs) Explored in the Study*

LCU Type	LCU Name	Abbreviation	Manufacturer
Quartz-tungsten-halogen (QTH; control)	Optilux 401	O	Kerr, Orange, CA, USA
Multiple-emission peak light-emitting diode (LED)	Bluephase Style (with the updated light guide tip)	BS	Ivoclar Vivadent, Amherst, NY, USA
	SmartLight Max	SM	Dentsply, York, PA, USA
	Valo Cordless	V	Ultradent, South Gordon, UT, USA
Single-emission peak LED	DEMI (with a turbo tip)	D	Kerr, Orange, CA, USA
	Demi Ultra	DU	Kerr, Orange, CA, USA

roughly maintain the radiant exposure at 10-11 J/cm^2 on the top surface. This was consistent with manufacturer's irradiance and curing time guidelines for the dual-photoinitiator RBC (Tetric EvoCeram Bleaching shade XL, Ivoclar Vivadent, Amherst, NY, Lot No. T25427). Each LED unit was fully charged before collecting measurements, and the quartz-tungsten-halogen (QTH) unit fan was allowed to completely turn off between measurements. The RBC contained camphorquinone (CQ) and diphenyl (2,4,6-trimethylbenzoyl) phosphine oxide (TPO) photoinitiator systems, with less concentration of CQ compared with other Tetric EvoCeram shades.[24] This particular RBC was selected with the intent of accentuating potential differences in polymerization using single- or multiple-emission peak LED units.

Specimen Fabrication

Each LCU was positioned over the bottom MARC-RC sensor in a setup similar to the top sensor. Square specimens ($5 \times 5 \times 2$ mm) were fabricated using a Delrin mold as described in a previous study (n=3/LCU/distance).[22] The RBC was placed in the mold and sandwiched between two 0.002-mm-thick clear Mylar strips (Matrix Strips, DuPont MYLAR, Chester, VA) and glass slides to remove the excess material. The glass slides were removed, and the mold with Mylar strips was placed in the bottom sensor well. Each light guide tip was positioned at 2- or 8-mm curing distance from the top specimen surface, to represent a good and worst clinical case scenario, respectively.[3] Each curing unit was activated, and specimens were cured from the top using the adjusted curing times. The bottom sensor recorded the irradiance, radiant exposure, and spectral emission measurements passing through the 2-mm-thick specimens. The Mylar strip placed on the top specimen surfaces absorbed 3.5%-6.3% of the LCUs' irradiation. This absorbance was similar to another study.[25] The Mylar strips were removed, and the specimens were placed in a container, then wrapped with aluminum foil to prevent specimen exposure to light. Specimens were stored dry in a 37°C incubator for 24 hours.[26]

DC Measurements

The top and bottom specimen surfaces were finished using a Struers Rotopol 4 polishing unit with 1200-, 2400-, and 4000-grit SiC abrasive paper and polished using a 1-μm alcohol-based diamond polishing suspension (Struers, Ballerup, Denmark) to produce a flat and smooth surface. Specimens were ultrasonically cleansed for 20 minutes in deionized water to produce clean surfaces for DC testing. The DC measurements were collected using micro-Raman spectroscopy (FORAM, CRAIC Technologies, San Dimas, CA, USA) with a 785-nm laser excitation. Five scans for each spectrum measurement were collected and processed with FORAM PC software. Spectra of the uncured and cured RBC were recorded (n=3). The fourth day after specimen preparation, DC measurements were collected from the top and bottom surfaces (50/surface) in standardized locations of a 3×3-mm checkerboard grid pattern. The measurements obtained were at least 1-mm away from all edges of the specimen. The DC calculation was attained by comparing the relative change of the vinyl C=C band peak height (1640 cm^{-1}) before and after the polymerization and the aromatic C=C reference band peak height (1610 cm^{-1}) using the following equation[27]:

$$DC\% = \left(1 - \frac{\text{cured}\left(\frac{\text{peak height at 1640}}{\text{peak height at 1610}}\right)}{\text{uncured}\left(\frac{\text{peak height at 1640}}{\text{peak height at 1610}}\right)}\right) \times 100$$

Statistical Analysis

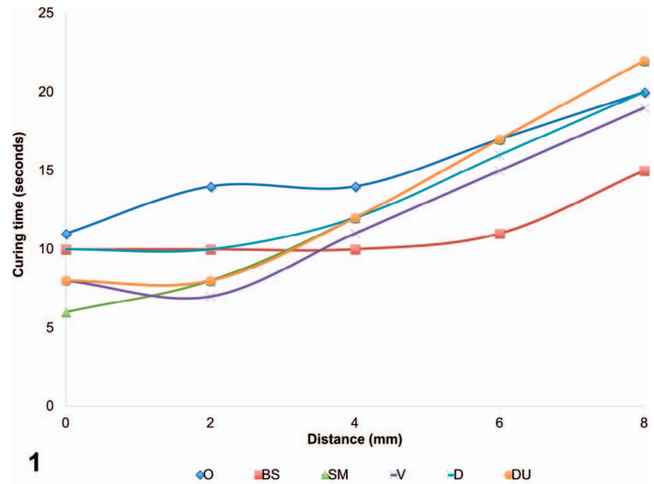
The effects of the LCUs and distance from the specimen (2 or 8 mm) on irradiance, radiant exposure, and DC were analyzed using multiple-way analysis of variance (ANOVA), with each LCU-distance combination allowed to have a different variance. Pearson correlation coefficients were calculated to evaluate the linear associations among irradiance, radiant exposure, and DC. The percentage decrease in irradiance, radiant exposure, and DC between the top and bottom surfaces for each LCU at each curing distance was calculated using a Student *t*-test. A 5% significance level was used for all tests. The normality assumptions were assessed and met for the ANOVA.

RESULTS

Irradiance and Spectral Irradiance Measurements

Figure 1 shows an inverse relationship between irradiance and curing distance in a distinct pattern for each LCU. Figure 2 displays a positive relationship between curing distance and curing time to achieve a similar radiant exposure, which was unique for each curing unit. When curing with Bluephase Style (BS), a relatively equivalent irradiance and curing time were displayed for up to 6 mm from the top sensor. On the other hand, when the distance was increased, the remaining LCUs revealed a relatively gradual increase in curing time and decrease in irradiance. Table 2 depicts that curing with Optilux 401 (O) and BS showed the least decrease in irradiance and the least increase in the required curing time between 2- and 8-mm distances to achieve the targeted radiant exposure. On the other hand, SmartLight Max (SM), Valo Cordless (V), and Demi Ultra (DU) showed the most decrease in irradiance and the most increase in the required curing time.

Figure 3 displays the spectral irradiance of the curing units combined with the spectral absorption of CQ and TPO photoinitiators at 2-mm distance. Figure 3a shows a broad spectral irradiance curve for the QTH unit that fell within the absorption ranges of CQ (peaks approximately at 470 nm) and TPO (peaks approximately at 380 nm). The multiple emission peak LED units emitted two spectral peaks, one in the blue range (420-520 nm) and one in the violet range (380-425 nm), which fell within the absorption range of CQ and TPO, respectively. Both the QTH and multiple-emission peak LED units had higher output in the CQ range than the TPO range. However, the multiple-emission peak LED units had a higher output than the QTH unit in the CQ and TPO ranges. The single-emission peak LED units had one spectral peak in the blue range that fell within the maximum absorption range of the CQ. Each LCU exhibited a unique peak wavelength and peak height. Furthermore, Figure 3b shows that the spectral irradiance dramatically



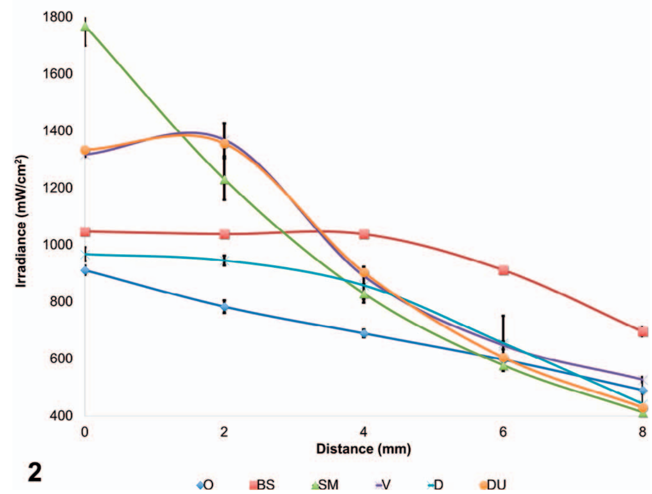


Figure 1. *Mean (SD) irradiance (mW/cm^2) measurements at multiple distances (mm) for the LCUs collected using the MARC-RC top sensor. The irradiance decreased with the increase in the distance in a pattern that was unique for each LCU.*

Figure 2. *Curing time (seconds) needed to maintain the radiant exposure (10-11 J/cm^2) at multiple curing distances (mm) for each LCU using the MARC-RC top sensor. The curing times were adjusted by maintaining the radiant exposure at 0-, 2-, 4-, 6-, and 8-mm distances based on the manufacturer's information to polymerize Tetric EvoCeram bleaching shade XL RBC. The curing times increased with the increase in the distance in a pattern that was unique for each LCU.*

decreased on the bottom surfaces of the 2-mm-thick specimens compared with the top. Also, the bottom sensor no longer effectively detected the violet curves when using the multiple-emission peak LED lights. Similar trends were observed at 8-mm distances.

Irradiance, Radiant Exposure, and DC Measurements

Figure 4 shows the comparison of irradiances received on the top and bottom surfaces among the LCUs, where significant differences were detected

Table 2: *Percentage Decrease in Irradiance and Percentage Increase in Curing Time to Maintain a 10-11 J/cm² Radiant Exposure*

LCU	Irradiance, % Decrease Between 2- and 8-mm Distances	Curing Time, % Increase Between 2- and 8-mm Distances
O	37	43
BS	33	50
SM	67	175
V	62	171
D	53	100
DU	68	175

regardless of the surface or curing distance. The irradiance was significantly higher at 2-mm than 8-mm curing distance for all LCUs, regardless of surface. Generally, the trend of significant differences in irradiance among the LCUs for the top was not the same for the bottom, regardless of the curing distance. On the top (Figure 4a), the irradiance values at 2-mm distance revealed that V was significantly higher than the remaining LCUs, with the lowest values seen when curing with O. At 8 mm, the top surface values for BS were significantly higher than the remaining units, and DEMI (D) was significantly lower. On the bottom surfaces (Figure 4b), SM and DU at 2-mm curing distance showed significantly higher irradiance, and O had the lowest values. At 8 mm, BS was significantly higher than the remaining lights, and SM and D were significantly lower. The irradiance values decreased significantly between the top and bottom surfaces irrespective of the original values received on the top.

The radiant exposure comparison among the LCUs at each distance showed values that were significantly higher on the top than the bottom, regardless of the curing distance or LCU (Table 3). The values significantly decreased between 85.6%-92.6% on the bottom regardless of the original values received on the top. On the bottom surfaces, radiant exposure was significantly lower at 2 mm than 8 mm, except when using O.

On the top surfaces, the DC value at 2-mm distance was significantly higher when using SM than when using the QTH or single-emission peak LED units (Figure 5a). Also, using the single-emission peak LED units resulted in significantly lower DC values than the remaining LCUs, except that DU did not show significant differences from BS. At the 8-mm curing distance, O and BS showed significantly higher top surface DC values than the

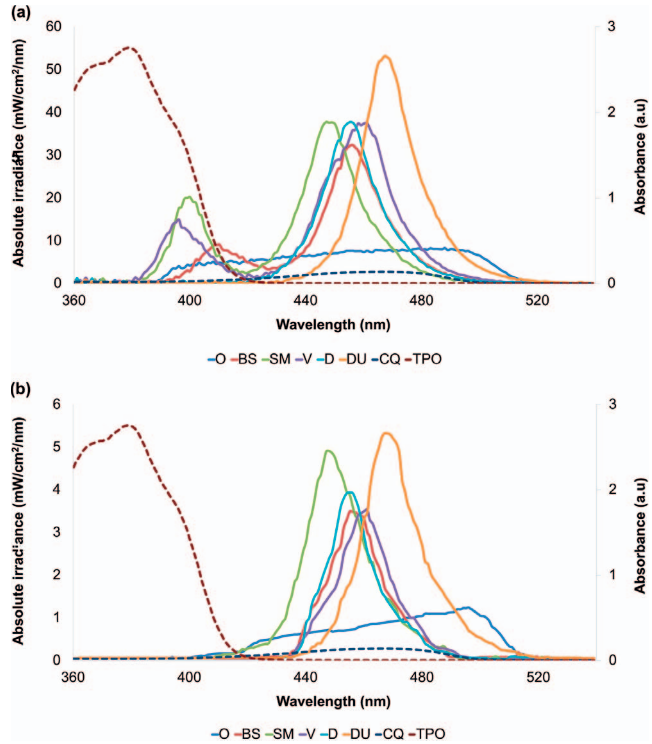


Figure 3. *Representative spectral irradiance curve of the LCUs collected using the top and bottom MARC-RC sensors combined with the measured absorbance spectrum of CQ and TPO photoinitiators at 0.005 M concentration. (a) Spectral irradiance curve at 2-mm distance from the top MARC-RC sensor, representing the irradiance received on the top surfaces. The spectral irradiance of the longer-wavelength curve encompasses the CQ photoinitiator absorption range. The shorter wavelength curve for the QTH and multiple-emission peak LED units encompasses the TPO photoinitiator absorption range. (b) Spectral irradiance curve at 2-mm distance from the top specimen surfaces passing through the 2-mm increment and detected by the bottom MARC-RC sensor, representing the irradiance received on the bottom surfaces. The spectral irradiance dramatically decreased on the bottom. The spectral irradiance of the shorter-wavelength curves was no longer detected by the bottom sensor when using the multiple-emission peak LED units.*

single-emission peak LED units. Using DU revealed significantly lower DC values than the remaining LCUs, except for D. At 2 mm, D had significantly lower bottom surface values than O, BS, and SM (Figure 5b). At 8 mm, V had significantly higher DC on the bottom than SM and D. In addition, D had significantly higher DC than SM. The DC values were significantly higher at 2-mm than 8-mm distance when using SM regardless of the surface (Figure 6).

The percentage decrease in the DC values between the top and bottom surfaces ranged from 0.2%-7.4% and was significant at 2-mm distance when using the QTH or multiple-emission peak LED lights (Figure 7). At 8 mm, O and SM showed a significant decrease in DC values from the top to the bottom surfaces.

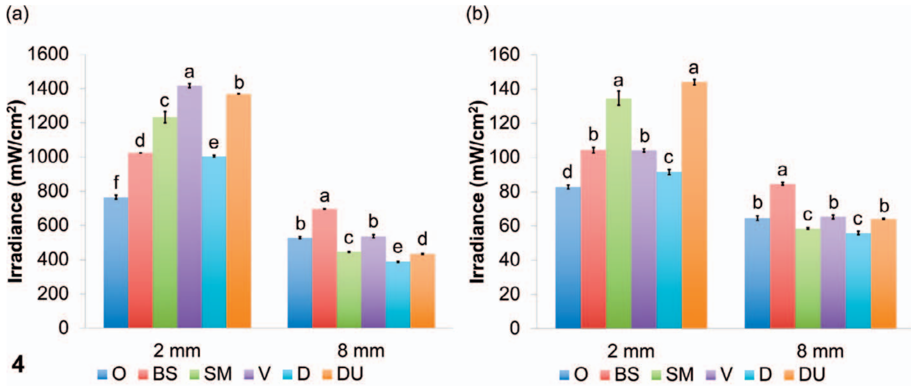


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Figure 4. *Mean (SE) irradiance (mW/cm^2) values received by the RBC specimens at 2- and 8-mm distances. (a) Mean irradiance on the top surfaces. (b) Mean irradiance on the bottom surfaces. The irradiance measurements were collected from a MARC-RC system. The top MARC-RC sensor recorded the irradiance values representing those received on the top specimen surfaces at 2- and 8-mm distances. The bottom sensor detected the irradiance values passing through the 2-mm-thick RBC increment at 2- and 8-mm distances. Letters represent significant differences among the LCUs at each distance for each surface. For each LCU, the irradiance values on the top for each LCU was significantly higher than the bottom, regardless of the distance. 4b was smoothed for clarity.*

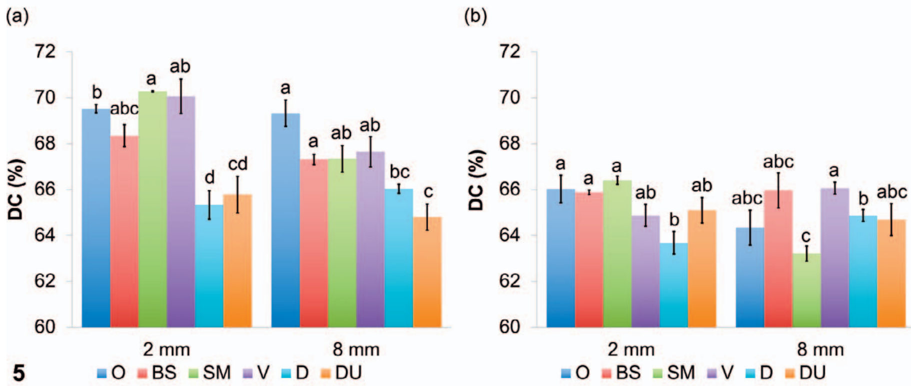

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Figure 5. *Mean (SE) DC (%) values for RBC specimens at 2- and 8-mm distances. (a) Mean DC values on the top surfaces. (b) Mean DC values on the bottom surfaces. The DC measurements were collected using micro-Raman spectroscopy. Letters represent significant differences among the LCUs at each curing distance for each surface.*

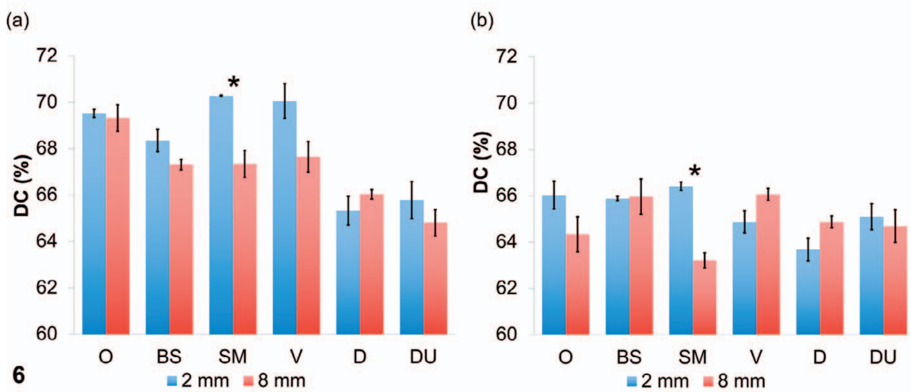

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Figure 6. *Mean (SE) DC (%) values for RBC specimens at 2- and 8-mm distances. (a) Mean DC values on the top surfaces. (b) Mean DC values on the bottom surfaces. The DC measurements were collected using micro-Raman spectroscopy. The asterisk represents significant differences between the 2- and 8-mm distance for each LCU on each surface.*

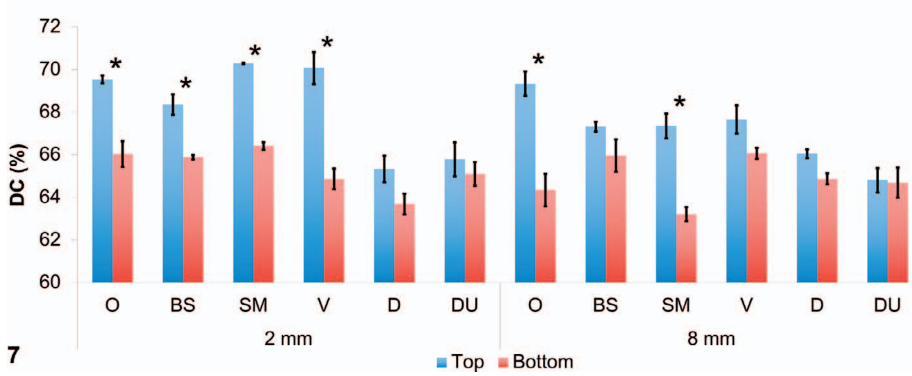

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Figure 7. *Mean (SE) DC (%) values on the top and bottom surfaces of the specimens at 2- and 8-mm distances. The asterisk represents significant differences between the top and bottom surfaces for each LCU.*

Table 3: *Mean (SE) Radiant Exposure (J/cm^2) Received on the Top and Bottom Specimen Surfaces[a]*

Distance, mm	LCU	Radiant Exposure, J/cm^2	
		Top	Bottom
2	O	10.63 (0.16)	1.15 (0.017)
	BS	10.34 (0.04)	1.05 (0.019)
	SM	9.72 (0.24)	1.07 (0.022)
	V	10.06 (0.04)	0.74 (0.007)
	D	10.26 (0.05)	0.93 (0.016)
	DU	10.54 (0.10)	1.11 (0.016)
8	O	10.08 (0.13)	1.15 (0.037)
	BS	10.29 (0.21)	1.26 (0.015)
	SM	9.89 (0.08)	1.30 (0.017)
	V	10.81 (0.19)	1.29 (0.029)
	D	10.44 (0.10)	1.51 (0.031)
	DU	9.83 (0.05)	1.43 (0.015)

[a] *The radiant exposure measurements were collected from a MARC-RC system. The top MARC-RC sensor recorded the radiant exposure values received on the top specimen surfaces at 2- and 8-mm distances. The bottom sensor detected the radiant exposure values passing through the 2-mm RBC increment at 2- and 8-mm distances. At each distance for each LCU, the radiant exposure values on the top surfaces were significantly higher than on the bottom.*

The ANOVA revealed that the interaction between the LCU and curing distance had a significant effect on the irradiance and radiant exposure received on the top and bottom surfaces and on the DC values on the bottom surfaces.

Correlation Among Irradiance, Radiant Exposure, and DC

An overall strong positive correlation between irradiance and radiant exposure was detected (0.87-1) regardless of the curing distance, with a few exceptions: on the top surfaces at 2 mm distance, a moderate positive correlation was detected (0.57) when V was used, and a negative correlation was shown (−0.73 and −1) when O and DU were used, respectively. On the top surfaces of 8-mm distance, a weak positive correlation was detected (0.14 and 0.13) when D and DU were used, respectively. A moderate correlation was found between DC and irradiance and between DC and radiant exposure regardless of distance. However, the correlations varied for each LCU, at each distance, and on each surface (data not shown).

DISCUSSION

Influence of Distance on Irradiance

The outcomes of this study showed an inverse relationship between the curing distance and irradiance, resulting in a direct relationship between curing time and distance to maintain a similar radiant exposure (Figures 1 and 2). However, the pattern was unique for each LCU. The percentage change in irradiance and curing time between 2- and 8-mm distances was the least for O and BS (Table 2). A more uniform spectral radiant power has been reported for the QTH and from the BS's updated guide tip than with the remaining LED units.[22] On the other hand, relatively similar patterns of change were seen when using SM, V, and DU, requiring the greatest percentage increase. Those three curing units had their LED chips located within the light guide head and not the body. This may suggest that irradiance values at different distances are affected by the location of the LED chips within the curing unit. The overall results agree with previous studies that reported that mean irradiance values for a given location are negatively affected by increased curing distance as emitted light diverges over a larger surface area.[3,8,28,29]

Spectral Irradiance Received on the Specimen Surfaces

The outcomes showed variations in spectral irradiance between the QTH and LED units, in addition to differences among the LED units (Figure 3). This agreed with similar studies.[1,30] Interestingly, spectral irradiance showed a large drop from the top to the bottom, and the peak heights varied for each LED unit on each surface. These differences may be attributed to the LCU type. A QTH unit has a wide spectral emission curve (390-520 nm), which includes the wavelengths needed by most photoinitiators.[4,31] However, a QTH unit may not activate TPO as effectively as CQ because it has a lower spectral irradiance in the TPO adsorption region compared with the CQ region. A multiple-emission peak LED unit emits light within narrow spectral ranges that fall within the maximum absorption range of CQ (450-470 nm) and TPO (380-420 nm).[4,31] The outcomes agree with the literature.[1,4,31] The LED units may provide equivalent polymerization in a shorter curing time because more photons are being provided in more effective absorption ranges.[4,31] This was relatively supported by our study, in which the QTH unit needed more curing time at 2- and 8-mm distances compared with the LED units.

The spectral irradiance peaks in the shorter wavelength region on the bottom surfaces were not effectively detected compared with the top, regardless of the LED unit used. These observations may be partially explained by the extent of light transmission through the specimens[23,32,33]: the shorter wavelength becomes more scattered or refracted compared with the longer wavelengths. These findings were in agreement with previous work and the results of other authors.[22,34] Also, photoinitiators, pigments, and filler particles may have hampered light transmission through the specimens by absorbing, scattering, or refracting the light at the resin-filler interface.[2,10]

Influence of Distance on Irradiance, Radiant Exposure, and DC Measurements on Specimen Surfaces

Comparisons of the mean irradiance values among the LCUs showed significant differences regardless of the distance and surface (Figure 4). It was intriguing to see that the curing unit that exhibited higher irradiance values at 2-mm distance did not necessarily provide a higher irradiance at 8-mm distance. Similarly, the unit that exhibited higher irradiance values on the top did not necessarily show higher irradiance on the bottom. Since the curing unit position was standardized, the overall observations were highly influenced by the differences in light sources.[4,31] An LCU's effectiveness depends on the radiant power and photons it emits that activate the photoinitiators within an RBC.[35] For D, the significantly lower mean irradiance values detected at 8-mm curing distance compared with the remaining curing units could be attributed to the Turbo light guide tip, which has an exit diameter smaller than the entry diameter, producing a wider light cone as the distance increases.[28] Consequently, irradiance values are negatively affected because less radiant power strikes any delineated portion of the surface with increasing distance. It is important to note that the measurements reported from the sensors do not reflect the irradiance of the entire light guide tip but only of the guide tip area that fell over the sensor. In this study, the measurements collected were from the center of each guide tip, and the DC measurements obtained from the specimens relatively coincided with the sensor dimensions. Thereby, the irradiance and radiant exposure values recorded reflected the irradiance and radiant exposure received on the top and bottom specimen surfaces.

Comparisons of the irradiance and radiant exposure between the top and bottom surfaces showed that the irradiance transmitted through the specimen and radiant exposure detected on the bottom significantly decreased compared with the top (Figure 4; Table 3). Interestingly, the irradiance and radiant exposure decreased between 85.2%-92.6% from the top to the bottom. This suggests that the light from the LCUs may have transmitted through the specimens in a similar manner, regardless of the distance or irradiance values on the top. The nonsignificant difference in the mean radiant exposure values on the bottom was consistent with similar radiant exposure provided on the top. The results support previous work.[22]

Sufficient conversion of monomer into polymer during RBC polymerization is essential to produce an RBC with satisfactory properties.[2,36] The DC measurement may estimate the properties of the final restoration because a correlation was suggested between DC and microhardness, elastic modulus, glass transition temperature, wear, marginal breakdown, elutable substances from the composite, and volumetric shrinkage.[13,36-43] The clinical performance of an RBC may be predicted based on the DC values, in which higher DC values may predict higher mechanical and physical properties. Assessment of the bottom/top hardness ratio is used as an indicator of the curing effectiveness of the RBC. A bottom/top hardness ratio of 80% is commonly used as the minimally acceptable ratio for RBCs.[23,44]

The DC results showed several interesting findings. First, similar DC values were achieved with similar radiant exposure, although some variation in DC values occurred regardless of the LCU, distance, and surface (Figure 5). This was true even with significant irradiance reduction on the bottom surface and with increased distance (Figure 4).

Second, at each distance, significant differences in DC values were observed among the LCUs. It was intriguing that the unit that showed a higher irradiance value did not necessarily display higher DC values and vice versa, regardless of the surface or curing distance (Figures 4 and 5). DC values of 50%-75% are typically achieved when using a conventional RBC.[45] In our study, all LCUs resulted in DC values greater than 63%, regardless of the surface or curing distance. Therefore, our results indicated that sufficient polymerization may be achieved when radiant exposure values between 0.7-1.5 J/cm^2 and irradiance values between 55.9-84.6 mW/cm^2 are received on the bottom. These findings were in agreement with those of another study.[19,22]

Interestingly, although using the single-emission peak LED units exhibited the lowest DC values on the top among the LCUs, the same was not true on the bottom. This suggests that light was not attenuated to a degree that compromised polymerization on the bottom. Our results agreed with those of another study that explored various LCUs[46] and agreed with a study that evaluated bulk-filled RBCs and concluded that light transmission did not alter polymerization kinetics and that DC cannot be related to light transmittance.[47] Another possible explanation for the higher DC values on the bottom is the reflection of the light off the radiopaque bottom sensor. The findings agreed with other studies, which suggested that a similar degree of polymerization could be achieved when using a QTH or single- or multiple-emission peak LED units.[48,49]

Third, when comparing the 2- and 8-mm distances for each LCU, it was revealed that distance did not have a significant influence on DC values, except for SM (Figure 6). The significant differences among the LCUs at each distance may also be explained by the differences in the units and the amount of photons received by the specimens. The nonsignificant differences between the 2- and 8-mm distances for each LCU may be attributable to the similar radiant exposure values received by the specimens allowing for sufficient generation of free radical growth centers and satisfactory polymerization.[1,25] In addition, the prolonged curing time at the 8-mm distance may have increased heat generation favoring polymerization.[2,50] The significantly higher mean DC values for SM at 2-mm than 8-mm distance regardless of the surface may be due to the angled position of the blue and violet LED chips within the unit head. This may have allowed the emitted light to be more focused at 2 mm than 8 mm. The number of photons hitting the specimens may have impacting the amount of photoinitiators activated and the rate of polymerization.

Finally, the percentage decrease in DC values from the top to bottom was significantly higher with the QTH and multiple-emission peak LED units at 2-mm distance and with O and SM at 8-mm distance (Figure 7). At 2-mm distance, the significantly higher DC values on the top when using the QTH and multiple-emission peak LED units may be because TPO was effectively activated on the top but not at the deeper parts of the specimen compared with CQ.[20] In addition, this suggests that TPO was not effectively activated when using the single-emission peak LED units due to the absence of the violet LED chip. Nevertheless, polymerization was not compromised when using the single-emission peak LED units, which may indicate sufficient free radicals were generated, allowing satisfactory polymerization activation. However, at 8-mm distance, the significant differences in DC percentage decrease when using O and SM may also be partially explained by the amount of photoinitiator activation and complexity of polymerization kinetics.

The ANOVA outcomes showed that interaction between the LCU and distance had a significant effect on irradiance and radiant exposure received on the top and bottom surfaces and on the DC values on the bottom. This may be explained by the differences among the LCUs, light transmission through the specimens, and complexity of polymerization kinetics, as mentioned. Nevertheless, it is important to note that the observations in this study may translate to RBCs with similar composition, shade, and translucency, but the findings may differ to some extent when using different RBCs.

Correlation Among Irradiance, Radiant Exposure, and DC

The correlation outcomes demonstrated that the strength of the correlation among the average irradiance, radiant exposure, and DC values on the top and bottom surfaces was dependent on LCU and curing distance. Although a generally positive, strong correlation between the average irradiance and radiant exposure values existed, this did not necessarily result in a strong correlation between the average irradiance and DC values nor between radiant exposure and DC, regardless of the LCU used, curing distance, or specimen surface.

Clinical Impact

The findings are of clinical value because they show the relationship between distance and curing time. Using the multiple-emission peak curing unit, BS can be convenient for clinicians because the manufacturer's recommended curing time may be used up to a 6-mm distance from the restoration. When increasing to an 8-mm distance between the guide tip and cavity floor, it was necessary to almost double the curing times when using a QTH or a single-emission peak curing unit that had the LED chip in the body of the unit. The curing time was tripled when using the curing unit that had the LED chips within the unit's head.

For all units, obtaining similar radiant exposure resulted in satisfactory polymerization. Although not an exact predictor, radiant exposure received by the restoration was an effective guide for polymerization. This may be a helpful guide for clinicians when specific curing instructions are not provided for clinically relevant distances.

There is potential benefit for manufacturers to provide curing protocol guides for a given RBC using different LCUs at multiple distances. Further investigation is needed to explore the influence of these distances on RBC mechanical properties.

CONCLUSIONS

1. Achieving similar radiant exposure with increased curing distance using the LCUs investigated resulted in satisfactory polymerization on the top and bottom surfaces of the RBC explored with respect to DC, although the same DC values were not reached.
2. Sufficient polymerization was achieved when the bottom RBC surfaces received radiant exposure values between 0.7-1.5 J/cm^2 and irradiance values between 56-85 mW/cm^2.
3. A moderate correlation existed among irradiance, radiant exposure, and DC.

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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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Full-mouth Rehabilitation of Hypocalcified-type Amelogenesis Imperfecta With Chairside Computer-aided Design and Computer-aided Manufacturing: A Case Report

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Clinical Relevance

This case report describes the use of a few sessions of chairside computer-aided design and computer-aided manufacturing for esthetic restoration of dentition severely affected by amelogenesis imperfecta. We describe the successive treatment steps to help practitioners treat similar disorders.

SUMMARY

Background: This case report describes the complete full-mouth treatment of hypocalcified amelogenesis imperfecta (AI) by chairside computer-aided design and computer-aided manufacturing (CAD/CAM).

Case summary: After several years of interrupted dental care, a 17-year-old female patient presented with pain and also esthetic and functional discomfort. With loss of enamel and dyschromia affecting all teeth, the diagnosis was hypocalcified AI. Affected tissues were eliminated, gingivectomy with laser was performed, an indented jig was used to record the centric relationship during optical impres-

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sions, and 28 full ceramic crowns were created by chairside CAD/CAM in four sessions. The patient reported rapid pain relief and an overall improvement of well-being.

Conclusion: AI sequelae can be treated promptly and conservatively with chairside CAD/CAM, obtaining esthetic and functional results.

INTRODUCTION

Amelogenesis imperfecta (AI) is a rare inherited disease.[1] It may assume different phenotypic forms related to anomalies in the structure and appearance of the enamel and affect all or almost all of the teeth in both the primary and permanent dentition.[2] Regardless of the AI type, the follow-up of young patients is difficult, first because of the evolution of the dentition, then because of the extent of tooth destruction or dyschromia, and finally because of the psychological and often financial difficulties associated with treatment. Until the young permanent dentition has been established, conservative temporary restorations are needed to preserve dental tissues and provide acceptable esthetics. In the early permanent dentition, permanent restorations are required. To improve the quality of life and limit the psychological impact of AI, the practitioner must restore function but also esthetics.[3-5] Because of the diversity of AI phenotypes, no clinical trial has been performed to help choose the best treatment option; hence, the amount of tooth destruction and dyschromia guide this choice.[6] Treatment planning and implementation are often long and tedious with conventional prosthetics.

The use of chairside (ie, made in a dental office) computer-aided design and computer-aided manufacturing (CAD/CAM) may be advantageous for these full-mouth rehabilitations: with computer-aided planning, digital wax-ups can be obtained almost immediately and then transferred to the mouth by machining mock-ups; tooth preparation, fabrication of restorations, and bonding can be performed in the same session, avoiding provisional restorations and limiting the number of treatment sessions; finally, the patient can be a participant in the treatment, especially in the planning and design of future restorations, which enhances adherence to treatment. In fact, AI-affected patients receive numerous care sessions at a specialist beginning in childhood, often during school hours and not necessarily near their home, which often leads to demotivation and missing appointments. A limited number of care sessions and the patient's involvement in treatment may enhance patient observance.

AI-affected patients have been previously treated partially with chairside CAD/CAM or completely with indirect CAD/CAM (made in a dental laboratory),[7-9] but, to our knowledge, not completely with chairside CAD/CAM.

This case report presents, in a step-by-step manner, the full-mouth and entirely digital CAD/CAM chairside rehabilitation of a patient with hypocalcified AI in the early permanent dentition.

METHODS AND MATERIALS

Patient Information

A 17-year-old girl in good general health presented at the clinic with pain when eating or drinking something cold, as well as masticatory difficulties. She also complained of her unsightly teeth and being mocked by others. In her younger years, she had received treatment for her primary and then permanent teeth in the pediatric dentistry department of Charles Foix Hospital, Ivry-sur-Seine, France, but the follow-up had been interrupted for various reasons, particularly financial. The patient was an only child. Her father had AI, as did several individuals in the maternal line.

Clinical Examination, Complementary Examinations, Diagnostic Assessment, and Therapeutic Proposal

Extraoral examination revealed three balanced facial thirds (Figure 1a). The profile was hyperdivergent, and the patient presented a retrusive chin associated with slightly lower retrusive lip (Figure 1b). The patient was in early permanent dentition.

Intraoral examination revealed generalized loss of the tooth structure and a yellowish-brown enamel with a relatively crumbly texture, which rapidly wore off, characterizing hypocalcified AI (type III). Because the maternal and paternal lines were affected, the dominant (type IIIa) or recessive (type IIIb) character of this type III AI was difficult to determine. In addition, there were inadequate old restorations: provisional restorations on teeth 5 to 12; composite restorations on 3, 14, 19, 23, 26, and 30; and provisional crowns on 4 and 13, which were lost (Figures 1c-g). The patient had a thick periodontium, moderate to severe gingivitis (especially in the mandibular anterior area), and periodontal recession (in the mandibular incisor area). Oral hygiene was imperfect, with plaque and tartar, because of the pain caused by brushing. She had a

Figure 1. *(a,b): Extraoral and (c,g): intraoral views of the initial situation showing generalized loss of the tooth structure and inadequate old restorations.*

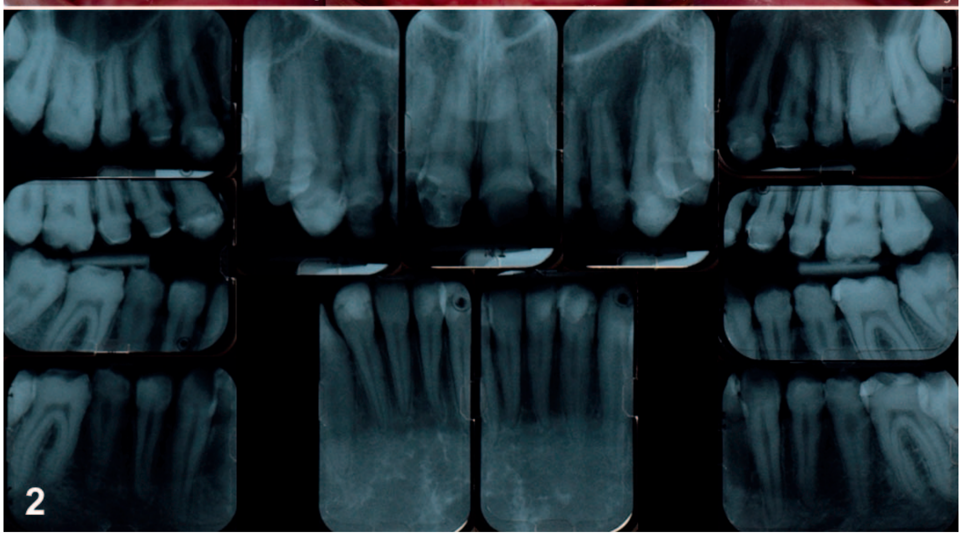

Figure 2. *Radiographic images: bitewings and periapical X-rays.*

class II malocclusion, an increased overjet (common with AI[10]), a right posterior crossbite, a slight midline deviation, a slight loss of the posterior vertical dimension, and a major open bite (from 4 to 13).

Complementary examinations (sensitivity and percussion tests, X-rays) confirmed the presence of primary caries (almost always associated with AI[10]) and secondary caries under provisional crowns, without an underlying pulpal pathology; the pulp chambers appeared retracted (Figure 2).

The patient had a high caries risk (presence of active lesions, enamel defects, defective restorations, and low socioeconomic status[11]), and all teeth needed to be restored. Because of the crumbly texture of the enamel over the whole tooth surface, full-coverage restorations were required. To combine strength and esthetics, the posterior teeth were restored with lithium-disilicate reinforced glass ceramic (e.max CAD, Ivoclar Vivadent, Liechtenstein) and the anterior teeth with leucite-reinforced glass ceramic (Empress CAD, Ivoclar Vivadent). In addition, for access to the entire affected tissue and to slightly increase the height of the clinical crowns, gingivectomies were also necessary.

Interventions

The interventions involved laser periodontal treatment and prosthetic restorations of all teeth. The treatment consisted of a preliminary session to study and plan the sessions, followed by four care sessions. The chronology of the treatment is described in Figure 3.

Preliminary Session: Optical Impressions for Digital Study Models—The first session consisted of taking optical impressions (CEREC Omnicam, Dentsply Sirona, York, PA, USA) to obtain digital study models (Figure 4), evaluate the clinical situation, and plan the treatment using CEREC v4.4 software (Dentsply Sirona) with a multidisciplinary approach: two general practitioners and a

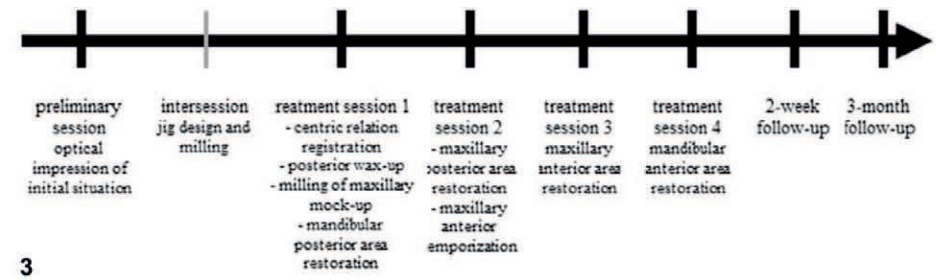

Figure 3. *Treatment planning and treatment timeline.*

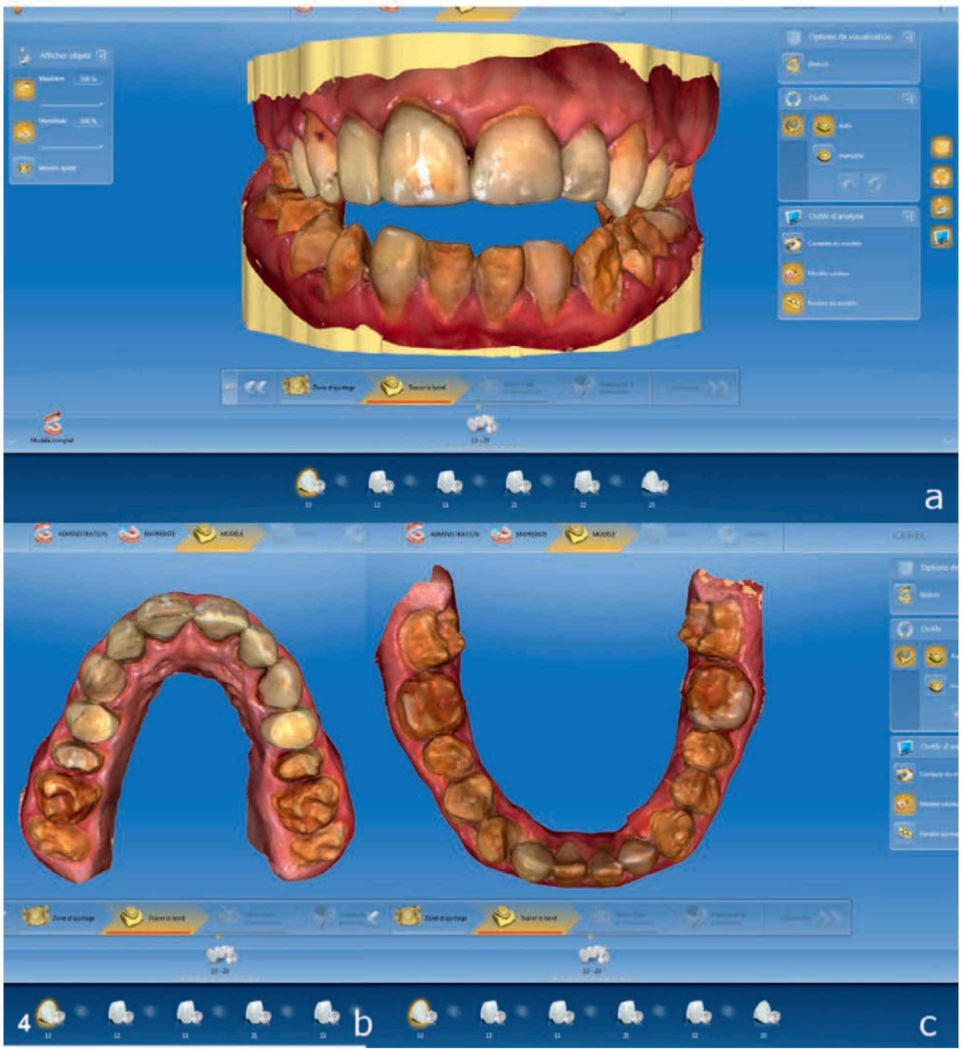

Figure 4. *Digital study models after optical impressions.*

pediatric dentist were involved in the treatment planning, and an orthodontist was asked for advice. One of the general practitioners (CM) performed all steps. Two dental students were also present during the care sessions to help the practitioners.

Intersession: Jig Fabrication—For restorations in centric relation occlusion, the digital models were used to model a jig (Figure 5a), which was machined (MC XL, Sirona, Bensheim, Germany) in a block of polymethyl methacrylate (PMMA; Telio CAD, Ivoclar Vivadent; Figure 5b,c). The jig (assigned as "bridge" in the CEREC software) consisted of crowns connected via a lingual extension. It was modeled in the static position (but was then adjusted in the mouth). This jig also helped to maintain the existing vertical dimension. Indeed, as the three facial thirds were initially balanced, we needed to avoid exacerbating the anterior overjet and open bite.

First Session (January 7, 2017)—The first session consisted of bite registration, gingivectomy, tooth

Figure 5. *(a): Modeling of a jig. (b,c): Fabrication of the jig machined in a block of polymethyl methacrylate. (d): Sandblasting of the jig on the surface of contact with the mandibular incisors. (e): Light curing after application of a fluid methyl methacrylate resin.*

preparation, and crown placement in the mandibular posterior quadrants (right and left).

The jig was sandblasted on the surface of contact with the mandibular incisors (Figure 5d), and then a fluid methyl methacrylate resin (SR Connect, Ivoclar Vivadent) was applied and light cured (Figure 5e) to allow bonding between the PMMA and composite. The jig was placed on the maxillary anterior teeth (Figure 6a), and a microhybrid composite layer (Gaenial, GC, Japan) was applied with a spatula (Optrasculpt, Ivoclar Vivadent) on the sandblasted and primed area (Figure 6b). The mandible was guided and positioned in a centric relationship with the jig through the uncured composite (Figure 6c). When the centric relationship was reached, the composite was light cured in the mouth to fix the new bite (Figure 6d). The anterior mandibular teeth thus indented the jig, transforming it into a wedge. The jig was then removed, and light curing was completed outside the mouth (Figure 6e).

A buccal optical impression of the bite was taken with the jig in the mouth. The initial study models were then mounted in a centric relationship. Numerical wax-ups were created (Figure 7) to restore an optimal curve of Spee and obtain mock-ups to guide the preparations and gingivectomy. The posterior mock-ups (Figure 8a) corresponding to these wax-ups were simultaneously machined in

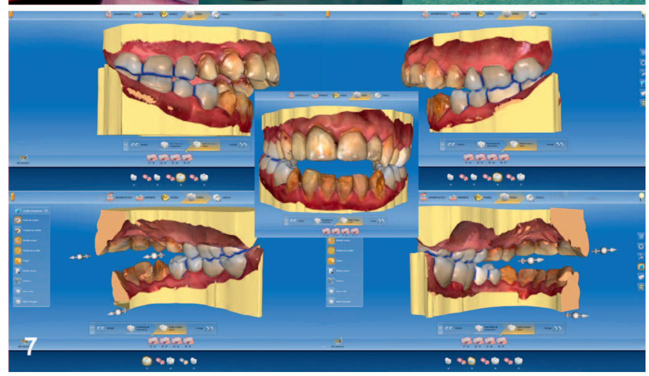

Figure 6. *(a): Fitting of the jig. (b): Application of a microhybrid composite layer on the sandblasted and primed zone. (c): Mandible positioning in a centric relationship with the jig through the uncured composite. (d): Light curing in the mouth in a centric relationship. (e): Extraoral light curing. (f): Final appearance of jig.*

Figure 7. *Models in a centric relationship after buccal optical impression of the occlusion with the jig.*

blocks of PMMA. In fact, we were equipped with three milling units.

The maxillary mock-ups were positioned in the mouth (Figures 8b,c), and the treatment was initiated in the right mandibular quadrant. Laser gingivectomy (Sirolaser blue, Dentsply Sirona) provided access to the entire loss of tooth structure and slightly increased the clinical crown height. Preparations involved the use of diamond burs and sonic inserts (Sonic flex, KaVo Kerr, Washington, DC, USA). Optical impressions of the right mandibular quadrant (Figure 9a) and of its antagonist with the mock-up were obtained (Figure 9b). The jig was placed, and a buccal optical impression of the bite (Figures 9c,d) was obtained. The crowns were designed using CEREC v4.4 software (Figure 10) and then machined in blocks of lithium-disilicate–reinforced glass ceramic (e.max CAD, Ivoclar Vivadent) of the A1-MT shade (Figure 11a,b). Three crowns were machined simultaneously via three milling units, and the fourth was machined immediately afterward. During the milling process, in the same way, the left mandibular teeth were prepared, optical impressions were obtained, and crowns were then designed and machined.

During the milling of the left mandibular crowns, the right milled crowns were evaluated in the mouth (Figure 11c), stained and glazed (IPS e.max CAD Crystall Shades/Stains/Glaze, Ivoclar Vivadent; Figure 11d), and crystallized in the furnace. During crystallization, the left mandibular milled crowns were evaluated in the mouth, stained and glazed, and then crystallized in the furnace.

During crystallization of the left mandibular crowns, each right mandibular crown was individually bonded using a rubber dam. The tooth surface was treated as follows: air abrasion with alumina (27 μm), enamel etching with orthophosphoric acid (Figure 12a), thorough rinsing, application on the enamel of 5% sodium hypochlorite for one minute (Figure 12b), thorough rinsing, and finally application of a one-step self-etch adhesive (Multilink Primer A+B, Ivoclar Vivadent) on the entire prepared tooth surface (Figure 12c).

In addition, another practitioner treated the inner surface of the crown as follows: application of 5% hydrofluoric acid for 20 seconds, rinsing with water in an ultrasonic tank for three minutes, and application of silane (Monobond Plus, Ivoclar Vivadent).

The crown was then bonded with a dual-cure resin composite cement (Multilink Automix, Ivoclar Vivadent; Figure 12d). The excess was removed with a disposable brush while maintaining the crown under pressure (Figure 12e). The excess residual cement was removed with a mini CK 6 scaler and dental floss. Final light curing was performed under glycerin (Figure 12f,g) for 20 seconds per surface. After rubber dam removal, the occlusion was checked with respect to the maxillary mock-up. In the same way, the left mandibular crowns were successively bonded.

Second Session (January 14, 2017)—The second session consisted of gingivectomy, tooth preparation, and crown placement in the maxillary posterior

Figure 8. *(a): Posterior mock-ups corresponding to wax-ups. (b,c): Positioning of the maxillary mock-ups in the mouth.*

Figure 9. *(a): Optical impressions of the prepared quadrant. (b): Optical impressions of its antagonist with the mock-up. (c,d): Bite registration with the jig by buccal optical impression of the posterior teeth.*

Figure 10. *(a,b,c,d): Virtual design of the mandibular posterior crowns.*

Figure 11. *(a,b): Fabrication of the crowns from blocks of lithium-disilicate–reinforced glass ceramic. (c): Fitting of the milled crowns. (d): Staining and glazing before crystallization in the furnace.*

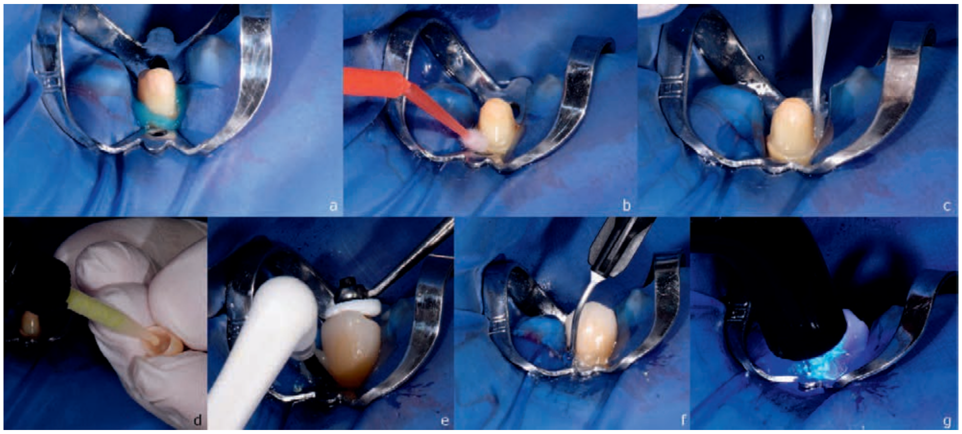

Figure 12. *(a): Enamel etching with orthophosphoric acid. (b): Application of 5% sodium hypochlorite for one minute on the enamel strip. (c): Application of a one-step self-etch adhesive on the entire prepared tooth surface. (d): Introduction of a dual-cure resin composite cement in the crown. (e): Removal of excess adhesive cement. (f): Application of glycerin. (g): Final light curing.*

quadrants (right and left) as well as preparation of the maxillary anterior teeth.

The following week, the session consisted of treating the right and left maxillary posterior teeth. The workflow was exactly the same as the first session. The mock-ups guided the gingivectomy (Figure 13a) as well as the depth of the preparation (Figure 13c). Then, right and left maxillary posterior teeth were prepared and restored.

Subsequently, a silicone key of the maxillary incisors and canines was made. The former anterior restorations were used as a reduction guide for the preparation: depth markers were generated (Figure 13b). The old restorations were removed or drilled, and then the preparations were finalized after caries excavation. A composite acrylic resin (Protemp4, 3M, St Paul, MN, USA) was poured into the silicone key, which was then applied onto the prepared incisors and canines to create a provisional bridge. After adjustment and polishing, the bridge was cemented with temporary cement without eugenol (Tempbond NE, KaVo Kerr, Washington, DC, USA; Figure 13d). Preparation of the anterior maxillary teeth at this step allowed more time for the following session, requiring considerable time for tooth characterization.

Figure 13. *(a): Gingivectomy guided by the mock-up. (b): Depth marking. (c): Depth of the preparation guided by the mock-up. (d): Cementation of the provisional bridge.*

Third Session (January 21, 2017)—The third session consisted of crown characterization and placement for the maxillary anterior teeth.

The following week, the marginal periodontium was sufficiently healthy for creating the maxillary anterior crowns. The gingival margin was corrected using a laser. The gingival retraction cord was placed, and the optical impression was obtained. Because of the open bite, optical impressions of the antagonist and bite registration were not necessary. The crown design was conducted using the "biogeneric" mode. The preparation margins and insertion axis were defined for the six anterior teeth, and then the crown volume was proposed by the software. The virtual model (Figure 14a) was incorporated into the patient's image using the "Smile Design" software (Figure 14b,c). Harmony of the teeth in the face could thus be confirmed. Position or volume changes were possible if necessary. Then, the proximal contact strength of each crown as well as the thickness of adjacent crowns could be checked (Figure 14d). Crowns were characterized with perikymata and vertical fissures (Figure 14e). The crowns were then machined three by three in leucite-reinforced glass-ceramic ceramic blocks with a shade and translucency gradient (EMPRESS CAD, multi A1, Ivoclar Vivadent). The block size was determined according to the tooth volume and its orientation. An oblique orientation in the block allowed full benefit for the shade gradient (Figure 14f). The transition lines and other characterizations of the buccal surfaces were finished with diamond

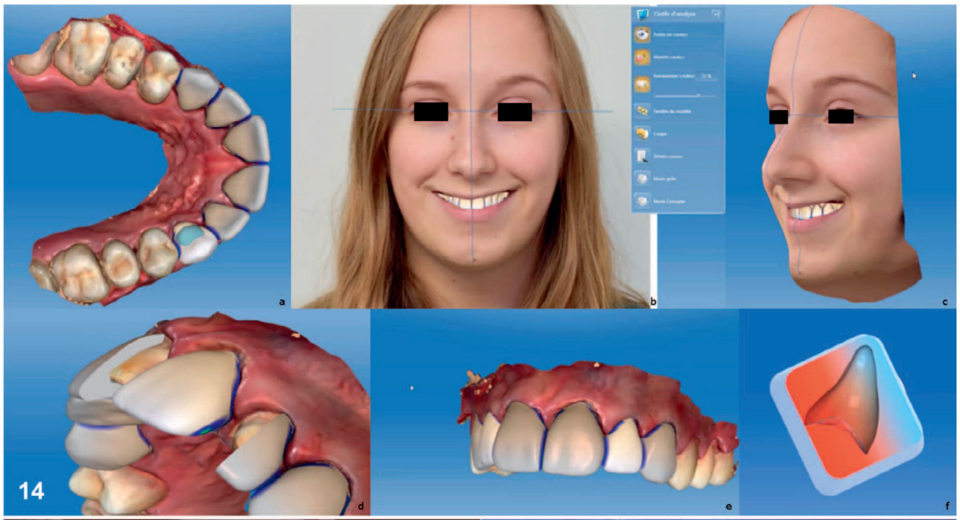

Figure 14. *(a): Crown design using the biogeneric mode. (b): Incorporation of the virtual model in the patient picture by Smile Design. (c): Profile picture obtained with Smile Design. (d): View of the proximal contact strength and thickness of adjacent crowns. (e): Crown characterization. (f): Oblique orientation of the crown in the block.*

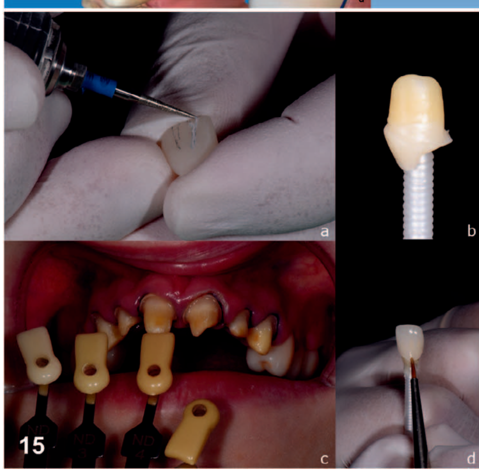

Figure 15. *(a): Design of the transition lines and other characterizations of the buccal surfaces. (b): Determination of the two shades with a dedicated shade guide. (c): Fabrication of bicolor dyes using a specific composite. (d): Staining and glazing of the crowns positioned on the dyes.*

Figure 16. *Bonding of the two central incisors simultaneously.*

burs for the handpiece (Figure 15a; H&D Crescenzo kit, ref TD2818, Komet, Rock Hill, SC, USA). Because the prepared teeth were bicolor, we chose two shades with a dedicated shade guide (Figure 15c) and then fabricated two-color dyes with a specific composite (Natural Die Material, Ivoclar Vivadent; Figure 15b). The crowns were positioned on these dyes for staining and glazing to simulate the final esthetic appearance (Figure 15d). The glaze and stains were fired in a furnace.

The crowns were then evaluated and bonded under a rubber dam using the same protocol applied for the posterior crowns. First, the central incisors were simultaneously bonded to avoid positioning error of the interincisal line (Figure 16), and then the canines and finally the lateral incisors were bonded. This chronology also aided in perfectly adjusting the proximal contact points.

Fourth Session (January 28, 2017)—The fourth session involved preparation and crown placement for the mandibular anterior teeth.

The following week, the final treatment session consisted of producing crowns for the mandibular incisors and canines. The teeth were prepared by simple removal of the affected enamel (Figure 17). Optical impressions were obtained, and then the crowns were designed. The height of the crowns was

Figure 17. *Preparation of the mandibular incisors and canines by simply removing the affected enamel.*

deliberately increased to reduce the open bite. The anteroposterior position was slightly modified by the labioversion of the crowns to improve support of the lower lip. The crowns were also machined three by three in leucite-reinforced glass-ceramic blocks with a shade and translucency gradient (EMPRESS CAD, multi A1, Ivoclar Vivadent). They were stained, glazed, crystallized, and bonded under a rubber dam using the same chronology as described for the maxillary anterior crowns (Figure 18b).

RESULTS

Follow-up and Outcomes After Two Weeks and Three Months

The gingiva showed good healing (Figure 18c-g), and the patient was satisfied with the esthetic integration of the restorations (Figure 18a). She reported a real improvement in well-being, with a noticeable decrease in sensitivity, a marked improvement in chewing, and greater self-confidence. At three months (Figure 19), no adverse events had occurred: no sensitivity, no loss of restoration, no marginal discoloration or staining of the material, no chipping, no excessive wear, and no periodontal damage. Even though the World Dental Federation has recommended an annual assessment for indirect restorations,[12] a biannual follow-up was agreed upon.

Follow-up and Outcomes After 1.5 Years

The gingival status seemed to be stable (Figure 20a-c). There were still no adverse events: no sensitivity, no loss of restoration, no marginal discoloration or staining of the material, no chipping, no excessive wear, no periodontal damage, and no secondary caries (Figures 20 and 21).

DISCUSSION

This case report describes four sessions of chairside CAD/CAM used to restore hypocalcified AI-affected teeth—loss of enamel and dyschromia reaching all the teeth—in a 17-year-old girl. The patient reported rapid pain relief and overall improvement in well-being after the treatment.

Chairside CAD/CAM Interest

The main feature of this case is that it was performed in full by chairside CAD/CAM. For this patient, who was tired of repeated dental treatment since childhood, we could obtain a rapid and effective final result in four long sessions.[13] In addition, the planning stages and design of the restorations were performed in partnership with the patient, which is difficult to do when the work is delegated to a dental technician. The involvement of the patient was of great importance in integrating the new restorations and for psychological success of the treatment. Of course, the sessions were long (approximately eight hours), but their painfulness seemed to be offset by the immediate effect on function and esthetics.

Gingival Management

The diode laser used for gingivectomy (wavelength 445 nm, optical fiber diameter 320 μm) allowed for precise gingival excision. Gingivectomy could be performed because of the sufficient height of the attached gingiva. The biological space was probably not respected everywhere, but a good adhesive interface and timely restoration seemed to allow for good periodontal healing.[14] The young age of the patient favored gingival maturation around the restorations.

Material Selection

In terms of material selection for the crowns, we hesitated to use composite or polymer-infiltrated ceramic network (PICN) material (Enamic, Vita, Bad Säckingen, Germany). Indeed, the periodontium is considered mature at approximately 20 years of age, and reintervention is easier with composite than with ceramic material. Our patient was 17 years old, and the periodontium was probably almost mature. It also seemed preferable to use homogeneous materials in the anterior and posterior teeth for homogenous wear and biomechanical deformation. We opted to use ceramic for the following reasons.

In terms of optical properties, glass ceramics were the most interesting materials. Moreover, surface staining and glazing of composites and PICNs is less durable. Hence, improved esthetics of ceramic crowns were found in a clinical trial.[15] In the anterior area, leucite-reinforced glass ceramic (Empress CAD Multi) was the best option because it is the most translucent CAD/CAM ceramic[16] and contains blocks with an optical gradient. Empress CAD Multi is not a very resistant material, but the anterior teeth are subjected to lower mechanical stress than the posterior teeth, in particular in this patient with an open bite. In terms of mechanical resistance and fracture risk, lithium-disilicate–reinforced glass ceramic (e.max) and zirconia (full or covered with e.max through the CAD-on system) were the two best options in the posterior area.[17,18] We could not sinter zirconia, so we opted for e.max. In terms of biocompatibility, ceramics are favorable

Figure 18. *(a): Photograph of the smile at the two-week follow-up. (b): Slight modification of anteroposterior position by labioversion of the crowns to improve support of the lower lip. (c-g): Final intraoral view at the two-week follow-up.*

Figure 19. *Final intraoral views at the three-month follow-up.*

Figure 20. *Final intraoral views at the 1.5-year follow-up.*

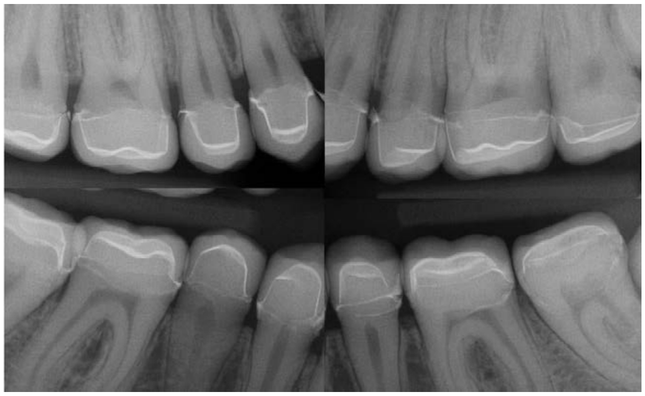

Figure 21. *X-rays at the 1.5-year follow-up.*

for periodontal health[19] and in general.[20] Finally, in terms of adhesion, CAD/CAM glass ceramics provided higher bond strength values than composites/hybrids.[21]

Bonding to AI-Affected Teeth

It seemed preferable to bond the crowns rather than cement them, not only because the preparations were sometimes not very retentive but also because of biomechanical reasons, to reinforce the ceramic and the tooth,[22,23] which were already weakened by the structural defects.

Furthermore, the absence of temporization allowed the achievement of the same objectives as with immediate dentin sealing. With chairside CAD/CAM, the adhesive system does not need to be light cured under glycerin, in contrast to immediate dentin sealing, allowing for an improved copolymerization between the adhesive system and the resin composite cement.

Bonding involved the use of a dual-cure resin composite cement (Multilink Automix) together with its bonding agent (Multilink primer), which is a one-step self-etch adhesive system. Multilink Automix was recently compared with Rely X Ultimate + Scotchbond Universal and NX3 Nexus + Optibond XTR for the retention of lithium-disilicate crowns; Multilink Automix and RelyX Ultimate yielded the best retention, and clinical experience with Multilink Automix has been much more frequently documented.[24] Moreover, Multilink Automix is a copper-containing cement, which was recently shown to reduce biofilm formation at the margins of restorations.[25]

A one-step self-etch adhesive system (Multilink primer) was chosen to achieve adhesion to the enamel and dentin. Indeed, etch-and-rinse systems did not seem to be more reliable than self-etch systems in the context of AI.[26] In addition, a self-etch system seemed particularly indicated because of the patient's sensitivities.[27,28] Selective enamel etching was performed in accordance with current recommendations.[29-31] A two-step self-etch adhesive could have been preferred to optimize the adhesion durability,[32,33] but it is better to use a cement with its corresponding bonding agent.

A reliable and long-lasting adhesion is difficult to obtain for AI-affected tissues. Superficial enamel and crumbly tissue were removed during the tooth preparation. Thus, except on the margins, bonding was carried out on sound dentin. Regarding the enamel, it seemed beneficial to treat it with 5% sodium hypochlorite after etching and before adhesive application[34-36] to reduce the excess of proteins of AI-affected enamel and thus improve the bond strength. Regarding the dentin, a conventional adhesion protocol was performed because hypochlorite does not significantly increase the bond strength.[37] Crowns were individually (or by two for central incisors) bonded with a rubber dam for moisture control when applying the adhesive system and the resin composite cement and to prevent contamination of the margins.

Centric Relationship and Jig

The proposed PMMA jig is an adaptation of Lucia's jig[38-40] used to guide the mandible in a centric relationship and as a wedge for optical impressions of the posterior quadrants. A methyl methacrylate resin was applied onto the PMMA jig (Figure 5e) to increase the bond of the resin composite before bite registration. In fact, the sole application of PMMA is not very efficacious, particularly because of the evaporation of the monomer. Although it seems desirable for better penetration to leave the primer or the composite on the PMMA surface for a long time, we followed the protocol recommended by the manufacturer (waiting 30 seconds before light curing).[41] Indeed, the jig was to be used in the mouth only temporarily, and maximum bond strength was not necessary.

Caries Risk Management and Treatment Prognosis

Longevity will depend on regular follow-up and maintenance by the patient. Because the protocols were rigorously followed, the prognosis seemed favorable; the weakest link in this treatment probably resides in the adhesion to hard tissues, which may be affected in part by the AI. Therefore, the risk of recurrent caries or pulpal involvement must be rigorously monitored. Use of ceramics prevents the adherence of plaque and thus also contributes to reducing the initial caries risk.

After the treatment, tooth sensitivity was resolved and mastication improved, which allowed the patient to achieve better oral hygiene and to reduce consumption of soft and sticky food. In fact, the patient was carefully advised about oral hygiene and diet. She was educated regarding optimal oral hygiene practices, including brushing with fluoride toothpaste twice a day and flossing daily. She was instructed to consume a healthy diet, limiting the amount and frequency of sugar intake and high-acid foods and drinks, especially between meals. She was also motivated to chew sugar-free gum with xylitol to promote salivary flow and to stop carbohydrate metabolism by cariogenic bacteria.

The wisdom teeth were impacted but did not cause complications, and we decided not to extract them immediately. Orthodontic treatment could have been planned. However, it could not be initiated before tooth restoration because of the bonding difficulty in the initial situation. In addition, orthosurgical treatment would be needed because of the severe skeletal discrepancy.[42,43] At the time, the patient did not want orthodontic treatment. However, we will encourage her to continue with such treatment in the near future.

Our treatment seems to have had a significant psychosocial impact, and the patient reported rapid improvement in quality of life and social and mental well-being. Thus, good management of the dental consequences of AI seems to positively affect all dimensions of the health of patients.[13,44,45]

CONCLUSION

Four sessions of entirely chairside CAD/CAM were used to treat the entire dentition affected by hypocalcified AI in a 17-year-old patient. We used a jig to secure the registration of the centric relation by optical impression before making the posterior permanent restorations. Her 28 teeth were restored with ceramic crowns, bonded under a rubber dam to ensure good longevity.

Hypocalcified AI can be rapidly treated with CAD/CAM, with restoration of function and esthetics while preserving residual tissues as much as possible. The latter objective is important to maintain the patient's teeth over the long term.

Regulatory Statement

This study was conducted in accordance with all the provisions of the local human subjects oversight committee guidelines and policies of Paris Descartes University. The patient read the article before its submission and accepted its publication.

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. The patient did not pay for the treatment. The practitioner was partly paid by French social security and the patient's private insurance.

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