

## Original Article

# Volume fraction and location of voids and gaps in ultraconservative restorations by X-ray computed micro-tomography

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## ABSTRACT

**Background:** Volume fraction ( $V_f$ ) and location of internal voids and gaps in relation to material type and cavity dimensions in ultraconservative restorations were investigated in this study.

**Materials and Methods:** Forty-eight round cavities of 1.3 mm mean diameter and 2.6 mm mean depth were made on buccal and lingual surfaces of recently extracted human teeth. These were filled and thermocycled with two low viscosity composites (AeliteFlo LV [AF], PermaFlo [PF]), one high viscosity composite (Aelite aesthetic enamel [AA]) and one glass-ionomer (GCFuji IX GP). X-ray microtomography, following a specific procedure, was applied to all cavities before and after their restoration, using SkyScan-1072 microtomographer.  $V_f$  percent ( $V_f\%$ ) and location of voids and gaps were recorded and analysed statistically at  $\alpha = 0.05$ . Kruskal-Wallis nonparametric analysis of variance, *post-hoc* analysis, Mann-Whitney test, Spearman's correlation analysis were used to analyze data.

**Results:** Cavities filled with AF and PF showed significantly lower  $V_f\%$  of voids and gaps than all other restorations ( $P < 0.05$ ). Only for the cavities filled with AA, cavity width and depth was significantly correlated with  $V_f\%$  ( $P < 0.05$ ). 50-75% of the filled cavities contained internal voids regardless of the restorative material ( $P > 0.05$ ). The proportion of cavities with gaps at the bottom and side walls was lower in those filled with AF and PF ( $P < 0.05$ ).

**Conclusion:** Cavities filled with low viscosity composites presented the lowest amount of internal voids and gaps. Glass-ionomer and high viscosity composite restorative materials showed the highest amount of interfacial gaps. Only in the high viscosity composite restorations the amount of voids and gaps correlated with the cavity depth, width and volume.

**Key Words:** Cavity preparations, composite resin, dental, dental marginal adaptations, micro-computed tomography, x-ray

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## INTRODUCTION

Gap formation at cavity wall-restorative material interface is always of great importance, because of its significance to microleakage, postoperative sensitivity and secondary caries formation.<sup>[1-3]</sup> Bond strength and polymerization shrinkage of restorative materials are directly related to their adaptation

to cavity walls<sup>[4-6]</sup> through their flow, modulus of elasticity and wettability.<sup>[6,7]</sup> Cavity factors<sup>[8,9]</sup> such as number of walls, access to the walls and wall quality, along with operator factors<sup>[10-13]</sup> such as material type, material handling and method of insertion are also very important to wall adaptation. If these

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factors are not properly handled, a gap of variable size will be formed between cavity walls and filling material, during or following the hardening of the material.

Light, scanning electron, laser and confocal microscopy, dyes, tracers, air-pressure, electrical conductance and optical coherence tomography have all been used in the investigation of this gap.<sup>[14-26]</sup> Most of the above methods measure representative two-dimensional sections of cavities, interpolating the results for three-dimensional estimations. Although, efforts in measuring the three-dimensional space in small cavities (2 mm in diameter) were made,<sup>[27,28]</sup> in minimally invasive interventions for caries,<sup>[29-32]</sup> the question of how well a material can be adapted to the walls of cavities with smaller diameters (1.0-1.5 mm), still remains.

Presence of voids is equally important to the formation of gaps. Opdam *et al.*<sup>[4]</sup> found that voids and wall gaps were greater for thicker in consistency materials than medium or thin materials. In another study, Olmez *et al.*<sup>[14]</sup> found that internal voids correlated with marginal microleakage in class II composite restorations. Since material voids are equally important to gap space, and both are depended on the manipulation of the material, it is important to see if voids are also affected by the size of the cavity, during clinicians' effort to insert the material to the bottom of the cavity. In the study of Lioumi,<sup>[16]</sup> it was noted that the width of material-cavity interface was not uniformly distributed over the entire cavity walls but it was different in different parts of the cavity, due to certain parameters. The widest gap formed at the internal line angles of the cavity when margins were beveled, etched and bonded, while a significant amount of voids appeared within the material close to or in contact with the interface. Boroujeni *et al.*<sup>[33]</sup> investigating the effect of configuration factor on gap formation in composites found that high C-factor values generate large gap formation.

X-ray computed micro-tomography (micro XCT) is a method that uses X-rays to create two-dimensional density images of the specimen's cross sections and then reconstruct the specimen in a three-dimensional model.<sup>[34]</sup> For this reason, it is very useful in many areas in dentistry<sup>[35-37]</sup> including the investigation of material adaptation to cavity wall and margins, with relative accuracy, visualizing the different in density

entities of the specimens. Until now, a number of studies have been published on the adaptation of several different composite materials on cavity walls.<sup>[32,38-43]</sup> However, most of these studies were focused on polymerization shrinkage in cavities of normal dimensions and the attention was given to a rather laboratory technique in order to facilitate measurements. For these reasons, a method that could permit the investigation of gaps in a more clinically relevant setting of the entire cavity preparation, and in dimensions closer to a very conservative cavity would be of significant importance to the study of gap formation and location in such restorations.

The purpose of this study was to validate a microtomographic procedure for the comparison of voids (densities) in different ultraconservative cavities and to test the hypotheses that:

- a. The materials used for direct restoration of the cavities present no differences in the amount of internal voids or at the material-wall interface,
- b. voids and gaps are not related to cavity dimension, and
- c. Location of voids is not dependent to a specific restorative material.

## MATERIALS AND METHODS

### Sampling

For the purpose of this study, 12 human molar teeth were used for the preparation of 48 cylindrical cavities and their restoration with four different materials. The required sample size at  $\alpha = 0.05$ , a power of 0.85 and an effect size of 0.6, was *a priori* computed using G × Power V.3.1.5 (Franz Ful, Universitat Kiel, Germany). Visually intact teeth were carefully selected from recently extracted teeth, without the presence of hypomineralized or hypoplastic areas, caries or fracture lines on their buccal or lingual surfaces. Teeth were kept continually in tap water until cavity preparations.

### Cavity preparations

In order to prepare cavities, as much as possible on the same horizontal tooth plane, the roots of all teeth, 2-3 mm below their cemento-enamel junction, were cut and removed. Their bottom surface was ground flat, parallel to their occlusal surface. Two buccal and two lingual cavities of 2.5 mm in depth were prepared in each tooth under air-water spray, with a diamond bur rotating in a high-speed hand piece. Two of the cavities were opened with a 0.8 mm in diameter

bur (FGD0, Strauss and Co) and two with a 1.0 mm diameter (FGD1, Strauss and Co). Cavity depth was established with a length mark on each bur and cutting direction was facilitated by guiding the tooth against a stabilized hand piece with a horizontally rotating bur [Figure 1]. No special attention was given for opening the cavities with an exact width or depth, in order to have a range of cavities with differences in width or depth and facilitate their correlation with restorations' gaps and voids. Only four cavities were allowed to be opened by the same bur and cavities of different diameter were distributed equally to labial and lingual surfaces.

### First microtomographic examination

After preparation of the cavities, all teeth were stored in water of 37°C until their first microtomographic examination by SkyScan 1072 microtomographer (micro XCT, Model 1072, SkyScan Aartselaar, Belgium). Its operating parameters are shown in Table 1. The cavities were examined before insertion of the filling material, to calculate the precise cavity dimensions and assist the estimation of gaps and voids in the restored cavities at the second microtomographic examination [Figure 2].

### Cavity filling

The restorative materials used to fill the experimental cavities are shown in Table 2, and the procedure followed for each material is described below. The assignment of restorative material and bur diameter on tooth surfaces was based on a Latin square design, in order to have teeth, with all the designed treatment variables, in a systematic rather than a random fashion. All cavities were acid etched with 37% ortho-phosphoric acid for 30 s, rinsed with

water for 2-3 s and dried with air for 4-5 s and 1-2 absorbent paper points. Cavities assigned to receive composite resins were lined carefully with adhesive according to manufacturer instructions (Prime and Bond NT, Dentsply Int Inc, Milford, USA) and polymerized for 20 s, using a curing unit with a light intensity of 550-600 mW/cm<sup>2</sup> (Demetron LC/Kerr GmbH, Rastatt, Germany). It must be mentioned that adhesive material was used with caution since excess of adhesive remain undetected by X-rays and even a small excess could be measured as gap.

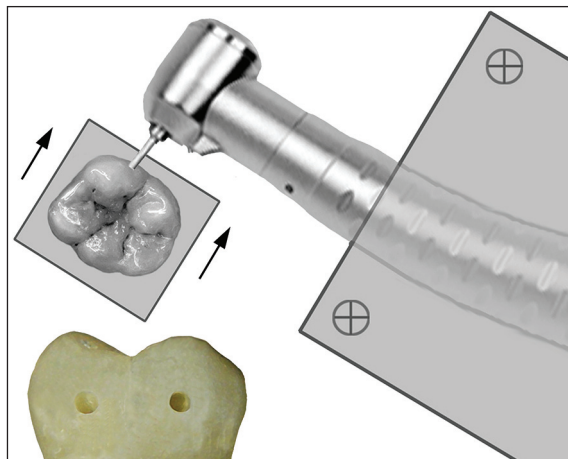
**Table 1: Operating parameters used for SkyScan 1072 microtomographer**

Parameter	Value
Source voltage	100 kV
Source current	0.0980 mA
Filter material	Aluminum
Filter thickness	1 mm
Image resolution	1024×1024
Pixel size	0.01417 mm
Rotation angle	180°
Rotation step	0.9
Exposure time	1900 ms

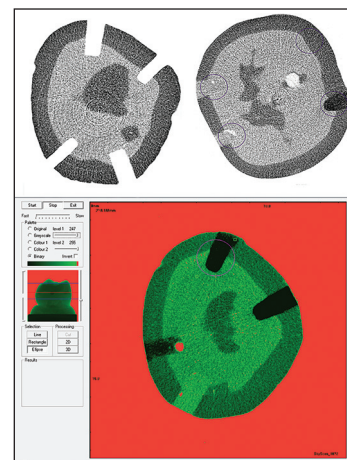
**Table 2: Materials used in the study**

Material	Company	Shade	Batch number
AF	Bisco Inc, Chicago, USA.	A2	0600007260
PF	Ultradent Products Inc, StLouis, USA	A2	B1W1D
FU	GC Corporation, Tokyo, Japan	A2	0412171
AA	Bisco Inc, Chicago, USA	A2-E	050009670

AA: Aelite aesthetic; AF: AeliteFlo LV; PF: PermaFlo; FU: Fuji IX.



**Figure 1:** Arrangement of handpiece and tooth for preparation of the cavities.



**Figure 2:** Upper left: Microtomographic section of a tooth showing the prepared cavities. Upper right: Image showing all circular region of interest. Lower: A screen image showing the binarization settings with Tview software, before calculation starts.

AeliteFlo/Bisco Inc, Chicago, USA (AF) was placed in the cavity with a small diameter tip on material syringes. The tip was initially placed at the bottom of the cavity and was gradually withdrawn in an outward direction as the material was injected into the cavity. The material was polymerized for 30 s, and the excess, was finished and polished using Medium, Fine and SuperFine Sof-Lex discs (3M ESPE, Dental Products, St. Paul, MN, USA).

PermaFlo/Ultradent Products Inc, StLouis/USA(PF) was placed in the cavity exactly as AF. Aelite aesthetic/Bisco Inc, Chicago, USA (AA) was placed in the cavity in small parts and condensed with the use of a dentin excavator, modified to a small diameter condenser (0.8 mm), in order to enter the cavities. After condensation and polymerization, the same finishing and polishing procedure as in AF was followed.

Fuji IX/GC Corporation, Tokyo, Japan (FU) was inserted in the cavity after activation of the capsule according to manufacturer's instructions, by placing the capsule tip at the entrance of the cavity and condensing the material with the use of the same condenser, as before.

### Second microtomographic examination

Immediately after finishing and polishing of restorations, teeth were placed in distilled water of 37°C and retrieved after 24 h to receive 500 thermal cycles (5-55°C, 3 min each). The second X-ray microtomographic examination was made under the same operating parameters with the first examination, immediately after thermocycling procedure. All teeth were continuously kept in water of 37°C until their examination. The volume amount of empty spaces within the material or between material and cavity walls was calculated on this second series of digital sections, using the Tview v.1.3 software (Skyscan n.v. Aartelaar, Belgium) accompanying the instrument. The software calculates on binary images of sample's tomographic sections, the different in density areas, within a predefined region of interest (ROI). Running all relative sections, the total volume ( $V_t$ ) and the volume fraction percent ( $V_f$  %) of the interested densities (called active pixels) in the ROI can be calculated. A specific process had to be followed, to ensure that all calculations were based exactly on the same ROI. This process is described below.

#### Selection of measuring areas

Using Tview v.1.3/Skyscan n.v. Aartelaar, Belgium, the number of horizontal sections covering the width

of the cavity was determined. The sections showing all four cavities at their largest width were located and copied on a Photoshop CS file. A circular area over the cavity was drawn on a transparent layer with the marquee tool. Then, the circular marquee line was copied in new transparent layers, moved and applied to all four cavities for an exact positioning and all four layers were combined and saved as a single .bmp file. This process was repeated for all tooth cavities [Figure 2] and the saved .bmp files were placed as the last tomographic image, in order to remain available, but outside the range of the selected sections.

#### Measuring process

The inserted image in each set of tooth microtomographs was located and the ROI was drawn over the selected areas. The upper and lower sections of each cavity were inserted, and the color palette was set to binary colors (247 in Level-1 and 255 in Level-2), for best discrimination of empty spaces from tooth/material substance [Figure 2]. The three-dimensional analysis was used, in order to collect information from the set of predefined horizontal sections on the variables described below. This three-dimensional analysis was repeated three times for each cavity and for all teeth. Data collected concerned the following morphometric values:

- $V_t$ , the total selected volume throughout all the cross sections,
- $V_f$  %, the volume percent of the selected item (empty space) in an area,
- $S_p$ , the total surface area of the item. The interest was centered on  $V_f$  % and its relation to the initial volume of cavity dimensions and restorative material type.

#### Voids and gaps location

The location of voids and gaps was evaluated using the Tview software and its no1 color palette. All relative to each cavity.bmp images (1024 × 1024 pixels) were viewed by two examiners for the location of voids if present, on a 19' computer screen. For their classification three locations were recorded:

- The material itself,
- The side walls of the cavity and
- The bottom of the cavity. Voids at the walls or bottom of the cavity were actually the gaps at the material/cavity interface. For each cavity, one, two or all three locations were recorded, always based on the agreement of both examiners.



### Statistical analysis

Kolmogorov-Smirnov tests for normality and Bartlett's test for the equality of variances indicated the use of Kruskal-Wallis nonparametric test to analyze the data for differences between materials, in respect to the morphometric parameters. Mann-Whitney test was also used to search for possible differences between low and high viscosity materials, for each morphometric parameter. The degree of correlation of cavity dimensions with all morphometric parameters was analyzed by Spearman's test. All statistical tests performed with MedCalc v.10.0 (MedCalc Software, Mariakerke, Belgium) at a 0.05 level of significance.

## RESULTS

Unfilled cavity dimensions were measured and found to have a mean length of  $2.6 \pm 0.4$  mm and a mean width  $1.30 \pm 0.19$  mm. The mean values of all morphometric elements ( $V_t$ ,  $V_f$  and  $S_t$ ), estimated by three-dimensional analysis for the cavities filled with four restorative materials are shown in Table 3. Images of characteristic microtomographic sections of the filled cavities are shown in Figure 3.

Statistical analysis by Kruskal-Wallis nonparametric analysis of variance indicated significant differences among filled cavity groups, for all three parameters ( $KW_{V_t} = 38.0$ ,  $KW_{V_f} = 38.29$ ,  $KW_{S_t} = 29.28$ ,  $P < 0.0001$ ). *Post-hoc* analysis based on pairwise comparisons showed significantly higher values of  $V_f$  % in cavities filled with FU than those filled with other materials ( $P < 0.05$ ) [Table 3]. Restorations with

AF and PF materials showed the lowest  $V_f$  % values of all ( $P < 0.05$ ). Mann-Whitney test also indicated a significant difference between cavities filled with high and low viscosity materials ( $U = 565.5$ ,  $P < 0.0001$ ). Spearman's correlation analysis results are shown in Table 4. Cavity length, width and volume of high and low viscosity materials as well as in most individual materials correlated poorly and not significantly with  $V_f$  %. However, in cavities filled with AA, a significant correlation was found between  $V_f$  % and depth of the cavity.

The proportion of cavities with voids at different locations (within the material, bottom and side walls of the cavity) is shown in Table 5. In 50-75% of the restorations, voids were present within the material, without difference in their proportion among the different materials. In 90-100% of the cavities filled with AA and FU, gaps were present at the bottom of the cavity, and significantly higher than those filled

**Table 3: Morphometric parameters of voids and gaps**

Material		$V_t$ (mm <sup>3</sup> )		$V_f$ (pixels%)		$S_t$ (mm <sup>2</sup> )	
Code	Number	Mean	SD	Mean	SD	Mean	SD
AA	12	0.145	0.05	2.70 <sup>ab</sup>	0.89	12.90 <sup>a</sup>	4.38
AF	12	0.038	0.02	0.72 <sup>c</sup>	0.31	3.7b <sup>b</sup>	1.69
FU	12	0.564	0.30	10.67 <sup>a</sup>	5.51	11.26 <sup>a</sup>	4.18
PF	12	0.060	0.03	1.11 <sup>bc</sup>	0.62	5.10 <sup>b</sup>	2.60

Same superscript letters over means indicate no difference at the 0.05 level. SD: Standard deviation; AA: Aelite aesthetic; AF: AeliteFlo LV; PF: PermaFlo; FU: Fuji IX;  $V_t$ : Total volume;  $V_f$ : Volume fraction;  $S_t$ : Total surface.

**Table 4: Spearman's rho coefficients of  $V_f$  % with cavity dimensions**

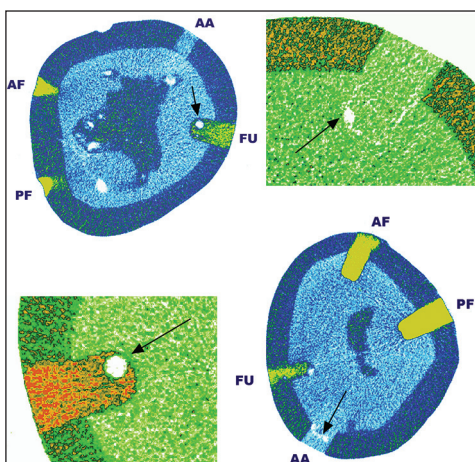
Cavity Parameter	AA	AF	FU	PF	High	Low
Depth	0.625*	0.170	0.543	0.130	0.154	0.108
Width	0.670*	0.244	0.140	-0.070	0.105	0.041
Volume	0.578	0.270	0.238	-0.035	0.124	0.068

High and low refers to materials' viscosity. \*Correlation is significant at the 0.05 level (two-tailed). AA: Aelite aesthetic; AF: AeliteFlo LV; PF: PermaFlo; FU: Fuji IX;  $V_f$ : Volume fraction.

**Table 5: Lower and upper limits of the 95% CI for the proportion of cavities with voids within the material, and gaps at the bottom or side walls of the cavity**

Material	Within	95% CI	Bottom	95% CI	Sides	95% CI
AA	0.67 <sup>a</sup>	0.39-0.86	1.00 <sup>a</sup>	0.76-1.00	1.00 <sup>a</sup>	0.76-1.00
AF	0.75 <sup>a</sup>	0.47-0.91	0.00 <sup>b</sup>	0.00-0.24	0.17 <sup>b</sup>	0.05-0.45
FU	0.67 <sup>a</sup>	0.39-0.86	0.92 <sup>a</sup>	0.65-0.98	0.25 <sup>b</sup>	0.09-0.53
PF	0.50 <sup>a</sup>	0.25-0.75	0.17 <sup>b</sup>	0.05-0.45	0.33 <sup>b</sup>	0.14-0.61

Based on overlapping CIs, same superscript letters over proportions indicate no difference at the 0.05 level. CI: Confidence interval; AA: Aelite aesthetic; AF: AeliteFlo LV; PF: PermaFlo; FU: Fuji IX.



**Figure 3:** Upper left: A tooth section showing two of the filled cavities with voids within Fuji IX (FU) material. Upper right: Gaps in a cavity filled with Aelite aesthetic (AA). Lower left: Void within FU material. Lower right: Voids at the bottom of an FU and in the middle of an AA restoration.

with AF or PF. All cavities filled with AA showed also gaps at the side walls of the cavity, significantly higher than all other materials.

## DISCUSSION

The results showed that the procedure followed to compare voids fraction among different cavities on the same sample, is capable of revealing significant differences. The study rejected all three hypotheses:

- For no differences between materials in  $V_f$  % of voids (and gaps),
- For no association of cavity dimensions with  $V_f$  % of voids (and gaps), and
- For no association of voids location with a specific restorative material.

The procedure introduced in this study for the selection of exactly the same ROI on all cavities was not a simple one, but since differences between repeated measurements ranged only from 0.002 to 0.005  $V_f$ %, this indicates that the method was able to reveal small differences in the volume of voids in very conservative cavities. However, the need to add extra digital sections to a number of cavities smaller in depth than others, or the inclusion in the experiment of materials with high variability in the volume of voids, like FU material, may introduce an error to the measurements.

In our study, the low viscous materials were the best among different materials in filling the ultraconservative cavities without gap and this is in agreement with the results of other studies for normal cavities.<sup>[4,24]</sup> Opdam *et al.*<sup>[4]</sup> found that thinner composites had fewer problems with voids and wall adaptation than thicker materials. Peutzfeldt and Asmussen,<sup>[5]</sup> who also studied gap formation, found a positive correlation of high viscosity and polymerization shrinkage with gap formation. Moreira da Silva *et al.*<sup>[6]</sup> found a correlation of gap and voids formation with high viscous flow and low flexural modulus of composite materials. These results can be explained by the high thixotropic effect of low viscous composite materials, and their low polymerization shrinkage due to their low modulus of elasticity. However, the effect of material insertion technique should not be overlooked. Opdam *et al.*<sup>[4]</sup> showed that injection technique, like the one we used with low viscous composites, leads to reduced voids formation within the material and a smaller interfacial gaps. Hence, in cavities of very small diameter (1.0-1.5 mm)

where the insertion of the restorative material and its adaptation to the cavity walls is difficult, low viscous material should be syringed deep into the cavity instead of using higher viscosity composites. Thicker composite materials even if they are managed to be inserted in such cavities can potentially form internal voids between layers, and for this reason their use should be done with caution.

Glass-ionomer material was inserted with difficulty in small cavities, due to its adherence to the instruments and the cavity walls during insertion. As a result of this, air bubbles were frequently entrapped at different areas of its mass. This type of material should not be used in such small cavities unless perhaps a special small in diameter tip designed to allow proper insertion of the material deep into the cavity before its hardening.

Our study also showed a significant correlation of initial cavity volume with  $V_f$  of spaces around and within AA filling material only. This positive correlation of deeper or wider cavities with the presence of voids is probably a result of higher polymerization contraction in larger restorations, as He *et al.*<sup>[12]</sup> reported on bonded composites. Their study showed that in larger cavities with a high C-factor (class I and V), the bonding was riskier than in small cavities. Therefore, larger cavities filled with high viscous composite material may present a higher amount of voids and gaps. Our study showed that the voids within the restorative material were not associated with a specific type of material. However, gaps at the bottom of the cavity were more frequently associated with the more viscous AA and FU materials, as other studies indicated.<sup>[28,40]</sup> They presented a higher polymerization contraction than AF and PF materials, and need a higher force and more attention to make a closer contact with the bottom of the cavity. Gaps at the sides of the cavity were more frequently associated with AA material. The reason is probably that polymerization contraction, which is evident with all cavity walls in a nonbonded restoration, creates a space at the sides of the cavity, more evidently than in other materials. FU, for instance, has the ability of creating a bond with the side walls of the cavity, but also seems to create larger gaps at the bottom of the cavity, which helps to accommodate a significant part of its contraction during hardening.

It must be noticed that pixel size in microtomographic images was 14  $\mu$  in this study, although system's

detection limit was 1.8  $\mu$ . For this reason, smaller in size voids could not be recorded or located and voids of such dimensions may exist in all types of materials and locations. This is probably the limitation of the suggested method and the reason why low viscous materials show a low proportion of voids or gaps. However, newer CT technology (X-ray computed nanotomography) will be able to estimate gaps and voids more accurately. Voids are present in the same frequency within the mass of all restorative materials, but gaps are present more frequently in restorative materials with high viscosity, at the bottom and the side cavity walls. For these reasons, more research is needed to refine the available techniques for placing correctly and precisely a restorative material within a very conservative cavity, the way of using adhesives in cavities of a very small opening, the type of material that can actually minimize the hardening shrinkage of the material and of course the measurement of voids of very small dimensions.

## CONCLUSION

1. There were differences between restorative materials in the  $V_f$  % of voids and gaps remaining after condensation of the materials in the cavities.
2. Low viscous composite resins were the best in filling cavities without voids or gaps.
3. High viscous composite and glass-ionomer materials produced the highest amount of internal voids and gaps.
4. Cavity depth, width and volume do correlate with the amount of voids and gap spaces, but only for the high viscous composite material.
5. Voids are located in the same frequency within all materials, but gaps are more frequently located within high viscous composites, both at the bottom and the side cavity walls.

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## Conflicts of interest

The authors of this manuscript declare that they have no conflicts of interest, real or perceived, financial or non-financial in this article.

## REFERENCES

1. Brännström M. The cause of postrestorative sensitivity and its prevention. *J Endod* 1986;12:475-81.
2. Opdam NJ, Feilzer AJ, Roeters JJ, Smale I. Class I occlusal composite resin restorations: *In vivo* post-operative sensitivity, wall adaptation, and microleakage. *Am J Dent* 1998;11:229-34.
3. Totiam P, González-Cabezas C, Fontana MR, Zero DT. A new *in vitro* model to study the relationship of gap size and secondary caries. *Caries Res* 2007;41:467-73.
4. Opdam NJ, Roeters JJ, Peters TC, Burgersdijk RC, Teunis M. Cavity wall adaptation and voids in adhesive Class I resin composite restorations. *Dent Mater* 1996;12:230-5.
5. Peutzfeldt A, Asmussen E. Determinants of *in vitro* gap formation of resin composites. *J Dent* 2004;32:109-15.
6. Moreira da Silva E, dos Santos GO, Guimarães JG, Barcellos Ade A, Sampaio EM. The influence of C-factor, flexural modulus and viscous flow on gap formation in resin composite restorations. *Oper Dent* 2007;32:356-62.
7. Boaro LC, Gonçalves F, Guimarães TC, Ferracane JL, Versluis A, Braga RR. Polymerization stress, shrinkage and elastic modulus of current low-shrinkage restorative composites. *Dent Mater* 2010;26:1144-50.
8. Feilzer AJ, De Gee AJ, Davidson CL. Setting stress in composite resin in relation to configuration of the restoration. *J Dent Res* 1987;66:1636-9.
9. Shono Y, Ogawa T, Terashita M, Carvalho RM, Pashley EL, Pashley DH. Regional measurement of resin-dentin bonding as an array. *J Dent Res* 1999;78:699-705.
10. Chuang SF, Liu JK, Chao CC, Liao FP, Chen YH. Effects of flowable composite lining and operator experience on microleakage and internal voids in class II composite restorations. *J Prosthet Dent* 2001;85:177-83.
11. Jacobsen T, Söderholm KJ, Yang M, Watson TF. Effect of composition and complexity of dentin-bonding agents on operator variability: Analysis of gap formation using confocal microscopy. *Eur J Oral Sci* 2003;111:523-8.
12. He Z, Shimada Y, Tagami J. The effects of cavity size and incremental technique on micro-tensile bond strength of resin composite in Class I cavities. *Dent Mater* 2007;23:533-8.
13. Kwon SR, Oyoyo U, Li Y. Influence of application techniques on contact formation and voids in anterior resin composite restorations. *Oper Dent* 2014;39:213-20.
14. Olmez A, Oztas N, Bodur H. The effect of flowable resin composite on microleakage and internal voids in class II composite restorations. *Oper Dent* 2004;29:713-9.
15. Hansen EK. Visible light-cured composite resin: Polymerization contraction, contraction patterns and hygroscopic expansion. *Scand J Dent Res* 1982;90:329-35.
16. Lioumi E. Study on the adaptation of materials to cavity walls in composite/glass-ionomer restorations. PhD thesis, Dental School University of Athens; 1995.
17. Watson TF. A confocal optical microscope study of the morphology of the tooth/restoration interface using Scotchbond 2 dentin adhesive. *J Dent Res* 1989;68:1124-31.
18. Sano H, Takatsu T, Ciucchi B, Horner JA, Matthews WG, Pashley DH. Nanoleakage: Leakage within the hybrid layer. *Oper Dent* 1995;20:18-25.
19. Granath LE, Svensson A. Studies of microleakage with restorative materials. A new air pressure method. *Scand J Dent Res* 1970;78:353-66.
20. Iwami Y, Yamamoto H, Ebisu S. A new electrical method for detecting marginal leakage of *in vitro* resin restorations. *J Dent* 2000;28:241-7.

21. Yoshikawa T, Sano H, Burrow MF, Tagami J, Pashley DH. Effects of dentin depth and cavity configuration on bond strength. *J Dent Res* 1999;78:898-905.
22. Irie M, Suzuki K, Watts DC. Marginal gap formation of light-activated restorative materials: Effects of immediate setting shrinkage and bond strength. *Dent Mater* 2002;18:203-10.
23. Haak R, Wicht MJ, Noack MJ. Marginal and internal adaptation of extended class I restorations lined with flowable composites. *J Dent* 2003;31:231-9.
24. Belli S, Inokoshi S, Ozer F, Pereira PN, Ogata M, Tagami J. The effect of additional enamel etching and a flowable composite to the interfacial integrity of Class II adhesive composite restorations. *Oper Dent* 2001;26:70-5.
25. Nazari A, Sadr A, Shimada Y, Tagami J, Sumi Y. 3D assessment of void and gap formation in flowable resin composites using optical coherence tomography. *J Adhes Dent* 2013;15:237-43.
26. Swain MV, Xue J. State of the art of Micro-CT applications in dental research. *Int J Oral Sci* 2009;1:177-88.
27. Iwami Y, Shimizu A, Hayashi M, Takeshige F, Ebisu S. Three-dimensional evaluation of gap formation of cervical restorations. *J Dent* 2005;33:325-33.
28. Kakaboura A, Rahiotis C, Watts D, Silikas N, Eliades G. 3D-marginal adaptation versus setting shrinkage in light-cured microhybrid resin composites. *Dent Mater* 2007;23:272-8.
29. White JM, Eakle WS. Rationale and treatment approach in minimally invasive dentistry. *J Am Dent Assoc* 2000;131 Suppl:13S-19.
30. Mjör IA, Holst D, Eriksen HM. Caries and restoration prevention. *J Am Dent Assoc* 2008;139:565-70.
31. Rindal DB, Gordan VV, Litaker MS, Bader JD, Fellows JL, Qvist V, *et al.* Methods dentists use to diagnose primary caries lesions prior to restorative treatment: Findings from The Dental PBRN. *J Dent* 2010;38:1027-32.
32. Rindal DB, Gordan VV, Fellows JL, Spurlock NL, Bauer MR, Litaker MS, *et al.* Differences between reported and actual restored caries lesion depths: Results from the Dental PBRN. *J Dent* 2012;40:248-54.
33. Boroujeni PM, Mousavinasab SM, Hasanli E. Effect of configuration factor on gap formation in hybrid composite resin, low-shrinkage composite resin and resin-modified glass ionomer. *J Investig Clin Dent* 2015;6:156-60.
34. Landis EN, Keane DT. X-ray microtomography. *Mater Charact* 2010;61:1305-16.
35. Schicho K, Kastner J, Klingsberger R, Seemann R, Enislidis G, Undt G, *et al.* Surface area analysis of dental implants using micro-computed tomography. *Clin Oral Implants Res* 2007;18:459-64.
36. Fan W, Fan B, Gutmann JL, Cheung GS. Identification of C-shaped canal in mandibular second molars. Part I: Radiographic and anatomical features revealed by intraradicular contrast medium. *J Endod* 2007;33:806-10.
37. Nakamura T, Wakabayashi K, Kawamura Y, Kinuta S, Mutobe Y, Yatani H. Analysis of internal defects in all-ceramic crowns using micro-focus X-ray computed tomography. *Dent Mater J* 2007;26:598-601.
38. Parkinson CR, Sasov A. High-resolution non-destructive 3D interrogation of dentin using X-ray nanotomography. *Dent Mater* 2008;24:773-7.
39. Sun J, Lin-Gibson S. X-ray microcomputed tomography for measuring polymerization shrinkage of polymeric dental composites. *Dent Mater* 2008;24:228-34.
40. Sun J, Fang R, Lin N, Eidelman N, Lin-Gibson S. Nondestructive quantification of leakage at the tooth-composite interface and its correlation with material performance parameters. *Biomaterials* 2009;30:4457-62.
41. Sun J, Eidelman N, Lin-Gibson S. 3D mapping of polymerization shrinkage using X-ray micro-computed tomography to predict microleakage. *Dent Mater* 2009;25:314-20.
42. Papadogiannis D, Kakaboura A, Palaghias G, Eliades G. Setting characteristics and cavity adaptation of low-shrinking resin composites. *Dent Mater* 2009;25:1509-16.
43. Zeiger DN, Sun J, Schumacher GE, Lin-Gibson S. Evaluation of dental composite shrinkage and leakage in extracted teeth using X-ray microcomputed tomography. *Dent Mater* 2009;25:1213-20.