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Evaluation of Interfacial Gap Volume of Two Low-shrinkage Composites Using Micro–Computed Tomography

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Clinical Relevance

The differences in the cavity configuration factor and volume of composite restorations do not always have a pronounced effect on gap volumes of low-shrinkage composites. Interfacial gaps result from an interplay of different factors related to the composition of the materials used and adhesive layer characteristics.

ABSTRACT

Objectives: To investigate the efficacy of X-ray micro–computed tomography (μCT) in the detection and quantification of interfacial gap formation in standardized Class I and Class II resin composite restorations, to compare the interfacial gaps for two low-shrinkage resin composites with a methacrylate composite material, and to determine any correlation between the cavity configuration factor (C-factor) and the volume of gaps formed.

Methods and Materials: Sixty standardized Class I and Class II cavities were prepared and divided into six groups. Three types of composites, with their recommended self-etching adhesive systems, were used: Filtek Z250 XT; Estelite Sigma Quick; and Filtek P90. Each of the composite materials was placed in 10 Class I and 10 Class II cavities. The specimens were digitized using Skyscan 1172 μCT. They were examined for gap volume measurements, the thickness of the adhesive layer, and location of interfacial gaps.

Results: There was a significant difference in the mean gap volume percentages of the three materials. The gap volume percent of Estelite Sigma quick was significantly lower than that of Filtek P90. No significant difference in the mean gap volume percentages of Class I and Class II restorations was found, except for Estelite Sigma Quick, in which the Class I gap volume percentage was higher than that of the Class II restorations.

Conclusions: μCT is an efficacious tool for the measurement of volumetric gaps formed at the tooth/restoration interface and for the evaluation of the adhesive layer. The differences in the C-factor do not always have a pronounced effect on the gap volumes of low-shrinkage composites.

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INTRODUCTION

Dental resin–based composites are complex materials that set through a free radical polymerization mechanism that involves cross-linking of monomer chains, resulting in a high polymerization shrinkage ranging between 2% and 6% by volume.[1-3] The volume reduction causes bond failure and, subsequently, gap formation at the weakest areas of the composite/tooth interface, leading to microleakage, postoperative sensitivity, and secondary caries.[4]

In recent years, manufacturers have attempted to reduce polymerization shrinkage through modifications in the chemical composition of the composite resin and filler material or through alterations in the size or percentages of filler content.[5-7] Resin-based composites with a higher filler content show reduced polymerization shrinkage as the volume of resin is minimized. Recent innovations in the field of restorative dentistry utilize nanotechnology to further enhance filler loading and esthetic properties of contemporary resin-based composites.[7-9]

Silorane-containing resin composites undergo a ring-opening polymerization reaction, in which monomers are linked together by opening, flattening, and extending toward each other. Reported volumetric shrinkage values are significantly lower than those of methacrylate-based composites.[10-12]

One factor that contributes to the amount of stress developed and, subsequently, the gap formed at the adhesive interface is the cavity configuration factor (C-factor). This term, created by Feilzer and others,[13] is a factor calculated as the ratio of bonded surfaces (restrained) to unbonded surfaces (free) of the resin composite restoration and is used in to describe the relationship between confinement conditions and stress values. de la Macorra and Gomez-Fernandez[14] suggested that it should be based on the calculation of the specific surface area of the cavity walls.[15,16] In addition, the volume of the composite resin increment is proportional to the degree of shrinkage that occurs, and it could be more detrimental than the C-factor itself.[17] In cavities with different volumes, the C-factor shows poor correlation with interfacial gaps; therefore, it may be a relevant parameter only when comparing restorations with similar volumes.[18,19]

Several methods have been used to study and measure the interfacial gap in dental restorative materials. However, most microleakage measurement methods are destructive, two-dimensional, and cannot allow study of the whole restoration interface.[20,21]

A standout among the progressive tools that have been introduced for the study of many focuses in dentistry is X-ray micro–computed tomography (μCT).[22,23] Early μCT-based studies[24-27] that compared internal adaptation of composite resin restoration were conducted without the use of a bonding agent. The use of bonded resin composites was reported in only a few studies.[28-30] In 2015, Hirata

Table 1: *Resin Composite Materials Used in the Study With Their Physical Properties*

Composite Material	Material Type	Composition	Filler Content	Shade	Elastic Modulus (GPA)	Volumetric Shrinkage	Manufacturer/ Lot No.
Filtek Z250 XT	Nanohybrid universal composite	Monomer: Bis-GMA, UDMA, Bis-EMA, PEGDMA, and TEGDMA Filler: ZrO_2/SiO_2	71% volume 82% weight	A2	12.5 (VOCO – Technical Guide)	1.7% (3M ESPE – Technical Report)	3M-ESPE, MN, USA/N261633
Filtek P90	Silorane-based microhybrid composite (low-shrinkage)	Monomer: Silorane (3,4 epoxycyclo-hexylethylcyclopoly-methylsiloxane,bis-3,4 epoxycyclo-hexylethylphenyl-methylsilane) Filler: SiO_2, ytterbium trifluoride	53% volume 73% weight	A2	12.8 (Ille and others[44])	0.9% (3M ESPE – Technical Report)	3M-ESPE, MN, USA/N326600
Estelite Sigma Quick	Supra–nano-spherical filled composite (low-shrinkage)	Monomer: Bis-GMA, TEGDMA Filler: SiO_2-ZrO_2, SiO_2-TiO_2	71% volume 82% weight	AO2	11.38 (Ille and others[44])	1.3% (Tokuyama – Technical Report)	Tokuyama, Tokyo, Japan/ W883

Abbreviations: Bis-GMA, bisphenol A-glycidyl methacrylate; UDMA, urethane dimethacrylate; Bis EMA, Ethoxylated bisphenol A dimethacrylate; PEGDMA, poly(ethylene glycol) dimethacrylate; TEGDMA, triethylene glycol dimethacrylate, SiO_2, silicon dioxide; ZrO_2,, zirconium dioxide; TiO_2, titanium dioxide.

and others[29] attempted to quantify the polymerization volumetric shrinkage of one regular and two low-shrinkage bulk fill composites in Class I cavities with or without an adhesive layer. The low-shrinkage composites showed less volumetric polymerization contraction than did the regular composite, and the use of dental adhesive decreased the total volumetric shrinkage for all evaluated composites. On the other hand, Carrera and others[30] developed a more comprehensive method to quantify interfacial leakage using silver nitrate infiltration and image subtraction.

μCT was also used in several studies[31-33] to evaluate the magnitude and direction of polymerization shrinkage. Recently, Van Ende and others[33] proposed a digital volume correlation enabling measurement and visualization of the regional shrinkage strain vectors within the entire volume of the composite restoration.

The first objective of this study was to investigate the efficacy of μCT in the detection and quantification of interfacial gap formation in standardized Class I and Class II resin composite restorations. The second objective was to compare the interfacial gap volume and distribution for two low-shrinkage resin composite materials with a conventional methacrylate nanohybrid composite material. The third objective of the study was to determine any possible correlation between the C-factor and the volume of gaps formed at the interface of Class I and II restorations for the three materials.

The null hypotheses were as follows:

1) μCT is not an effective tool for the evaluation of interfacial gap formation;
2) There is no difference between the three composite materials used in terms of the degree of interfacial gap volume, regardless of formulation; and
3) Different cavity configurations will not play a prominent role in the quantity or distribution of interfacial gaps for the three materials tested.

METHODS AND MATERIALS

This research was approved by the College of Dentistry Research Center and Deanship of Scientific Research at King Saud University (Research NF 2360). Sixty noncarious human premolars extracted for orthodontic reasons were cleaned with a hand scaling instrument, a rubber cup, and pumice, and were then stored in distilled water containing 0.05% thymol and refrigerated until use. After rinsing with water, all occlusal surfaces were flattened and polished using wet silicon carbide (SiC) papers (Buehler, Lake Bluff, IL, USA) mounted in an Automata machine (Jeanwirtz, Charlottenstrasse, Germany) to create a uniformly flat surface, starting with 240-grit, then 400-grit, and ending with 600-grit SiC papers. The teeth were then grouped into two preparation categories representing two configuration factors: Class I with a depth of 2 mm, width of 2 mm, and length of 3 mm; and Class II with an occlusal portion depth of 2 mm and dimensions of 2 × 2 mm, proximal box 3 mm deep from occlusal to gingival margin, and a 1-mm-wide gingival seat with rounded internal line angles and all enamel margins (Figures 1 and 2). All cavities were prepared using 330L pear-shaped tungsten carbide burs (Komet Brasseler, Savannah, GA, USA) and finished with a needle bullet finishing carbide bur (Komet Brasseler) on a high-speed handpiece (Sirona, Munich, Germany) under copious water irrigation. Burs were changed after preparation of five teeth. Cavities

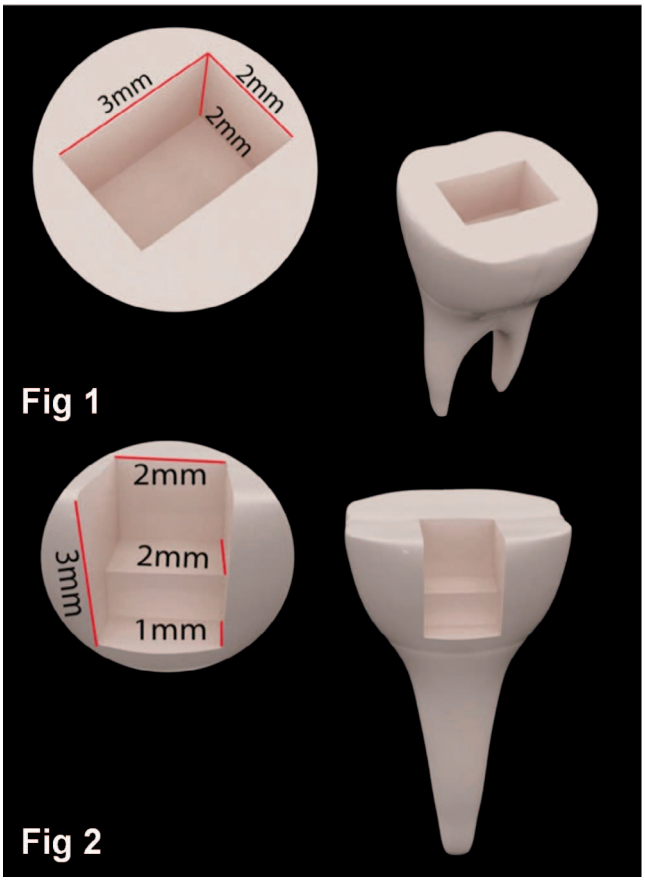

Figure 1. *Three-dimensional representation of Class I cavity preparations.*
Figure 2. *Three-dimensional representation of Class II cavity preparations.*

were precisely prepared by one operator using eye loupes (2.5×) and were standardized using an external verification method (Flexbar Tools, New York, NY, USA) with a depth-measuring digital micrometer and a custom indicator point stem that has a 0.120-inch (3.05-mm)–long measuring tip with a very small diameter that allows it to be easily inserted into the prepared cavity with an accuracy level of up to 0.05 mm. All teeth were restored within 24 hours of preparation, during which they were stored in 0.05% thymol solution.

The sample size was calculated to be at least eight teeth per group, based on an alpha level of significance of 0.05, a power of 0.87, and a standard deviation of mean interfacial gap volume of 0.7 mm^3. Cavities were divided into six groups of 10 teeth each. One group of each cavity type (Class I and Class II) was restored with one of the three types of composite materials used in this study (Table 1): the nanohybrid methacrylate-based composite Filtek Z250 XT (3M ESPE, St Paul, MN, USA); the low-shrinkage silorane-based microhybrid composite Filtek P90 (3M ESPE); or the low-shrinkage Supra–nano- spherical filled composite Estelite Sigma Quick (Tokuyama, Tokyo, Japan). All composites were used with their recommended self-etching adhesive system: Single Bond Universal (3M ESPE), P90 Self-etching Primer & P90 Bond (3M ESPE), and Bond Force (Tokuyama), respectively, according to the manufacturers' instructions (Table 2). Composite restorations were placed in one increment and cured for 40 seconds with Elipar™ S10 LED Curing Light (3M ESPE), with the light-curing tip placed perpendicular to the surface to be cured and 1 mm away from the top surface of the restoration. The light intensity was verified using a Demetron Optilux Radiometer (Kerr Corp, Orange, CA, USA) to be at 1000 mW/cm^2 prior to the placement of composite restorations for each group. All composite restorations were finished and polished using Soflex polishing discs (Kerr Corp) and a No. 12 blade.

Table 2: *Self-etching Adhesive Systems Used in the Study*

Composite Type	Self-etching Adhesive System	Composition	Manufacturer Instructions	Manufacturer/ LOT No.
Filtek Z250 XT	Single Bond Universal (one-bottle self-etch adhesive)	MDP phosphate monomer, dimethacrylate resin, HEMA, vitrebond copolymer, filler, ethanol, water, initiators, silane	Apply the adhesive to the prepared cavity and rub it in for 20 s Direct a gentle stream of air over the liquid for about 5 s until it no longer moves and the solvent has evaporated completely Light-cure the adhesive for 10 s	3M-ESPE, St Paul, MN, USA/495603
Filtek P90	P90 Self-Etch Primer and Bond (two bottle self-etch primer & bond)	P90 Self-Etch Primer: Phosphorylated methacrylates, Vitrebond copolymer, Bis-GMA, HEMA, Water, Ethanol, Silane-treated silica filler, Camphorquinone, Stabilizers P90 Bond: TEGDMA, Phosphoric acid methacryloxhexylesters, 1,6-hexanediol dimethacrylate, Bis-GMA, UDMA, Bis-EMA	Apply P90 Self-Etch primer and agitate primer on cavity surface for 15 s Light-cure for 10 s after drying with oil-free air Apply P90 Bond, disperse bond to a homogeneous film with oil-free air Light-cure for 10 s	3M-ESPE, St Paul, MN, USA/N239050, N239051
Estelite Sigma Quick	Bond Force (one bottle self-etching adhesive)	Phosphoric acid monomer, Bisphenol A di(2-hydroxy propoxy), dimethacrylate (Bis-GMA), Triethylene glycol dimethacrylate (TEGDMA),2-Hydroxyethyl methacrylate (HEMA), camphorquinone, dibutyl hydroxyl toluene	Apply the adhesive to the cavity walls and extend it to uncut enamel side Rub the adhesive under light finger pressure for 20 s Apply weak air flow for 5 s until the runny adhesive stays without any motion then finish with strong air flow for another 5 s Light-cure for 10 s	Tokuyama, Tokyo, Japan/175MM

Abbreviations: MDP Phosphate Monomer, 10-methacryloyloxydecyl dihydrogen phosphate monomer; HEMA, 2-hydroxylethyl methacrylate; Bis-GMA, bisphenol A-glycidyl methacrylate; TEGDMA, triethylene glycol dimethacrylate, UDMA, urethane dimethacrylate; Bis EMA, ethoxylated bisphenol A dimethacrylate

Table 3: *Mean and Standard Deviation Values and Multiple Comparisons of Gap Volume Percentages Among the Three Materials for Class I and Class II Restorations*

Type of Class	Z250 XT	Filtek P90	Estelite Material	*F*-Value	*p*-Value
Class I	0.4869 (0.21)	0.8016 (0.47)	0.3682 (0.16)*	4.841	0.017
Class II	0.4762 (0.25)	0.7966 (0.50)	0.1640 (0.14)*	7.886	0.003

** Statistically significant p<0.05.*

The specimens were then sealed with nail polish and orthodontic self-cure resin at the apices and stored in deionized water at 37°C for seven days. During this time, they were subjected to 5000 cycles of thermal stressing between 5°C and 55°C and with a dwell time of 30 seconds and transfer time of five seconds using a thermocycling apparatus (Thermocycler 1106/1206 SD Mechatronik, Feldkirchen-Westerham, Germany). Afterwards, specimens were sectioned at the cemento-enamel junction using an Isomet 2000 electronic saw (Buehler, Lake Bluff, IL, USA) under water irrigation to facilitate their ease of placement closer to the μCT scanning machine. The pulp chambers were sealed with sticky wax and two coats of Bosworth Copaliner varnish (HJ Bosworth Company, Skokie, IL, USA) and placed in deionized water until the time of their scan.

All specimens were digitized within two weeks of the time of their restoration using Skyscan 1172 μCT. The images were converted to tomograms (cross sections) to be examined for gap volume measurements using the SkyScan CT-analyser TM (CT-An) software (Bruker microCT, Kontich, Belgium). Gap volume was calculated (in mm^3) as air space that existed at the composite/adhesive/tooth interface only and did not include any air space related to voids within the composite mass.

Using Data Viewer TM software (Bruker microCT), the Class I images were qualitatively examined for the general quality of each restoration, location of the gaps (line angles, margins, inner or outer half of walls, pulpal floor), the interfaces at which gaps were formed (tooth/adhesive, composite/adhesive, or within adhesive layer), presence of voids in the composite mass (size and location), and possibility of adhesive pooling (floor, walls, margins, or corners). In Class II restorations, the same parameters were examined, along with the location of gingival margins (enamel or dentin), adaptation of composite at the axiopulpal line angle, and position of gaps in the proximal box. Representative samples of each group were chosen for three-dimensional (3D) reconstruction using the SkyScan CT-Voxel TM (CT-Vox) program (Bruker microCT).

Total volume of the cavities was calculated based on their dimensions, as follows: 12 mm^3 for Class I and 14 mm^3 for Class II. Gap volume was quantitatively measured as a percentage of the total volume of the restoration. The data were statistically analyzed using statistical software (SPSS, Version 16; SPSS Inc, Chicago, IL, USA). Two-way analysis of variance (ANOVA) was used to compare all six groups together and to determine possible interactions between composite material and between classes with the interfacial gap size. The multiple comparison test was used to test if there was a significant difference in gap size among the three materials within the same class for Class I and Class II. Significance level was set at $p < 0.05$. Only 52 specimens were used for the statistical analysis, as eight specimens were discarded as a result of cracks or large composite voids that interfered with gap volume measurements.

RESULTS

The results of the gap volume percentages for the three materials and multiple comparisons are shown in Table 3.

Two-way ANOVA revealed a statistically significant difference in the mean gap volume percentages of the three materials (Filtek P90, Filtek Z250 XT, and Estelite Sigma Quick) (F=12.597; p<0.0001), but no statistically significant difference in the mean gap volume percentages of the two classes (Class I and Class II) (F=0.709; p=0.404). The interaction of the class vs the material type was not statistically significant (F=0.593; p=0.557).

A multiple comparison test was used to compare differences between the mean gap volume percentages of the three different materials within each class (Table 3). The results showed a statistically significant difference in the mean values of gap volume percentages among the three materials of Class I and Class II (F=4.841, p=0.017 and F=7.886, p=0.003, respectively). For Class I and Class II, the mean gap volume percentage of the Estelite material was significantly lower than the mean gap volume percentage of the Filtek P90 material, but not significantly different from the mean gap volume

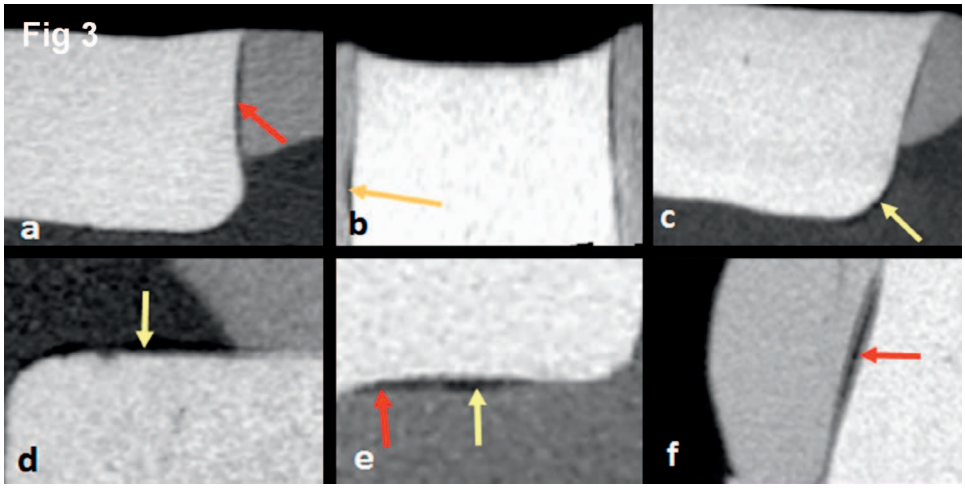

Figure 3. *Representative sections of μCT images taken for Classes I (Figure 3a through 3c) and II (Figure 3d through 3f) Filtek Z250 XT restorations showing locations of interfacial gaps; at the tooth adhesive interface (indicated with yellow arrows) and also showing separation within the adhesive layer (indicated with red arrow).*

percentage of the Filtek Z250 XT material. The data did not provide evidence of a statistically significant difference between the mean gap volume percentage values of the Filtek P90 and Filtek Z250 XT materials for either Class I or Class II.

On the other hand, the results showed a statistically significant difference between the mean values of gap volume percentage of Class I and Class II for Estelite Sigma Quick material, in which the mean gap volume percentage of Class I is significantly higher than that of Class II (p=0.01). However, there was no statistically significant difference in the mean values of gap volume percentages of Class I and Class II of the other two materials.

For the Filtek Z250 XT groups, gaps were seen in the inner and outer half of the walls in Class I restorations, predominantly in enamel margins, and along the axial wall in Class II restorations. The gaps were mainly between the adhesive and tooth structure (Figure 3b through d). Minimal pooling of adhesive was seen (in two specimens). The adhesive layer of the Single Bond Universal was around 70 μm in thickness. Small voids were noted within the composite mass in a few specimens (Figure 3c,d).

Images of the Filtek P90 specimens generally showed gaps on the inner half of the walls of Class I restorations and the inner half of the walls and line angles of Class II restorations. The gaps were mainly within the thick adhesive layer (Figure 4a,b,d) and between the composite and adhesive, predominantly in dentin margins (Figure 4a,e). Small to medium composite voids within the composite mass and pooling of the adhesive in the corners were seen in several specimens (Figure 4c,f). The adhesive layer presented by the Filtek P90 adhesive system was the thickest (around 80 μm) and was most evident on μCT images, in comparison to the other materials tested (Figure 4c,e).

The Estelite Sigma Quick groups showed the best composite adaptation, with minimal voids (Figure

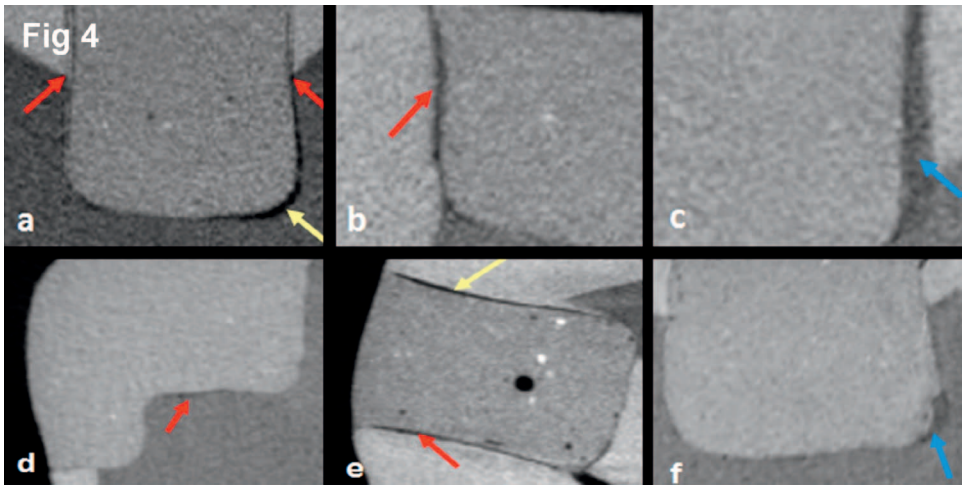

Figure 4. *Representative sections of μCT images taken for Classes I (Figure 4a through 4c) and II (Figure 4d through 4f) Filtek P90 restorations showing the interfacial gap as a separation between composite and Filtek P90 adhesive layer (indicated with yellow arrow), thick Filtek P90 adhesive layer with gaps within the adhesive layer (red arrows), and pooling of Filtek P90 adhesive (blue arrow).*

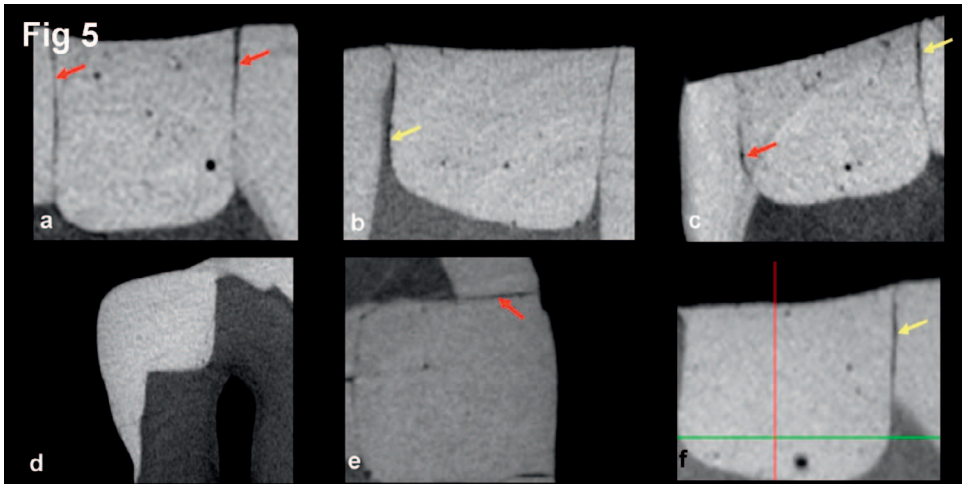

Figure 5. *Representative sections of μCT images taken of Classes I (Figure 5a through 5c) and II (Figure 5d through 5f) Estelite Sigma Quick restorations showing perfect adaptation of the composite, minimal adhesive layer, with interfacial gaps mostly present at the tooth/adhesive interface (yellow arrow) and some interfacial gaps within the adhesive layer (red arrow).*

5a,d), the thinnest adhesive layer (approximately 40 μm), and minimal gap formation. As a result of the minimal thickness of the adhesive layer, it was very difficult to distinguish gap position, but most of the gaps were seen on the walls and line angles between the tooth and adhesive layer (Figure 5b,c,f), with no obvious difference in the incidence of gap occurrence between the enamel and dentin/adhesive interfaces (Figure 5).

Sections of 3D reconstructed images using CT-Vox are displayed in Figures 6 and 7. The colored images show the adhesive layer clearly in yellow, with voids showing as dark brown or black air space.

DISCUSSION

The use of μCT imaging for examination of the internal adaptation of resin-based composite restorations is a new and innovative technology. Compared to traditional techniques that require sectioning of the specimen, μCT represents a precise and nondestructive 3D method that allows both linear and volumetric measurement of the gaps at the composite/tooth interface. In this study, the detection of gap volume (air space) was easy and accurate, and comparisons between different materials were possible. This method allowed 3D visualization of gap distribution, which represents possible pathways of interfacial leakage along the cavity walls; furthermore, it provided concomitant information about the spatial distribution of these gaps as well as the detailed characteristics of the adhesive layer. Therefore, the first null hypothesis can be rejected, as μCT proved to be an effective tool for the evaluation of interfacial gap formation and visualization of adhesive layer.

All of the resin-based composites used in this study demonstrated very low gap volume percentages, with Estelite Sigma Quick having the lowest gap volume in both classes. The Filtek P90 composite had a significantly higher gap volume percentage than did Estelite Sigma Quick. The gaps noted in the Filtek P90 group were mostly due to separations within the adhesive layer and between the adhesive and composite. This is likely due to the nature of the adhesive used, as the Filtek P90 adhesive is a viscous two-component 5%-10% filled adhesive[34] with poor wetting ability that gave rise to a thick adhesive layer, which may have contributed to void incorporation and microbubble formation.[16] This possibility is supported by the presence of voids within the adhesive layer, as opposed to at the cavity/restoration interface. In addition, voids in the adhesive layer act as stress concentration areas that could lead to an increase in the overall stress within the restoration and, ultimately, larger gap formation. The microbubbles seen within the Filtek P90 adhesive were also evident in the confocal microscopy images of D'Alpino and others,[35] who studied the adhesive interface after adding a fluorophore to the adhesive components.

As for the composite/adhesive interfacial separation, our finding is in agreement with previous reports[16,36] that showed adhesive failure of the Filtek P90 bond at the composite/adhesive interface to be the most prominent cause of bond failure with this composite. These authors[16,36] also reported that the higher modulus measured for some low-shrinkage resins like the Filtek P90 composite and its stiffer consistency may lead to air bubble incorporation within the composite mass that is more frequently enclosed near the bottom of the cavity. These pores can provide a free surface for the

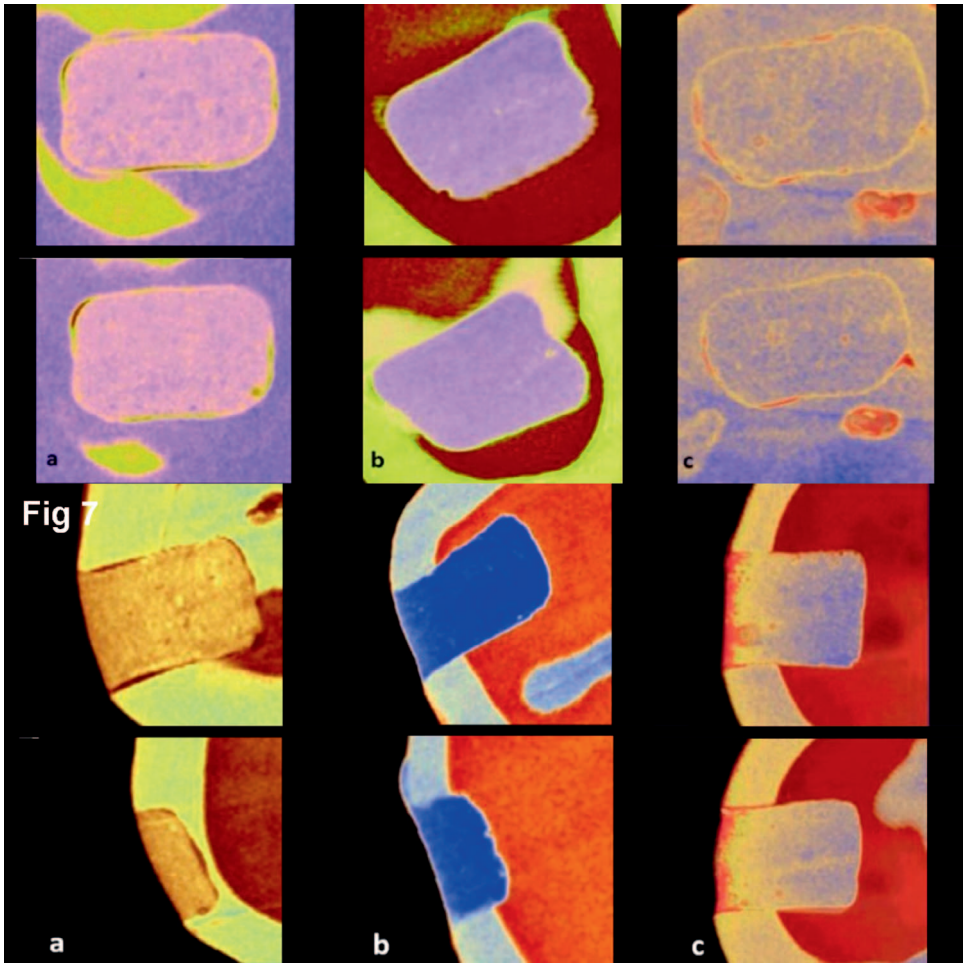

Figure 6. *Sections of Class I restorations using CT-Vox 3D reconstruction program showing clear adhesive layers (yellow), with voids showing as black air space: (a) Filtek Z250 XT; (b) Filtek P90; (c) Estelite Sigma Quick.*

Figure 7. *Sections of Class II restorations using CT-Vox 3D reconstruction program showing clear adhesive layers (yellow), with voids showing as black air space: (a) Filtek Z250 XT; (b) Filtek P90; (c) Estelite Sigma Quick.*

composite to flow and relieve shrinkage stresses,[37] but they can also affect bond strength, as they act as structural discontinuities within the restoration mass.[38]

In contrast, Bond Force self-etching adhesive is a single-component adhesive and has low viscosity, which facilitates wetting of the tooth surface and results in a thinly spread layer with minimal separation between tooth and adhesive. Similarly, Single Bond Universal self-etching adhesive showed minimal gaps within the adhesive layer and between the tooth and adhesive. As the results of this research showed that there was a difference in gap volume percentages among the different kinds of composites used, the second null hypothesis can be rejected.

The ease of manipulation of Estelite Sigma Quick and the low viscosity of the Bond Force adhesive may have contributed to the very small gap size measured with these materials. Although Bond Force is a one-bottle self-etch adhesive, it has shown very promising clinical results even when used on enamel without prior etching and after two years of clinical service.[39] In addition, Estelite Sigma Quick had a thin adhesive layer and the best cavity adaptation that could possibly be due to the low viscosity of this unfilled adhesive and the supra–nano-spherical fillers, which allowed a better adaptation and more efficient sealing of the cavity walls than were permitted by other types of fillers.[34]

Previous reports have looked at the effects of filler load and elastic modulus on polymerization shrinkage and shrinkage stresses. Researchers have reported a positive correlation between the elastic modulus and contraction stress. It has also been established that increasing the filler load results in reduced polymerization shrinkage, higher elastic modulus, and higher shrinkage stresses.[3,40] In this study, the Filtek P90 and Filtek Z250 XT gap volume percentage values were not significantly different from each other. This could be explained by the fact that although Filtek P90 has reportedly low volumetric shrinkage levels, it might have higher stress levels at the interface due to voids in

the adhesive layer and possible void incorporation within the composite mass. Filtek Z250 XT is not a low-shrinkage composite resin, but it is nano-filled with a higher filler content, which may have contributed to its small gap percentage values. As for Estelite Sigma Quick, which had the lowest gap percentage values, it is a low-shrinkage composite with a higher filler content than that of Filtek P90 and a lower elastic modulus (Tables 1 and 2). This combination of properties may have led to reduced contraction stress levels, which could have contributed to the minimal interfacial gap formation with this material.

The volumetric gap measurement is a very promising method with which to examine different composites and monitor their shrinkage behavior. However, gap volume percentage does not necessarily predict future microleakage or possible clinical performance. In this study, the interfacial gaps were detected only on some sections of the restorations and not along the entire walls of the preparation. However, while gaps present areas for potential microleakage, they cannot be used as a precise indicator for it. Sun and others[27] reported that microleakage results predicted by μCT analysis combined with 3D image analysis agreed well with those obtained by dye penetration, but they were not identical. Another study by Frankenberger and others[41] suggested that although *in vitro* testing of dental materials is routine for the preclinical investigation of restoratives because clinical performance cannot be predicted from lab results, clinical trials remain the ultimate instrument. In addition, the authors stated that marginal integrity is reliably predictable in laboratory *in vitro* studies by simulating clinical circumstances. However, marginal analysis of direct restorations *in vitro* is still limited in its ability to determine a lower borderline, and, actually, materials with worse *in vitro* results may still result in acceptable restorations *in vivo*.[41]

The change in cavity configuration between Class I and Class II in the present study changes the total volume from 12 mm^3 to 14 mm^3 and the C-factor from 5 to 4 if the number of walls of the cavity is to be calculated, and it changes it from 4.33 for Class I to 2.17 for Class II if the area of the walls is to be used for the C-factor calculation.[14] The results showed that the Class II restorations (with a smaller C-factor) had lower gap volume percentage measurements in comparison to the Class I restoration, but the difference was not statically significant, except in the Estelite Sigma Quick material. The results prove that the effect of cavity configuration on the gap volume percentages is neither predictable nor consistent. These results are in agreement with those of previous studies that reported no significant effect of the C-factor on gap volume. In 2011, Ghulman[42] suggested that although the microleakage score with silorane tended to increase as the C-factor increased, the effect of the C-factor on the low-shrinkage composite is much less evident than in methacrylate-based composites, as they generally shrink less and induce lower contraction stresses. Another study[43] comparing the microtensile bond strength of different composite materials showed that the increased C-factor had no effect on low-shrinkage composites, including Filtek Silorane, but did cause a significant drop in microtensile bond strength values for conventional methacrylate-based composite.

In the present study, only Estelite Sigma Quick was affected by the difference in the C-factor; therefore, the third null hypothesis is partially rejected. Estelite Sigma Quick has a rapid curing brought about by its unique initiator system, "Radical Amplified Photopolymerization Technology" (RAP), that results in faster stiffness attenuation and possibly high stress levels in restorations with a higher C-factor.[44] Furthermore, Estelite Sigma Quick displayed the thinnest adhesive layer of the materials tested, and it is possible that this contributed to the development of stress through lack of adhesive compensation through flow. Additionally, Estelite has a higher filler content and polymerization contraction than Filtek P90, and this may have led to a higher stress development and reduction of the Estelite's ability to deform elastically.[45]

The results of this study indicate that factors other than polymerization shrinkage and configuration influence the formation of gaps at the tooth/composite interface. Factors that may influence the marginal adaptation are related to the viscosity of the adhesive and the thickness of the adhesive layer. Therefore, reduction of polymerization shrinkage does not inevitably lead to a reduction in overall stress and better adaptation. Gap formation at the margins of a restoration is determined by a complexity of factors related to the material as well as the conditions under which it is placed.

CONCLUSIONS

Based on the results of this study, it can be concluded that

- μCT is a promising tool for evaluation of interfacial gaps of composite restoration as well as the adhesive layer.

- The differences in the C-factor and volume of composite restorations do not always have a pronounced effect on the gap volumes of low-shrinkage composites.
- Estelite Sigma Quick showed the best cavity adaptation and smallest gap volume compared to the two other materials.
- Interfacial gaps formed around composite restorations and within adhesive layers resulted from an interplay of different factors related to the composition of the composite material and adhesive, adhesive layer thickness, and physical properties of the composite resin used.

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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 CDRC. The approval code for this study is NF 2360.

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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