Influence of Curing Mode and Layering Technique on the 3D Interfacial Gap of Bulk-fill Resin Composites in Deep Class-I Restorations: A Micro-CT Volumetric Study

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Purpose: To three-dimensionally evaluate the interfacial gap of bulk-fill resin composites applied in deep Class-I restorations with different layering techniques and curing modes.

Materials and Methods: Ninety-six ($n = 96$) samples were prepared with standardized deep Class-I cavities and adhesive procedures. Four materials were tested: SDR (SDR), SonicFill2 (SF), Admira Fusion X-Tra (AFXT), Filtek Supreme XTE (FS). Four subgroups ($n = 6$) were created according to layering and curing techniques: 2+2mm increments with soft start curing (SG1), 2+2 mm with conventional curing (SG2), a 4-mm increment with soft start curing (SG3), a 4-mm increment with conventional curing (SG4). All samples underwent micro-CT scans; afterwards, voids surrounding the restorations automatically underwent a thresholding procedure (Mimics, Materialise; Geomagic Studio 12, 3D Systems) to analyze the 3D interfacial gap. Statistical analysis was performed using three-way ANOVA with Tukey's test (significance $p < 0.05$).

Results: Statistically significant differences were reported between materials, layering techniques and their interaction. No statistically significant differences were reported for polymerisation mode. Bulk-fill materials showed average interfacial gap volumes ranging from 0.031 mm^3 to 0.200 mm^3, while FS showed volumes ranging from 0.416 mm^3 to 1200 mm^3.

Conclusions: All bulk-fill materials performed statistically significantly better than did FS ($p < 0.05$), with no statistically significant differences between them. Curing mode did not influence interfacial gap volume in any group ($p > 0.05$), while bulk-filling vs layering influenced the volume of interfacial gaps only in the FS group, which performied better when incrementally applied. Regarding gap localisation, the floor of the cavity was the area with the highest likelihood of gaps in all samples.

Keywords: 3D interfacial gap, micro-CT, bulk-fill composites, layering techniques, curing modes.

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Resin composites are widely employed in dentistry, especially for posterior direct restorations. However, their durability remains an issue.[16] One of the main problems related to longevity is the volumetric contraction of resin composites, which is related to the conversion of monomers into polymer chains[6] and can cause clinical problems such as post-operative sensitivity, marginal discoloration,[33] enamel and dentin cracks[22] and interfacial gap formation.[27] The data on the volumetric shrinkage of resin composites reported in the literature is highly variable, with a range of 1.4%–7.1% and an average of 2%–3%.[21] This variability is related to the mechanical properties of the materials used, especially their viscosity, the quantity of monomer present, and the polymerization kinetics.[36,41,43] The data on the shrinkage stress that volumetric contraction can generate

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at the adhesive interface,[18] which is the weakest area of the restoration,[7] varies even more. Indeed, several factors can influence the quality of the tooth-restoration interface.

An important role in the quality of the tooth-restoration interface is played by the restorative material itself. Recently, bulk-fill composites have been introduced to increase the curing depth to up to 4 mm and minimize shrinkage stress. The manufacturers of these resin composites claim that the shrinkage stress of the materials is lower than that of either flowable or non-flowable traditional composites. Moorthy et al[23] reported that the minor shrinkage stress exhibited by bulk-fill flowable composites resulted in lower cuspal deflection compared to traditional composites placed using an oblique layering technique. In contrast, an in vitro study by Furness et al[12] showed that flowable and non-flowable bulk-fill materials resulted in proportions of gap-free external marginal interface similar to those of conventional composites. However, a paper by Oglakci et al[25] reported that different types of bulk-fill composite resins affected gap formation differently and that low-viscosity bulk-fill composites exhibited better adaptation to cavity walls.

Several layering techniques have also been proposed to optimize interfacial adaptation. These include incremental layering techniques[8,19] and the use of a liner with low elastic modulus.[20] A recent study by Alqudaihi et al[3] reported that an incremental technique is crucial for achieving high adaptation and reducing gap formation, even when using new bulk-fill composite materials.

Light-curing modes can also affect polymerization kinetics.[21] The process of resin composite polymerization involves a pre-gel and a post-gel phase. During the pre-gel phase, the reactive species can flow and undergo molecular rearrangement to compensate for the volumetric shrinkage without generating significant amounts of internal and interfacial stresses. When the resin reaches its post-gel phase, the formation of a semi-rigid polymer network hinders plastic deformation. The resin obtains a higher modulus of elasticity and transmits the stress generated by polymerization shrinkage to the tooth-restoration interface, potentially leading to several clinical disadvantages, such as postoperative sensitivity, microleakage, enamel cracking, cusp deflection, and marginal gaps. It has been reported that soft-start curing techniques lengthen the pre-gel phase, leading to a low monomer conversion rate, thus increasing material flow and improving shrinkage behavior and marginal adaptation.[28,42]

Despite the many studies on bulk-fill materials, there is no consensus on how they behave compared to traditional composites with regard to the volume of interfacial gaps. Moreover, little is known about the influence of horizontal or bulk layering strategies and conventional vs soft-start curing modes on the interfacial gap volume in cavities restored using bulk composites. Thus, the aim of the present in vitro study was to three-dimensionally evaluate interfacial gaps in deep Class-I cavities restored with different bulk materials, incremental layering strategies, and curing modes.

The null hypotheses are that the volume of interfacial gaps in deep Class-I restorations is not influenced by 1. the material used (conventional composite vs bulk fill composite), 2. the layering strategy (horizontal vs bulk), or 3. the curing mode (conventional vs soft start).

MATERIALS AND METHODS

Specimen Preparation

Ninety-six (n = 96) human molars extracted for periodontal reasons within the previous 3 months were selected and stored in distilled water after being disinfected with an ultrasonic device. The study was approved by the local ethics committee of the University of Turin Dental School (DS-2018 No. 001), Turin, Italy. The selected teeth had no previous restorations, carious lesions, demineralization, or cracks as observed under 20X magnification (optical microscope SZX9, Olympus Optical; Tokyo, Japan).

A single trained operator (>10 years of practice) performed a Class-I cavity preparation in each tooth, maintaining enamel margins along the entire cavity circumference and following standardized parameters: 3 mm (±0.1 mm) mesiodistally, 3 mm (±0.1 mm) oral-buccally, and 4 mm (±0.1 mm) deep. After preparation, each linear measurement was carefully checked using a periodontal probe.

All cavities were subjected to the same adhesive procedure: selective enamel etching for 30 s with 35% phosphoric acid (K-etchant, Kuraray Noritake; Tokyo, Japan), rinsing with water for 30 s, and air drying. A two-step self-etch adhesive (Clearfil SE Bond 2, Kuraray Noritake) was then applied following the manufacturer's instructions: primer applied for 20 s with a brush, dried for 5 s with a mild air flow, bonding agent applied then gentle air flow to make the layer uniform, light cured for 20 s with a multi-LED curing unit (Translux 2Wave, Heraeus Kulzer; Hanau, Germany) at 1400mW/cm^2.

Specimens were then divided into four groups (n = 24 each) according to the restorative material employed, following the respective manufacturer's instructions (except G4, SG3-4 that were used as control):

- Group 1, SDR: Surefill SDR (Dentsply Sirona; Konstanz, Germany). The cavity was restored with this flowable bulk-fill material. A setting time of 10 s was allowed before light curing to achieve optimal adaptation of the material to the cavity walls.
- Group 2, SF: SonicFill 2 (Kerr; Orange, CA, USA). The cavity was restored with this sonically applied (SonicFill Handpiece, Kerr) bulk-fill composite, selecting an extrusion speed of 2 for better control.
- Group 3, AFXT: Admira Fusion X-Tra (VOCO; Cuxhaven, Germany). The cavity was restored with this bulk-fill ormocer material. A special instrument (Composculp #3/4, Hu Friedy Italy; Milan, Italy) was used to compact the material and achieve proper adaptation.
- Group 4, FS: Filtek Supreme XTE (3M Oral Care; St Paul, MN, USA). The cavity was restored with this standard nanohybrid packable composite. The same special instrument as in group 3 (Composculp #3/4) was used to compact the material and achieve proper adaptation.

Table 1 Brand name, type, manufacturer, composition and volumetric shrinkage (%) of the materials used

Material	Type	Manufacturer	Composition	Volumetric shrinkage (%) and reference
Smart dentin replacement (SDR)	Flowable bulk-fill resin composite	Dentsply Sirona; Konstanz, Germany	Resin matrix: modified UDMA EBP-DMA, TEG-DMA Inorganic filler: barium and strontium fluoroaluminosilicate glasses (4.2 µm). Camphoroquinone, BHT, UV stabilizer, titanium dioxide, iron oxide 68 wt%, 44 vol%	3.38%[44]
SonicFill 2 (SF)	Sonically applied bulk-fill packable resin composite	Kerr; Orange, CA, USA	Resin matrix: bis-GMA, TEG-DMA, EBP-DMA Inorganic filler: SiO_2 glass oxide, barium glass, YbF_3, mixed oxide 81.3 wt%	2.03%[1]
Admira Fusion X-Tra (AFXT)	ORMOCER bulk-fill packable resin composite	VOCO; Cuxhaven, Germany	Resin matrix: ORMOCER (aromatic and aliphatic dimethacrilates, methacrylate-functionalized polysiloxane) Inorganic filler: Ba-Al-glass, pyrogenic SiO_2 Photoinitiator: camphoroquinone Synergist: NI 84 wt%, 78 vol%	1.24%[29]
Filtek Supreme XTE (FS)	Nanohybrid packable resin composite	3M Oral Care; St Paul, MN, USA	Resin matrix: bis-EMA, bis-GMA, UDMA, TEG-DMA, PEG-DMA. Inorganic filler: SiO_2 (20 nm), ZrO_2 (4–11 nm), aggregated ZrO_2/SiO_2 cluster filler 78.5 wt%, 63.3 vol%	1.21%[2]

Each group was further divided into four subgroups (n = 6) according to the layering technique and the polymerization mode. Polymerization was carried out with the same multi-LED curing unit (Translux 2Wave, Heraeus Kulzer) at 1400mW/cm^2:

- Subgroup 1 (SG1): The restoration was made by applying two horizontal layers, each 2 mm thick, which were each light cured for 20 s with a soft-start curing program (light intensity increased from 50% to 100% in 2 s).
- Subgroup 2 (SG2): The restoration was made by applying two horizontal layers, each 2 mm thick, which were each light cured for 20 s with a conventional program.
- Subgroup 3 (SG3): The restoration was made by applying a single bulk increment of composite, 4 mm thick, which was light cured with a soft-start curing program as described for SG1.
- Subgroup 4 (SG4): The restoration was made by applying a single bulk increment of composite, 4 mm thick, which was light cured with a conventional curing program as described for SG2.

Each layer was cured with the same multi-LED lamp (Translux 2Wave, Heraeus Kulzer) using either a conventional or a soft-start curing program. The curing tip was placed at a standardized distance of 3 mm from the occlusal surface of the specimen. A radiometer (CM-2500, DEI Italia; Varese, Italy) was used to monitor the curing lamp output at the beginning of each subgroup preparation. The surfaces were finished and polished with diamond burs and silicon points to obtain a smooth surface without over or under contouring.

A summary of the materials employed, including a manufacturer, type of material, composition, and volumetric shrinkage are presented in Table 1.

Micro-CT Scanning

After preparation, samples were stored in distilled water for 24 h before micro-CT scanning, taking care to avoid any light exposure during storage. After 24 h, samples were scanned using microcomputed tomography (micro-CT) (SkyScan 1172, Bruker; Billerica, MA, USA). High-resolution scans were performed using the following parameters: voltage = 100 kV; current = 100 µA; aluminum and copper (Al+Cu) filter; pixel size = 10 µm; averaging = 5; rotation step = 0.5 degrees. Images were reconstructed using NRecon software (Bruker) to obtain DICOM files with standardized parameters: beam hardening correction = 25%; smoothing = 2; ring artifact reduction = 7; total scan time = 55 min.

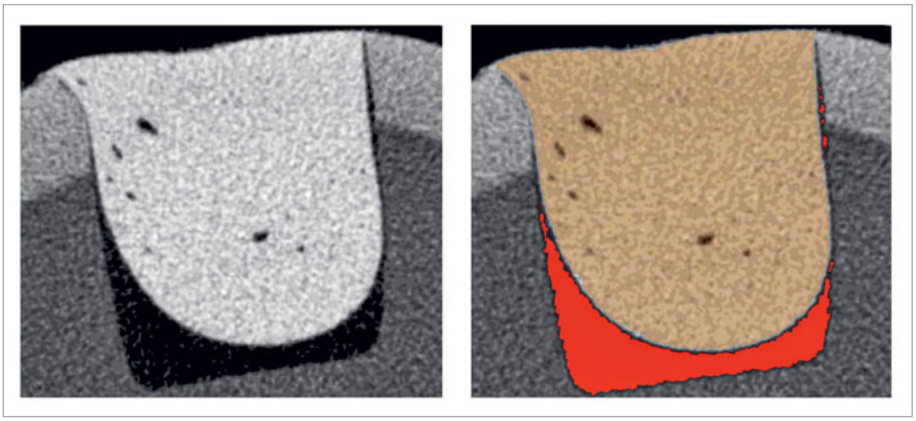

Fig 1 Representative image of the technique (control group G4, SG4). Random sample segmentation performed with Mimics software (v. 20.0, Materialise). The orange area represents the restoration, while the red one represents the analyzed void volume.

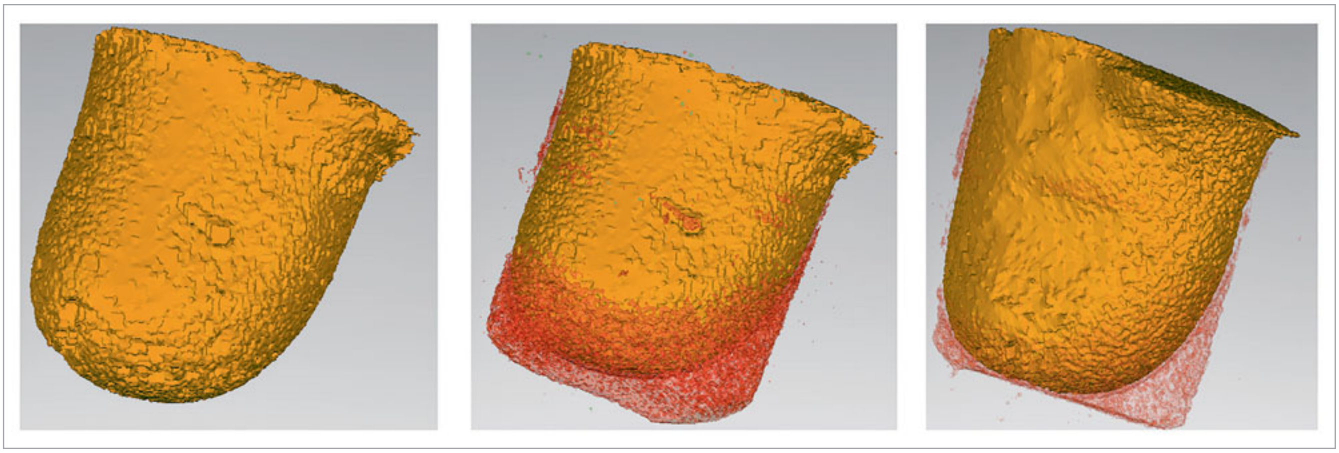

Fig 2 Representative image of the technique (control group G4, SG4). Three-dimensional rendering using Geomagic Studio 12 software (3D systems) of the same sample shown in Fig 1. The orange area represents the restoration, while the red area represents the analyzed void volume. The areas have different translucencies for better visualization.

Three-dimensional Interfacial Gap Analysis

A recently developed 3D method was used to analyze the volume of internal interfacial gaps.[34,35] Mimics software (v. 20.0, Materialise; Ann Arbor, MI, USA) was used to automatically perform the thresholding of voids surrounding the restoration within a 300-µm range with a Hounsfield unit (HU) range of 1,024 to 970 to maximize void visualization (Fig 1).

To ensure consistency across the data, the same protocol with the same HU parameters was applied to all samples. Standard Triangulation Language (.stl) files were then created at optimum quality (sampling ratio 1:1), and volumetric calculation of the resulting mask was performed on the .stl files using Geomagic Studio 12 software (3D Systems; Rock Hill, SC, USA). Volume data expressed in mm^3 were collected for all samples (Fig 2).

Statistical Analysis

To examine the effects of the variables “material,” “layering strategy,” “curing mode,” and their interactions on interfacial gap formation, a three-way ANOVA was conducted. Post-hoc pairwise comparison was performed using Tukey’s test.

A p-value < 0.05 was considered significant. All statistical analyses were performed using STATA software (12 v. 0, Stata; College Station, TX, USA).

RESULTS

Interfacial gap data, expressed as means and standard deviations, for soft-start curing (SG1 and SG3) and conventional curing (SG2 and SG4) modes are summarized in Table 2.

The results of three-way ANOVA showed significant differences between materials ($p < 0.001$), layering techniques ($p = 0.024$), and their interactions ($p < 0.001$). No significant differences were reported for the polymerization mode variable ($p = 0.21$). Tukey’s post-hoc test showed that FS performed significantly worse in terms of the volume of in-

Table 2 Summary of interfacial gap data, expressed as mean ± standard deviation (mm^3)

	SG1 (2+2mm, soft start)	SG2 (2+2mm, conventional program)	SG3 (4 mm, soft start)	SG4 (4 mm, conventional program)
SDR	0.031 ± 0.016^{aA}	0.052 ± 0.028^{aA}	0.133 ± 0.094^{aA}	0.058 ± 0.030^{aA}
SF	0.200 ± 0.093^{aA}	0.186 ± 0.104^{aA}	0.115 ± 0.037^{aA}	0.112 ± 0.046^{aA}
AFXT	0.152 ± 0.037^{aA}	0.125 ± 0.068^{aA}	0.062 ± 0.049^{aA}	0.079 ± 0.045^{aA}
FS	0.530 ± 0.161^{bA}	0.416 ± 0.135^{bA}	1200 ± 0.781^{bB}	0.740 ± 0.561^{bB}

Same superscript capital letters indicate no statistically significant differences between rows. Same superscript lowercase letters indicate no statistically significant differences between columns.

terfacial volumetric gaps than all other tested materials. Moreover, the FS 4-mm bulk subgroups performed significantly worse than the FS 2+2-mm layered subgroups. No significant differences were reported for bulk-fill materials in terms of layering technique.

The 3D-rendering of all restorations including interfacial gaps showed that in all samples, the cavity floor had the largest volume of interfacial gaps. On the other hand, cavity axial walls showed smaller interfacial gaps. Moreover, subgroup 1 showed a small number of gaps and air bubbles in the interface between the two layers. Figure 3 shows the interfacial gaps in a random sample from each group and subgroup.

DISCUSSION

Although there are strategies to reduce their extent, interfacial gaps are still a major issue that contribute to the failure of adhesive restorations. The present study investigated gap volume and location in deep Class-I restorations restored with different bulk-fill resin composites with different layering strategies and polymerization modes.

Over the last decade, different methods have been used to analyze interfacial gaps.[28,38] Optical coherence tomography (OCT) has recently been used for this purpose, sometimes combined with contrasting agents.[11,15,34] Initial limitations in detecting gaps in deep cavities, related to light transmission ability through dental tissues and materials, have been overcome in recent years with new techniques and equipment.[4] However, a review by Sahyoun et al[31] showed that image scaling, deformable registration, and fusion methods must still be implemented to superimpose OCT data onto 3D surfaces. Micro-CT imaging, which enables high-quality 3D reconstructions with a non-destructive approach,[24] is an alternative option for studying and evaluating interfacial gaps. However, micro-CT images are usually analyzed using linear measurements and two-dimensional reconstructions, which can lead to operator bias.[17,39] Recent studies have demonstrated a non-destructive, standardized 3D method for evaluating gaps, involving quantitative measurement of the gap volume without operator bias and qualitative evaluation of the gap location through 3D rendering.[32,34,35]

In previous studies, in deep Class-I cavities, incremental layering techniques have been recommended and are considered the gold standard.[20,40] However, restoring deep cavities with multiple increments of resin composite is time consuming and increases the risk of incorporating air bubbles or contaminants between the increments.[10]

Regarding the first null hypothesis, all bulk-fill materials tested showed lower interfacial gap volume compared to conventional nanohybrid composites, regardless of their formulation (packable or flowable). Thus, the first null hypothesis was rejected. This result contrasts with the findings Furness et al,[12] which showed that bulk-fill materials, both flowable and non-flowable, resulted in a similar proportion of gap-free marginal interface compared to a conventional composite. However, the two-dimensional evaluation of the adhesive interface via dye penetration methods might explain the discrepancy between their results and those of the present study, which found no gap-free surfaces in any sample. It is worth mentioning that the dye penetration technique enables evaluating infiltration at the hybrid layer, even if some limitations related to the two-dimensional technique itself have been reported.[9,13] Besides, 3D micro-CT analysis allows non-destructive observation at the interface and a more comprehensive analysis of the samples, which could result in a higher mean presence of gaps.[13] Another recent study by Sampaio et al[32] highlighted the fact that volumetric shrinkage and interfacial gap are related but do not completely correspond, since stress development depends on the molecular characteristics of the material itself.[11] Similarly, the present in vitro study shows that volumetric shrinkage is not linearly correlated with interfacial gaps, since mean shrinkage values reported in the literature did not correlate with interfacial gap volume results.

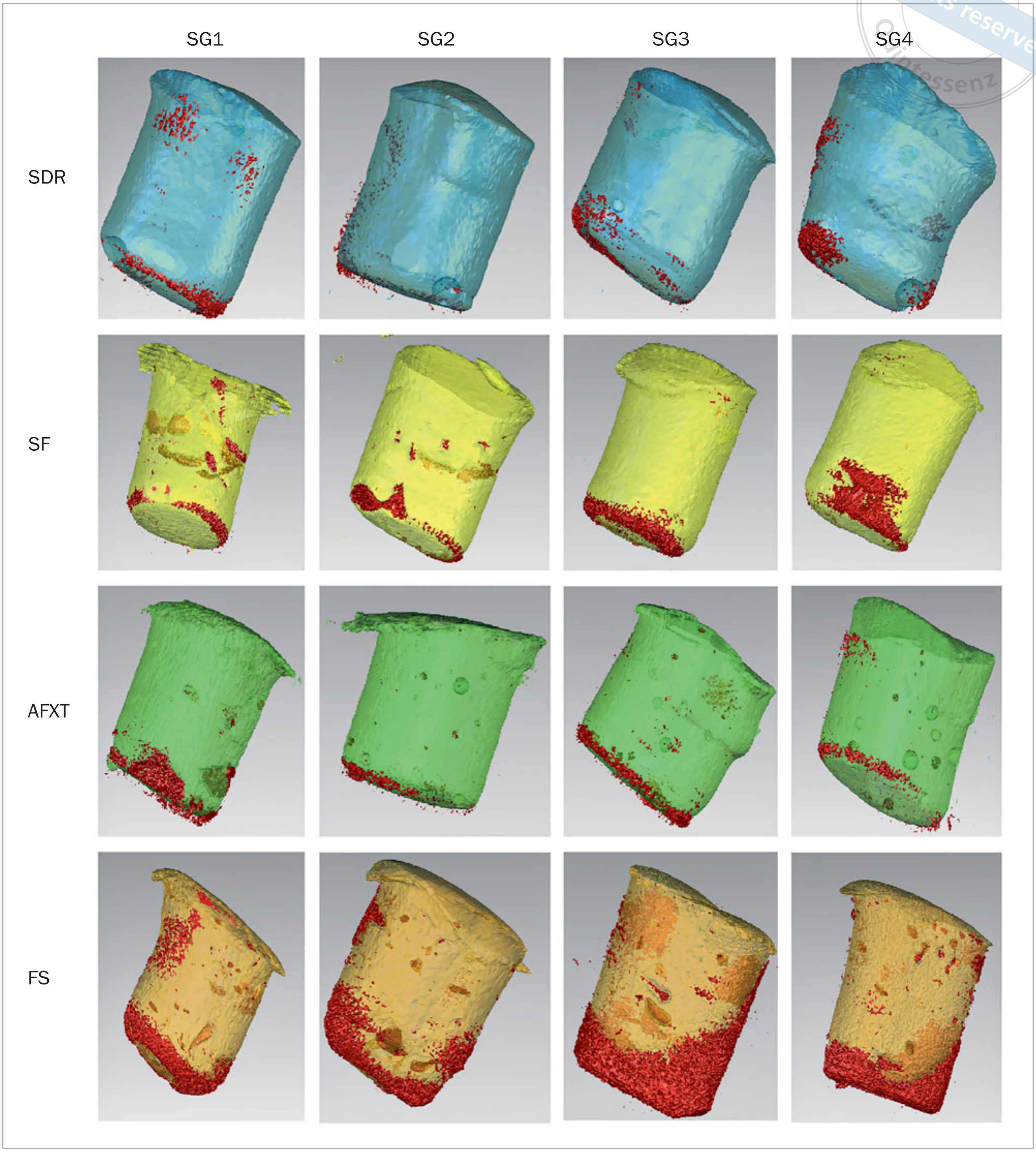

Fig 3 Representative image of the technique. Random samples from each group and subgroup. The red areas represent the gaps. It should be noted that internal bubbles were automatically excluded by filling voids in the mask of the composite, to focus the analysis specifically on the interface. The red area was analyzed by calculating the STL volume using Geomagic software.

Concerning the layering technique, the second null hypothesis was partially rejected, since layering statistically significantly influenced gap volume only in the FS group, when comparing 2+2-mm incremental layering to 4-mm bulk placement. These results are supported by recent in vitro (with SEM) and in vivo (with clinical sensitivity tests) studies, which have found that bulk layering with traditional composites is inferior to incremental layering.[20,21,26] This might also be related to the degree of conversion: it has been demonstrated that conventional composites cannot guarantee proper monomer conversion into polymer chains at a depth of 4 mm, whereas bulk-fill composites can.[43,44] The results of the present study are, therefore, in line with those of other papers, which reported that the layering technique significantly influences the performance of traditional nano-filled composites.[23,30] Regarding interfacial gaps, Haak et al[14] found no significant differences between traditional layered and bulk-fill composites in terms of marginal or internal gaps after artificial aging. However, this might be explained by the different cavity design and depth tested in their study. Moreover, micro-CT may more realistically analyze internal gaps, compared to slice sectioning, since the cutting procedure can produce biases and artifacts.

Since the curing mode did not significantly influence interfacial gap volume, the third null hypothesis was accepted. A recent review showed much discussion regarding whether a longer pre-gel phase, facilitated by ramp curing, and the consequently lower stress at the interface, is less important than other parameters in preventing interfacial gap formation.[21] Another review confirmed that even if the rationale for ramp curing is solid, there is no consensus on the advantages of different light-application protocols. Moreover, the paucity of clinical data available does not show whether such a light-curing protocol provides significant benefits at the adhesive interface.[37]

Finally, 3D rendering showed that interfacial gaps concentrated chiefly at the cavity floor in all groups. This may agree with the findings of Ausiello et al,[5] who reported a high concentration of stress in this area when applying shrinkage forces in a finite element analysis model, even if the present study did not focus on shrinkage stress itself but on interfacial gap volume between cavity walls and restorative materials. Hayashi et al[15] drew similar conclusions when using real-time OCT to analyze the sealing floor area percentage (SFA%).The previously cited study by Furness et al[12] also reported a significantly lower percentage of gap-free margins at the pulpal floor interface than at the enamel interface, which confirms that this might be the most affected area by interfacial gaps using bulk composites. However, one of the biases concerning gap volume at the bottom of the cavity could be operator experience in composite layering. Specifically designed studies should be conducted to better analyze the influence of operator experience on material adaptation to cavity floors. Further studies are needed to analyze microgaps three-dimensionally and determine how they might be effectively prevented.

CONCLUSIONS

The volume of interfacial gaps is not related to either the layering technique or the curing mode when using bulk-fill materials. Rather, it is influenced by the layering technique when using conventional resin composites, with incremental application leading to better performance. Gap volume was significantly lower in all tested bulk-fill materials compared to a conventional nanohybrid resin composite. Gaps were mostly concentrated at the cavity floor, regardless of the material employed.

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Clinical relevance: In deep class I restorations, the volume of interfacial gaps, which mainly concentrate at the cavity bottom, could be reduced with bulk-fill composites, independent of the layering technique and the curing mode.