Simulated cuspal deflection and mechanical properties of bulk-fill and conventional flowable resin composites

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Contents

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Summary

Resin composites have come to be considered the first-choice material for direct posterior restorations because of their improvements in the mechanical properties. However, volumetric shrinkage in the range from 1.5 to 5% were still reported with newly developed resin composites, including bulk-fill resin composites, and this volumetric shrinkage leads to the development of polymerization shrinkage stress as the resin composite is bonded to the tooth structures of the cavity. One of the methods for analyzing polymerization shrinkage stress of resin composites is measuring the simulated cuspal deflection using aluminium blocks with linear variable differential transformers (LVDT), but LVDT measurements are not widely used. Therefore, to find an alternative to the LVDT measurement, a method of simulated cuspal deflection resulting from the polymerization of resin composite bonded to a precisely prepared mesio-occlusal-distal (MOD) cavity within an aluminium block using a digimatic micrometer (micrometer) or a confocal laser scanning microscope (CLSM) was investigated in this study. This study aimed to evaluate methods for measuring the polymerization shrinkage stress of bulk-fill and conventional flowable resin composites by measuring simulated cuspal deflection and to compare these values with those of flexural properties.

Six bulk-fill flowable resin composites were evaluated: Bulk Base (BB), Beautifil Bulk Flowable (BF), Filtek Fill and Core Flowable Restorative (FF), SDR (SD), Tetric EvoFlow Bulk Fill (TE), and X-tra base (XB). Six conventional flowable resin composites were also evaluated: Clearfil Majesty ES Flow (CE), Clearfil Majesty LV (CM), Estelite Universal Flow (EU), Filtek Supreme Flowable Restorative (FS), G-ænial Universal Injectable (GI), and UniFil LoFlo Plus (UF). Aluminum blocks with an MOD cavity (4 [W] x 8 [L] x 4 [D] mm) were fabricated using a milling machine, creating two remaining cusps. The inside of the cavity was air abraded with 50

μm Al_2O_3 powder for 10 s to create microroughness for improved adhesion. A universal adhesive was applied prior to placing the resin composites. The aluminium blocks were randomly divided into four groups for different measurement techniques and were further subdivided according to the type of resin composite. Simulated cuspal deflection was calculated from the difference in the distance between the centers of the two remaining cusps prior to resin composite placement with universal adhesive and 10 min after polymerization, as measured by micrometer or CLSM. The flexural properties of the resin composites were measured using a three-point bending test at a crosshead speed of 1.0 mm/min according to the ISO 4049 specification. Scanning electron microscopy (SEM) observations of the polished surfaces of the resin composites were also conducted.

Two-way analysis of variance (ANOVA) was used to analyze cuspal deflection data followed by Tukey's post hoc honestly significant difference (HSD) test with a significance level of 0.05. Flexural strength and modulus data were analyzed using one-way ANOVA followed by the Tukey HSD test with a significance level of 0.05.

Simulated cuspal deflections of the resin composites were material dependent, ranging from 7.2 to 20.3 μm for micrometer and 7.6 to 20.6 μm for CLSM. There was no significant difference between the cuspal deflections measured using micrometer and using CLSM. In the bulk-fill flowable resin composites, SD, FF, and BB showed significantly lower cuspal deflection than did BF, TE, and XB. Simulated cuspal deflection of the conventional flowable resin composites was significantly higher than those of SD, FB, and BB, and most cuspal deflections were similar to those of BF, TE, and XB. The flexural strength of the resin composites ranged from 68.9 to 132.8 MPa, and the elastic modulus ranged from 2.0 to 7.4 GPa. There were statistically significant differences in flexural strength and elastic modulus depending on the material, regardless of the type of resin composite. The rank order was different for flexural properties and for simulated cuspal deflection. In the SEM observations, a wide variation of filler size and shape were observed in the resin composites.

Some resin composites used in this study showed significantly lower cuspal deflections because the resin matrix contains high molecular weight polymerization modulators. There was a lower ratio of functional groups for making double bonds through polymerization to molecular weight in comparison with a typical resin matrix, which is purported to reduce polymerization shrinkage. Thus, the results of the present study for cuspal deflection of resin composites appeared to have been mainly influenced by the modifications of the resin matrix. In the present study, a novel micrometer or CLSM cuspal deflection measurement method was used to measure the cuspal deflection of resin composites as a more accessible replacement for the LVDT method. There was no significant difference between the cuspal deflection measured using the micrometer and using the CLSM.

From the results of this study, following conclusions were obtained.

1. Simulated cuspal deflection of bulk-fill and conventional flowable resin composites might be measured using either a micrometer or CLSM.
2. Simulated cuspal deflections of bulk-fill flowable resin composites were material dependent, ranging from 7.2 to 20.2 μm for the micrometer and 7.6 to 19.9 μm for CLSM.
3. The flexural strengths of the bulk-fill flowable resin composites were material dependent, and ranged from 68.9 to 119.8 MPa, and the elastic modulus ranged from 2.0 to 7.2 GPa.
4. From the SEM observations, the resin composites used in this study were composed of a wide variety of fillers, and filler particle size and shape were material dependent.

Introduction

Resin composites have come to be considered the first-choice material for direct posterior restorations because of their improvements in the mechanical properties (1). However, Alvanforoush *et al.* (2) reported that the fracture rates of resin composite showed a notable increase depending on the increase in the number of cases of larger resin composite restorations in posterior teeth (1995-2005, 28.84%; 2006-2016, 39.07%) and it might be important to consider their mechanical properties when planning larger restorations. Thus, manufacturers have continued to develop resin composites with enhanced physical properties. During the formation of a highly crosslinked polymer, adequate polymerization of resin monomers is thought to be essential to attain superior physical properties in resin composites (3).

However, volumetric shrinkage in the range from 1.5% to 5% were still reported with newly developed resin composites (4), and this volumetric shrinkage leads to the development of polymerization shrinkage stress as the resin composite is bonded to the tooth structures of the cavity (5). Some researchers have reported that resin composites with higher mechanical properties typically demonstrated higher polymerization shrinkage stress (6–8), which suggested that modifying the formulation of resin composites to obtain higher mechanical properties may increase the risk of problems related to polymerization shrinkage stress. While the mechanisms of polymerization shrinkage stress development within resin composite restorations are quite complex, measurement of polymerization shrinkage stress have been researched extensively for 50 years and many researchers are still investigating the best methods for measuring the polymerization shrinkage stress of resin composites (5).

One of the methods for analyzing polymerization shrinkage stress of resin composites is measuring the simulated cuspal deflection using aluminium blocks with linear variable differential transformers (LVDT) developed by Park and others (9). The advantage of this measurement method is that the cuspal deflection during polymerization of resin composites can be measured in real time. However, LVDT measurements are not widely used, and most of the studies based on simulated cuspal deflection using LVDT have been conducted at a single research institute (9–11). Therefore, to find an alternative to the LVDT measurement, a method of simulated cuspal deflection resulting from the polymerization of resin composite bonded to a precisely prepared mesio-occlusal-distal (MOD) cavity within an aluminium block using a digimatic micrometer (micrometer; MDH-25M, Mitutoyo, Kawasaki, Japan) or a confocal laser scanning microscope (CLSM; VK-9710, Keyence, Osaka, Japan) was investigated in this study.

Recently, using bulk-fill flowable resin composites has expedited the restoration process by enabling increments for up to 4 mm in thickness to be light polymerized, thereby avoiding the time-consuming incremental filling technique (12). Manufacturers claim that the polymerization shrinkage stress of bulk-fill flowable resin composites may be reduced using advanced technology for the treatment of filler particles, monomer synthesis, and development of modulators to retard the polymerization rate (13). However, few independent studies have compared the cuspal deflection between bulk-fill and conventional flowable resin composites using different filling techniques.

This study aimed to evaluate the methods for measuring the polymerization shrinkage stress of bulk-fill and conventional flowable resin composites by measuring simulated cuspal deflection and to compare these values with those of flexural properties. The null hypotheses to be tested were; 1) there would be no differences in simulated cuspal deflection between bulk-fill and conventional flowable resin composites, 2) there would be no differences in the cuspal deflection of resin composites measured using different methods, and 3) there would be no relationship between simulated cuspal deflection and flexural properties for any measurement method.

Materials and Methods

1. Study materials

Six bulk-fill flowable resin composites were evaluated: 1) Bulk Base (BB; Sun Medical, Moriyama, Japan), 2) Beautifil Bulk Flowable (BF; Shofu, Kyoto, Japan), 3) Filtek Fill and Core Flowable Restorative (FF; 3M Oral Care, St. Paul, MN, USA), 4) SDR (SD; Dentsply Sirona, York, PA, USA), 5) Tetric EvoFlow Bulk Fill (TE; Ivoclar Vivadent, Shaan, Liechtenstein), and 6) X-tra base (XB; Voco, Cuxhaven, Germany). Six conventional flowable resin composites were also evaluated: 1) Clearfil Majesty ES Flow (CE; Kuraray Noritake Dental, Tokyo, Japan), 2) Clearfil Majesty LV (CM; Kuraray Noritake Dental), 3) Estelite Universal Flow (EU; Tokuyama Dental, Tokyo, Japan), 4) Filtek Supreme Flowable Restorative (FS; 3M Oral Care), 5) G-ænial Universal Injectable (GI; GC, Tokyo, Japan), and 6) UniFil LoFlo Plus (UF; GC). The tested materials are listed in Table 1 with their associated lot numbers and main components.

2. Simulated cuspal deflection measurement

Aluminum blocks (10 [W] x 8 [L] x 15 [D] mm) with an MOD cavity (4 [W] x 8 [L] x 4 [D] mm) were fabricated using a milling machine, creating two remaining cusps. The inside of the cavity was air abraded with 50 µm Al_2O_3 powder for 10 s to create microroughness for improved adhesion. The air pressure was set to 0.2 MPa, and the distance between the orifice and metal surface was approximately 10 mm (Jet Blast II, J. Morita Mfg., Osaka, Japan). A universal adhesive (Scotchbond Universal Adhesive, 3M Oral Care) was applied prior to placing the low-viscosity bulk-fill and conventional flowable resin composites according to the manufacturer's instructions. The adhesive was light cured for 10 s at a standardized distance of 1 mm using a quartz-tungsten-halogen (QTH) curing unit (Optilux 501, Demetron/Kerr, Danbury, CT, USA). The power density (700 mW/cm^2) of the QTH curing unit was confirmed using a dental radiometer (model 100, Demetron) prior to specimen preparation.

The aluminium blocks were randomly divided into four groups for different measurement techniques (micrometer vs CSLM) and were further subdivided according to the type of resin composite (bulk-fill vs conventional flowable resin composite).

Group 1 (Micrometer × Bulk-fill flowable resin composite): Bulk-fill flowable resin composites were placed in bulk and were light cured from the three exposed surfaces for 40 s each. Simulated cuspal deflection was calculated from the difference in the distance between the centers of the two remaining cusps prior to resin composite placement and 10 min after polymerization, as measured by a micrometer.

Group 2 (Micrometer × Conventional flowable resin composite): Conventional flowable resin composites were placed in two horizontal consecutive layers (2 mm each). Each increment was light cured from the three exposed surfaces for 40 s each to ensure that an identical curing time was maintained. Simulated cuspal deflection was measured in the same manner as in group 1.

Group 3 (CLSM × Bulk-fill flowable resin composite): Bulk-fill flowable resin composites were placed using the same method as in group 1. Simulated cuspal deflection was calculated from the distance between the center of the two remaining cusps prior to resin composite placement and 10 min after polymerization, as measured by a CLSM with built-in analysis software (VK-Analyzer, Keyence).

Group 4 (CLSM × Conventional flowable resin composite): Conventional flowable resin composites were placed in the same manner as in group 2. Simulated cuspal deflection was measured in the same manner as in group 3.

3. Flexural properties measurement

A Teflon split mold (2.0 [W] x 25 [L] x 2 [D] mm) was used to prepare the specimens, which minimized the stresses applied to the specimens during their retrieval. The top side of the mold was covered with a matrix strip, and the resin composites were pressed with a glass slide under a load of 5 N. The exit window of the QTH curing unit was placed against the glass plate at the center of the specimen, which was light cured for 40 s. Next, the exit window was moved to the section next to the center in such a way that the previous section was overlapped by approximately one-half. Light curing was performed by sequentially curing overlapping regions until the entire sample surface had been light cured. The hardened specimens were carefully removed from the mold after light curing, and #600-grit silicon carbide (SiC) papers (Struers, Cleveland, OH, USA) were used to polish the specimens to obtain smooth and flat surfaces. Fifteen specimens for each resin composite were prepared under ambient laboratory conditions of 23 ± 2˚C and 50 ± 10% relative humidity. Specimen dimensions were measured using a high-accuracy submicron digimatic caliper (ADS Digimatic Caliper CD-30AX, Mitutoyo), and the accepted specimen size was 2 ± 0.020 mm in width and height and 25 ± 0.025 mm in length. The specimens were immersed in distilled water in an incubator (IC802, Yamato Scientific, Tokyo, Japan) at 37˚C for 24 h.

The specimens for each resin composite underwent a three-point bending test on a universal testing machine (5500R, Instron, Norwood, MA, USA) at a crosshead speed of 1.0

mm/min until specimen fracture occurred as outlined in ISO 4049 (Dentistry-Polymer-based restorative materials). The stress-strain curve was used to determine the flexural strength in MPa and elastic modulus in GPa using a custom software package (Bluehill 2 ver. 2.5, Instron) linked directly to the testing machine.

4. Scanning electron microscopy observation

The polished surfaces of the resin composites underwent ultrastructural observation conducted through scanning electron microscopy (SEM). A Teflon mold with a diameter and height of 10.0 and 2.0 mm, respectively, was used to form the specimens of the resin composites. The mold was placed on a glass slide covered with a matrix strip, and the resin composites were placed into the mold using a condenser instrument. The top side of the mold was covered with a matrix strip, and the resin composites were pressed with a glass slide under a load of 5 N. The exit window of the QTH curing unit was placed against the glass slide, and the resin composite was light cured for 40 s. After light curing, the hardened specimens were removed from the mold and the specimens were immersed in distilled water in an incubator at 37˚C for 24 h. After storage in the incubator, the specimen surfaces were prepared and polished using a gradually increasing sequence (#320-, #600-, #1200-, #2000-, and #4000-grit) of SiC papers in a grinder/polisher (Minitech 333, Presi, Eybens, France). Finally, the surfaces were polished with a soft cloth using 1.0 μm grit diamond paste (DP-Paste, Struers, Ballerup, Denmark). To enhance the filler visibility, the polished surfaces were etched for 30 s with an argon ion-beam (EIS-200ER, Elionix) directed perpendicular to the surface at an accelerating voltage and ion current density of 1.0 kV and 0.4 mA/cm^2, respectively. Next, the surfaces were coated with a thin film of gold in a vacuum evaporator (Quick Coater SC-701, Sanyu Electron, Tokyo, Japan) and observed using field-emission SEM (ERA-8800FE, Elionix) with an operating voltage of 10 kV.

5. Statistical analysis

Two-way analysis of variance (ANOVA) was used to analyze cuspal deflection data using the factors 1) type of resin composite and 2) cuspal deflection measurement, followed by Tukey's post hoc honestly significant difference (HSD) test with a significance level of 0.05. Flexural strength and modulus data were analyzed using one-way ANOVA followed by the Tukey HSD test with a significance level of 0.05.

Results

1. Simulated cuspal deflection

Results for the simulated cuspal deflection of bulk-fill and conventional flowable resin composites using both the micrometer and CLSM are shown in Table 2. Simulated cuspal deflections of bulk-fill flowable resin composites were material dependent, ranging from 7.2 to 20.2 µm for the micrometer and 7.6 to 19.9 µm for CLSM. In the bulk-fill flowable resin composites, SD, FF, and BB showed significantly lower cuspal deflection than did BF, TE, and XB. Cuspal deflection of conventional flowable resin composites was also material dependent, ranging from 15.3 to 20.3 µm for the micrometer and 15.5 to 20.6 µm for CLSM. Simulated cuspal deflection of the conventional flowable resin composites was significantly higher than those of SD, FB, and BB, and most cuspal deflections were similar to those of BF, TE, and XB.

2. Flexural properties

The results for the flexural strength and elastic modulus of bulk-fill and conventional flowable resin composites are shown in Table 3. The flexural strength of the bulk-fill flowable resin composites ranged from 68.9 to 119.8 MPa, and the elastic modulus ranged from 2.0 to 7.2 GPa. For the conventional flowable resin composites, the flexural strength ranged from 79.9 to 132.8 MPa, and elastic modulus ranged from 3.3 to 7.4 GPa. There were statistically significant differences in flexural strength and elastic modulus depending on the material, regardless of the type of resin composite. The rank order was different for flexural properties and for simulated cuspal deflection.

3. SEM observation

Representative SEM micrographs of bulk-fill and conventional flowable resin composites are shown in Fig. 1. The resin composites were composed of a wide variety of fillers, and filler particle size and shape were material dependent. In the bulk-fill flowable resin composites, BF, BB, SD, TE and XB showed a wide size range (<1–5 μm for BF, BB and TE, <1–20 μm for SD, and <1–30 μm for XB) of irregular- shaped fillers, and FF showed relatively uniform, small-sized (<1–2 μm) irregular-shaped fillers. In the conventional flowable resin composites, CE showed a wide size range (<1–10 μm) of irregular-shaped fillers, and CM showed nonuniform, small-sized (<1 μm) irregular-shaped fillers and small-sized (1–4 μm) spherical-shaped fillers. Nonuniform, small-sized (<1 μm) spherical-shaped fillers for EU, and irregular-sized fillers for UF were observed, and some fillers were aggregated. FS showed a wide size range (<1–7 μm) of irregular-shaped fillers, and GI showed uniform, small-sized (<1 μm) irregular-shaped fillers.

Discussion

Some of the bulk-fill flowable resin composites (SD, FF, and BB) used in this study showed relatively lower simulated cuspal deflections than their conventional counterparts, and the cuspal deflections of BF, TE, and XB were similar to those for most conventional flowable resin composites, regardless of the measurement system. Thus, the first null hypothesis that there would be no differences in simulated cuspal deflection between bulk-fill and conventional flowable resin composites was partially rejected. A previous study reported that the cuspal deflection of resin composites using the bulk-filling technique was significantly higher than that with the incremental filling technique regardless of type of resin composite, implying that the bulk-filling technique led to significantly more cuspal deflection than did the incremental filling technique in those experiments (14). In the present study, the cuspal deflection of bulk-fill and conventional flowable resin composite was investigated using the filling technique specified in the manufacturers' instructions. Simulated cuspal deflection of bulk-fill flowable resin composites using the bulk-filling technique was lower than or similar to that of conventional flowable resin composites with the incremental filling technique.

The cuspal deflection of the tested resin composites was material dependent regardless of filling technique, which suggests that the cuspal deflection of resin composites is primarily influenced by their composition rather than the filling technique. In the SEM observations, a wide variation of filler type was seen in the resin composites, but there was no clear relationship among filler particle size, shape, and cuspal deflection. Although previous study reported an effect of filler particle size and shape on shrinkage stress (15), a systematic review of the polymerization shrinkage stress of resin composites found that modification of the resin matrix had the largest impact on minimizing stress development (16). SD, FB, and BB showed significantly lower cuspal deflection than did BF, TE, and XB because the resin matrix contains high molecular weight polymerization modulators. There was a lower ratio of functional groups for making double bonds through polymerization to molecular weight in comparison with a typical resin matrix, which is purported to reduce polymerization shrinkage (17). Thus, the results of the present study according to the cuspal deflection of bulk-fill resin composites appeared to have been mainly influenced by the modifications of the resin matrix.

In the present study, micrometer or CLSM were used to measure the cuspal deflection of resin composites as a more accessible replacement for the LVDT method. There was no significant difference between the cuspal deflection measured using micrometer and using CLSM. This was consistent with previous study with high viscosity resin composites (18). Hence, the second null hypothesis that there would be no difference in the cuspal deflection of resin composites measured with different methods was not rejected.

One of the concerns with using micrometer was the possible influence of instrument-related stress exerted on the aluminium block, while errors arising from the process of combining the scanned micrographs were a concern with CLSM; both of these factors could potentially influence the measured values. Simulated cuspal deflection measured with micrometer ranged from 7.2 to 20.3 μm and ranged from 7.6 to 20.6 μm for CLSM. Previous studies (6–8, 19) reported that cuspal deflection measured using an aluminium block with LVDT was approximately 5–30 μm, although differences in the wall thickness of aluminium and size of the trench made direct comparison difficult (8). If the micrometer did apply stress during the measurement period, it would be expected to cause a greater deformation of the block during the pre-polymerization measurement, especially prior to resin composite filling, which would lead to a lower cuspal deflection. However, this overestimation was not observed, suggesting that stress from the micrometer was not a significant factor. On the other hand, stitching individual micrographs together to form a complete three-dimensional rendering from CLSM could bias the values in either direction, but no such deviations were observed; thus, the original concerns did not appear to be justified.

During the experiment, a serious problem was noted with CLSM; it could not measure the cuspal deflection precisely after 10 min of polymerization because of the time required (5–8 min) for scanning. In this study, the measurement was conducted 10 min after polymerization based on a previous study; thus, the scanning duration is thought to have a minimal influence. However, the values of cuspal deflection slightly increased over a longer time period (6–8). There is a small possibility that the cuspal deflection measured with CLSM will be higher than that with micrometer, but this was not observed in the present study. Since there was no significant difference in the cuspal deflection of resin composites measured using different methods (micrometer vs CLSM), investigators may rely on these methods for measuring cuspal deflection. In comparison with the LVDT method, the micrometer may be more accessible and easier, and CLSM may allow for more automation in the process used to measure cuspal deflection. Overall, micrometer and CLSM measurement methods of cuspal deflection of the aluminium block may be effective for evaluating the polymerization shrinkage stress of resin composite restorations. Further research is needed to determine the best experimental setup for measuring cuspal deflection as an indicator of polymerization shrinkage stress.

The flexural strength and elastic modulus of resin composites were material dependent, but the rank order of the results was different from that of cuspal deflection. Therefore, the third null hypothesis that there would be no relationship between cuspal deflection and flexural properties for any measurement method was not rejected. Previous studies reported higher mechanical properties typically demonstrate higher polymerization shrinkage stress (6–8, 20). However, while the results did not directly support the results of cuspal deflection, they are not decisive evidence against a connection.

Conclusion

1. Simulated cuspal deflection of bulk-fill and conventional flowable resin composites might be measured using either a digimatic micrometer or CLSM.
2. Simulated cuspal deflections of bulk-fill flowable resin composites were material dependent, ranging from 7.2 to 20.2 µm for the micrometer and 7.6 to 19.9 µm for CLSM.
3. The flexural strengths of the bulk-fill flowable resin composites were material dependent, and ranged from 68.9 to 119.8 MPa, and the elastic modulus ranged from 2.0 to 7.2 GPa.
4. From the SEM observations, the resin composites used in this study were composed of a wide variety of fillers, and filler particle size and shape were material dependent.

References

1. Lynch CD, Opdam NJ, Hickel R, Brunton PA, Gurgan S, Kakaboura A, Shearer AC, Vanherle G, Wilson NHF, Academy of Operative Dentistry European Section (2014) Guidance on posterior resin composites: Academy of Operative Dentistry–European Section. J Dent 42, 377-383.
2. Alvanforoush N, Palamara J, Wong RH, Burrow MF (2017) Comparison between published clinical success of direct resin composite restorations in vital posterior teeth in 1995-2005 and 2006-2016 periods. Aust Dent J 62, 132-145.
3. Cramer NB, Stansbury JW, Bowman CN (2011) Recent advances and developments in composite dental restorative materials. J Dent Res 90, 402-416.
4. Tsujimoto A, Barkmeier WW, Takamizawa T, Latta MA, Miyazaki M (2016) Mechanical properties, volumetric shrinkage and depth of cure of short fiber-reinforced resin composite. Dent Mater J 35, 418-424.
5. Kaisarly D, Gezawi ME (2016) Polymerization shrinkage assessment of dental resin composites: A literature review. Odontology 104, 257-270.
6. Condon JR, Ferracane JL (2000) Assessing the effect of composite formulation on polymerization stress. J Am Dent Assoc 131, 497-503.
7. Ferracane JL (2005) Developing a more complete understanding of stresses produced in dental composites during polymerization. Dent Mater 21, 36-42.
8. Pfeifer CS, Ferracane JL, Sakaguchi RL, Braga RR (2008) Factors affecting photopolymerization stress in dental composites. J Dent Res 87, 1043-1047.
9. Park J, Chang J, Ferracane J, Lee IB (2008) How should composite be layered to reduce shrinkage stress: Incremental or bulk filling?. Dent Mater 24,1501-1505.

10. Kwon Y, Ferracane J, Lee IB (2012) Effect of layering methods, composite type, and flowable liner on the polymerization shrinkage stress of light cured composites. Dent Mater 28, 801-809.

11. Kim YJ, Kim R, Ferracane JL, Lee IB (2016) Influence of the compliance and layering method on the wall deflection of simulated cavities in bulk-fill composite restoration. Oper Dent 41, e183-e194.

12. Tsujimoto A, Barkmeier WW, Takamizawa T, Latta MA, Miyazaki M (2017) Depth of cure, flexural properties and volumetric shrinkage of low and high viscosity bulk-fill giomers and resin composites. Dent Mater J 36, 205-213.

13. Yu P, Yap A, Wang XY (2017) Degree of conversion and polymerization shrinkage of bulk-fill resin-based composites. Oper Dent 42, 82-89.

14. Tsujimoto A, Jurado CA, Barkmeier WW, Sayed ME, Takamizawa T, Latta MA, Miyazaki M, Garcia-Godoy F (2020) Effect of layering techniques on polymerization shrinkage stress of high- and low-viscosity bulk-fill resins. Oper Dent 45, 655-663.

15. Satterthwaite JD, Maisuria A, Vogel K, Watts DC (2012) Effect of resin-composite filler particle size and shape on shrinkage-stress. Dent Mater 28, 609-614.

16. Meereis CTW, Münchow EA, de Oliveira da Rosa WL, da Silva AF, Piva E (2018) Polymerization shrinkage stress of resin-based dental materials: A systematic review and meta-analyses of composition strategies. J Mech Behav Biomed Mater 82, 268-281.

17. Leprince JG, Palin WM, Vanacker J, Sabbagh J, Devaux J, Leloup G (2014) Physico-mechanical characteristics of commercially available bulk-fill composites. J Dent 42, 993-1000.

18. Tsujimoto A, Nagura Y, Barkmeier WW, Watanabe H, Johnson WW, Takamizawa T, Latta MA, Miyazaki M (2018) Simulated cuspal deflection and flexural properties of high viscosity bulk-fill and conventional resin composites. J Mech Behav Biomed Mater 87, 111-118.
19. Lee CH, Lee IB (2021) Effects of cuspal compliance and radiant emittance of LED light on the cuspal deflection of replicated tooth cavity. Dent Mater J 40, 827-834.
20. Ilie N, Hickel R (2011) Resin composite restorative materials. Aust Dent J 56, 59-66.

Tables and Figure

Table 1: Low viscosity bulk-fill and conventional flowable resin composites used in this study

Resin composite (Shade)	Type of resin composite (Code)	Resin matrix composition	Inorganic filler composition	Manufacturer (Lot No.)
Bulk Base (Universal)	Low viscosity bulk-fill resin composite (BB)	Bis-MPEPP, UDMA	Barium-silicate glass, strontium-fluoro-alumino-silicate glass	Sun Medical, Moriyama, Japan (RG12)
Beautifil Bulk Flowable (Dentin)	Low viscosity bulk-fill resin composite (BF)	Bis-GMA, Bis-MPEPP, TEGDMA, UDMA	Fluoro-alumino-silicate glass	Shofu, Kyoto, Japan (031719)
Filtek Fill and Core Flowable Restorative (A3)	Low viscosity bulk-fill resin composite (FF)	Bis-GMA, UDMA	Inorganic fillers	3M Oral Care, St. Paul, MN, USA (N863610)
SDR (Universal)	Low viscosity bulk-fill resin composite (SD)	Bis-EMA, modified TEGDMA, UDMA	Barium-fluoro-alumino-silicate glass, strontium-fluoro-alumino-silicate glass	Dentsply Sirona, York, PA, USA (1508033)
Tetric EvoFlow Bulk Fill (A3)	Low viscosity bulk-fill resin composite (TE)	Bis-EMA, Bis-GMA, UDMA	Silanated barium glass filler	Ivoclar Vivadent, Shaan, Liechtenstein (T31312)
X-tra base (Universal)	Low viscosity bulk-fill resin composite (XB)	Aliphatic dimethacrylate, Bis-EMA	Inorganic fillers	Voco, Cuxhaven,Germany (1208392)
Clearfil Majesty ES Flow (A3)	Conventional flowable resin composite (CE)	Hydrophobic aromatic dimethacrylate, TEGDMA	Silanated barium glass filler, slanated silica filler	Kuraray Noritake Dental, Tokyo, Japan (BA0207)
Clearfil Majesty LV (A3)	Conventional flowable resin composite (CM)	Hydrophobic aromatic dimethacrylate, TEGDMA	Silanated barium glass filler, slanated colloidal silica	Kuraray Noritake Dental (850029)
Estelite Universal Flow (A3)	Conventional flowable resin composite (EU)	Bis-GMA, Bis-MPEPP, TEGDMA, UDMA	Silica-zirconia filler	Tokuyama Dental, Tokyo, Japan (019957)
Filtek Supreme Flowable Restorative (A3)	Conventional flowable resin composite (FS)	Bis-GMA, Substituted dimethacrylate, TEGDMA	Silane treated cramic, silane treated silica, yterbium trifluoride	3M Oral Care (N838182)
G-ænial Universal Injectable (A2)	Conventional flowable resin composite (GI)	Bis-EMA, Dimethacrylate, UDMA	Strontium glass	GC, Tokyo, Japan (1702081)
UniFil LoFlo Plus (A2)	Conventional flowable resin composite (UF)	Dimethacrylate, UDMA	Fluoro-alumino-silicate glass	GC (1702161)

Table 2: Simulated cuspal deflection of low viscosity bulk-fill and conventional flowable resin composites

Rank order	Resin composite	Type of resin composite	Simulated cuspal deflection (μm)	
			Micrometer	CLSM
1	SD	Bulk-fill	7.2 (3.5)^{a,A}	7.6 (1.5)^{a,A}
2	FF	Bulk-fill	8.1 (1.6)^{a,A}	8.2 (1.4)^{a,A}
3	BB	Bulk-fill	10.9 (0.7)^{b,A}	11.1 (1.0)^{b,A}
4	TE	Bulk-fill	14.3 (1.6)^{c,A}	14.9 (1.0)^{c,A}
5	CE	Conventional	15.3 (2.6)^{c,A}	15.5 (0.6)^{c,A}
6	UF	Conventional	16.0 (3.8)^{c,A}	16.7 (0.9)^{c,A}
7	CM	Conventional	16.7 (2.1)^{c,A}	17.0 (1.1)^{c,A}
8	XB	Bulk-fill	17.2 (1.5)^{c,A}	16.8 (1.0)^{c,A}
9	GI	Conventional	19.8 (2.8)^{d,A}	19.6 (0.8)^{d,A}
10	FS	Conventional	20.1(0.4)^{d,A}	20.6 (1.0)^{d,A}
11	BF	Bulk-fill	20.2 (0.6)^{d,A}	19.9 (0.6)^{d,A}
12	EU	Conventional	20.3 (2.3)^{d,A}	20.3 (0.9)^{d,A}

Values in parenthesis are standard deviations (n=5).
Same small letter in same vertical column indicates no significant difference ($p>0.05$).
Same capital letter within individual rows indicates no significant difference ($p>0.05$).

Table 3: Flexural properties of low viscosity bulk-fill and conventional flowable resin composites

Rank order	Resin composite	Type of resin composite	Flexural strength (MPa)	Elastic modulus (GPa)
1	CM	Conventional	132.8 (9.2)^{a}	7.4 (0.5)^{a}
2	GI	Conventional	128.8 (8.5)^{a}	6.5 (0.4)^{b}
3	TE	Bulk-fill	119.8 (7.8)^{b}	5.2 (0.3)^{c}
4	FF	Bulk-fill	116.1 (6.7)^{b}	5.3 (0.4)^{c}
5	FS	Conventional	113.9 (7.2)^{b}	5.2 (0.4)^{c}
6	EU	Conventional	110.6 (7.1)^{b,c}	5.8 (0.4)^{c}
7	XB	Bulk-fill	110.4 (6.8)^{b,c}	5.0 (0.3)^{c}
8	SD	Bulk-fill	105.7 (6.9)^{c}	7.2 (0.5)^{a}
9	CE	Conventional	104.7 (7.3)^{c}	6.3 (0.5)^{b}
10	BF	Bulk-fill	102.1 (6.9)^{c}	6.3 (0.6)^{b}
11	UF	Conventional	79.9 (6.1)^{d}	3.3 (0.3)^{d}
12	BB	Bulk-fill	68.9 (5.4)^{e}	2.0 (0.2)^{e}

Values in parenthesis are standard deviations (n=15).
Same small letter in same vertical column indicates no significant difference (*p*>0.05).

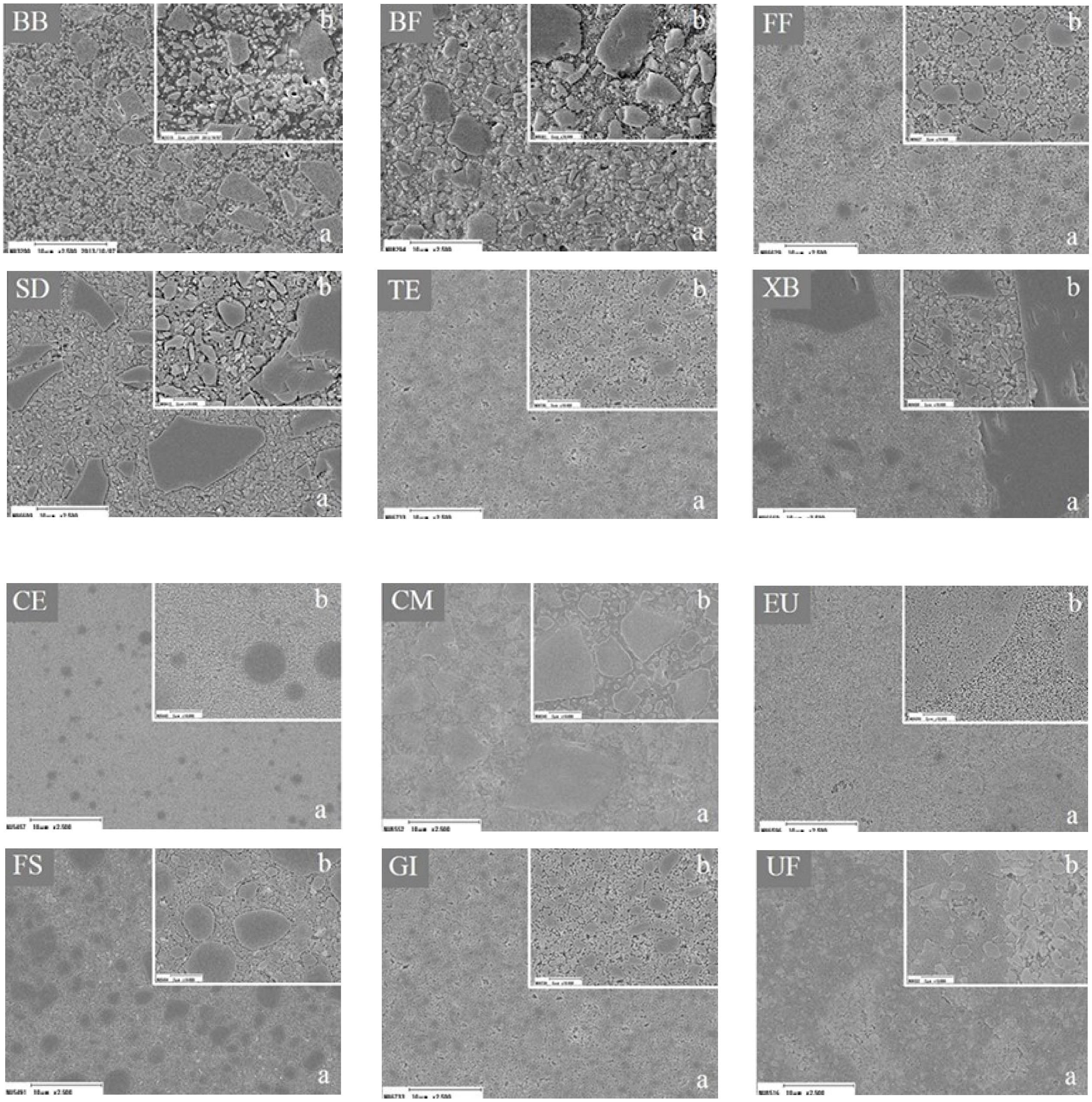

Fig. 1 Representative SEM images of the surfaces of bulk-fill and conventional flowable resin composites at (a) 2500x and (b) 10,000x magnifications. BB, Bulk Base; BF, Beautifil Bulk Flowable; FF, Filtek Fill and Core Flowable Restorative; SD, SDR; TE, TetricEvo Flow Bulk Fill; XB, X-tra base; CE, Clearfil Majesty ES Flow; CM, Clearfil Majesty LV; EU, Estelite Universal Flow; FS, Filtek Supreme Flowable Restorative; GI, G-ænial Universal Injectable; UF, UniFil LoFlo Plus.