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Comparison of Internal Adaptation in Class II Bulk-fill Composite Restorations Using Micro-CT

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Clinical Relevance

A flowable bulk-fill composite can demonstrate inferior internal adaptation compared with that of a packable bulk-fill composite. Internal adaptation may be worse at the gingival floor of the proximal box and at the pulpal floor of the cavity than it is at the buccal and lingual walls of the proximal box.

SUMMARY

Purpose: This study compared the internal adaptation of bulk-fill composite restorations in class II cavities and explored the relationship between internal adaptation and polymerization shrinkage or stress.

Methods and Materials: Standardized mesio-occluso-distal cavities were prepared in 40 extracted human third molars and randomly divided into five groups (n=8). After having been applied by total-etch XP bond (Dentsply Caulk, Milford, DE, USA) and light curing, the teeth were restored with the following resin composites: group 1, Filtek Z350 (3M ESPE, St. Paul, MN, USA); group 2, SDR (Dentsply Caulk, Milford, DE, USA) + Z350; group 3, Venus Bulk Fill (Heraeus Kulzer, Dormagen, Germany) + Z350; group 4, Tetric N-Ceram Bulk Fill (Ivoclar Vivadent, Schaan, Liechtenstein); and group 5, SonicFill (Kerr, West Collins, Orange, CA, USA). After thermo-mechanical load cycling, cross-sectional microcomputerized tomography (micro-CT) images were taken. Internal adaptation was measured as imperfect margin percentage (IM%), which was the percentage of defective margin length relative to whole margin length. On the micro-CT images, IM% was measured at five interfaces. Linear polymerization shrinkage (LS) and polymerization shrinkage stress (PS) were measured on each composite with a custom linometer and universal testing machine. To explore the correlation of IM% and LS or PS, the Pearson correlation test was used.

Results: The IM% of the gingival and pulpal cavity floors were inferior to those of the cavity walls. The IM% values of the groups were found to be as follows: group 5 $\leq$ groups 1 and 4 $\leq$ group 2 $\leq$ group 3. The correlation analysis showed that the p value was 0.006 between LS and IM% and 0.003 between PS and IM%, indicating significant correlations ($p<0.05$).

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Conclusion: Flowable bulk-fill composites had a higher IM% and polymerization shrinkage stress than did packable bulk-fill and hybrid composites. In class II composite restoration, the gingival floor of the proximal box and pulpal floor of the cavity had higher IM% than did the buccal and lingual walls of the proximal box. LS and PS, which were measured under compliance-allowed conditions, were significantly related to internal adaptation.

INTRODUCTION

To fill a large cavity with composite resin, the composite can be placed by incremental layering or bulk filling. To reduce polymerization shrinkage stress, the incremental technique has been recommended.[1] The incremental technique can be used to reduce C-factor and allow a certain amount of flow to decrease the shrinkage stress.[2,3] Bulk filling has been reported to yield significantly higher cuspal deflection than incremental filling when the composites were sufficiently cured.[4,5] The incremental filling technique showed higher bond strength to the floor in a large cavity than did the bulk filling technique.[2,6,7] A previous study compared microleakage of a composite restoration performed with the two techniques.[8] Gingival microleakage from bulk filling was significantly greater than that from incremental filling. Another reason for recommending an incremental technique is the compromised ability of light to penetrate the resin composite. Even when the composite surface is adequately cured, the base of composites thicker than 2 mm may not be completely polymerized, especially with micro- or nano-hybrid composites of a darker shade.[9-11]

In the last few years, new resin composites have been introduced for bulk filling. Bulk filling technology allows placement of up to 4- or 5-mm thick resin composite in a single fill, without compromising polymerization efficiency.[12,13] Bulk-fill resins can be divided into two categories: flowable and packable. The first bulk-fill materials on the market, such as SDR (Dentsply Caulk, Milford, DE, USA), Venus Bulk Fill (Heraeus Kulzer, Dormagen, Germany), x-tra base (Voco GmbH, Cuxhaven, Germany), and Filtek Bulk Fill (3M ESPE, St. Paul, MN, USA), needed a capping layer of micro- or nano-hybrid composite resin.[14] Later bulk-fill resins, like SonicFill (Kerr, West Collins, Orange, CA, USA), Tetric EvoCeram Bulk Fill (Ivoclar Vivadent, Schaan, Liechtenstein), and x-tra fil (Voco), can be placed without a capping layer. SonicFill can be placed with the help of a sonic-activated handpiece.

Many studies have evaluated microleakage from bulk-fill composite restorations.[15-17] Moorthy and others evaluated cuspal deflection and cervical microleakage on the margins of class II cavities that had been incrementally filled with composites or flowable bulk-fill resins.[15] They found that cuspal deflection was lower with flowable bulk-fill resin, whereas cervical microleakage did not differ between the composites. Roggendorf and others evaluated the marginal integrity of bonded composite resin fillings on mesio-occluso-distal (MOD) cavities with and without a flowable bulk-fill 4-mm base.[16] They inspected the marginal gap using scanning electron microscopy (SEM) and found no negative influence on marginal quality when a 4-mm layer of bulk-fill SDR was used. Campos and others investigated the marginal adaptation of bulk-fill composite restorations on class II mesio-occlusal cavities and concluded that bulk-fill materials do not allow better marginal adaptation than a standard composite resin applied by simple layering technique.[17]

Internal adaptation can be defined as how well a restoration adapts internally to the dental substrate. Internal refers to the location of the interface between a resin and tooth material inside. Internal adaptation may be related to hypersensitivity to cold or pain on mastication.[18] To evaluate internal adaptation or microleakage, dye and tracer penetration has been used.[19] However, the specimens need to be sectioned in these techniques, and this procedure might lead to false interfacial leakage.[19] The resin-dentin interface can also be examined by SEM after sectioning.[20] This method is very technique sensitive and has limitations with regard to quantitative assessment. Therefore, as a nondestructive method to evaluate internal adaptation, microcomputerized tomography (micro-CT) was introduced.[21] The two-dimensional (2D) information from micro-CT can be reconstructed into three dimensions to evaluate internal adaptation.[22,23] Because micro-CT is nondestructive, a specimen can be evaluated repeatedly before and after aging.[24] Due to the penetrating capacity of x-rays, micro-CT can be used to examine the internal aspects of a restoration irrespective of a specimen's shape or dimensions.

Because flowable resin was introduced as a restorative material, the advantages of flowable resin as a base material compared with composite restoration have been questioned. The rheology of flowable resins could allow better adaptation to cavity walls.[25] Flowable resin layers have been suggested to act as a stress-absorbing layer.[26]

Kwon and Park reported that the use of flowable composites of low elastic modulus as the base material could reduce marginal defects in overlying composite restorations.[27] Braga and others reported that using a flowable resin composite as a restorative material is not likely to reduce the effects of polymerization stress.[28] Therefore, it has been questioned if placing a base of flowable bulk-fill resin could improve internal adaptation at the resin-tooth interface.

The purpose of this study was to compare the internal adaptation of class II resin restorations filled with different bulk-fill resins. Internal adaptation was compared to analyze differences depending on location or material. We also investigated whether internal adaptation was correlated with polymerization shrinkage or stress.

The null hypotheses of this study were (1) the internal adaptation of class II composite restorations did not differ at different resin-tooth interface locations; (2) the internal adaptation of class II composite restorations did not differ with different bulk-fill composite materials; and (3) the internal adaptation was not correlated with the linear polymerization shrinkage or polymerization stress of the resin composite.

METHODS AND MATERIALS

Specimen Preparation

Forty caries-free, sound, lower third molars that had been extracted within the three previous months were collected and stored in 0.5% chloramine solution. The sizes of the specimen teeth were controlled so that the differences in bucco-lingual and mesio-distal length were less than 1 mm. The teeth were randomly divided into five groups, and standard MOD cavities were prepared with diamond burs (959 KR 018; Komet Dental, Lemgo, Germany). The cavity was 4.5 mm deep in the central fossa area, and the bucco-lingual isthmus was 3.5 mm wide. The proximal box of the cavity was prepared on the mesial side of the tooth. The cervical margin of the mesial proximal box was 1 mm below the cemento-enamel junction (CEJ), and the cervical margin of the distal proximal surface was 1 mm above the CEJ. Cavity dimensions were controlled by meticulously preparing the teeth with a magnifying glass and digital caliper. After the teeth were prepared, all roots were resected at 2 mm below the CEJ. Detailed dimensions of the cavity are depicted in Figures 1 and 2.

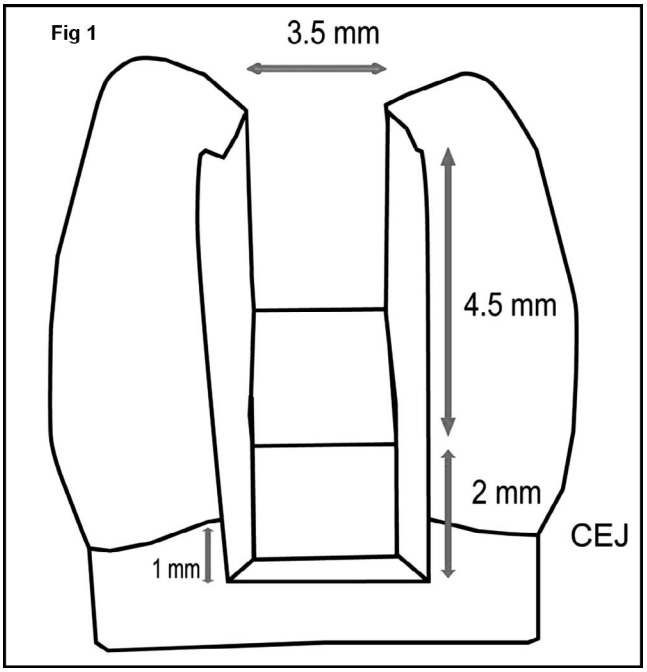

Figure 1. *Tooth preparation from the mesial view.*

Base and Composite Filling

The materials used in this study are shown in Table 1. All specimens were cleaned with distilled water after they were prepared. Enamel margins were etched with 34% phosphoric acid (Dentsply Caulk) for 15 seconds, irrigated with distilled water for 15 seconds, and then air-dried for 15 seconds according to the manufacturer's instructions. After XP bond (Dentsply Caulk) was applied to each cavity, the resin was light-cured 1 mm away from the occlusal, mesial, and distal sides for 20 seconds each with an LED-type light source (Bluephase, 800 mW/cm^2, Ivoclar Vivadent). Resin composite was placed after the adhesive treatment. Five different resin composites were used.

Group 1 (Z3, Control Group)—The control group was restored with a nano-hybrid composite, and the filling technique used was incremental layering. After the ivory retainer and matrix were applied to the tooth specimen, Filtek Z350 composite resin (A3, 3M ESPE) was applied. The first 2-mm increment was placed in the mesial proximal box and light-cured for 20 seconds from the occlusal side. The second and third 2-mm increments were placed in the mesial proximal box and the pulpal floor, respectively, and then light-cured for 20 seconds each from the occlusal side. The fourth and fifth increments were placed in the mesial and distal half of the remaining cavity, respectively, and were light-

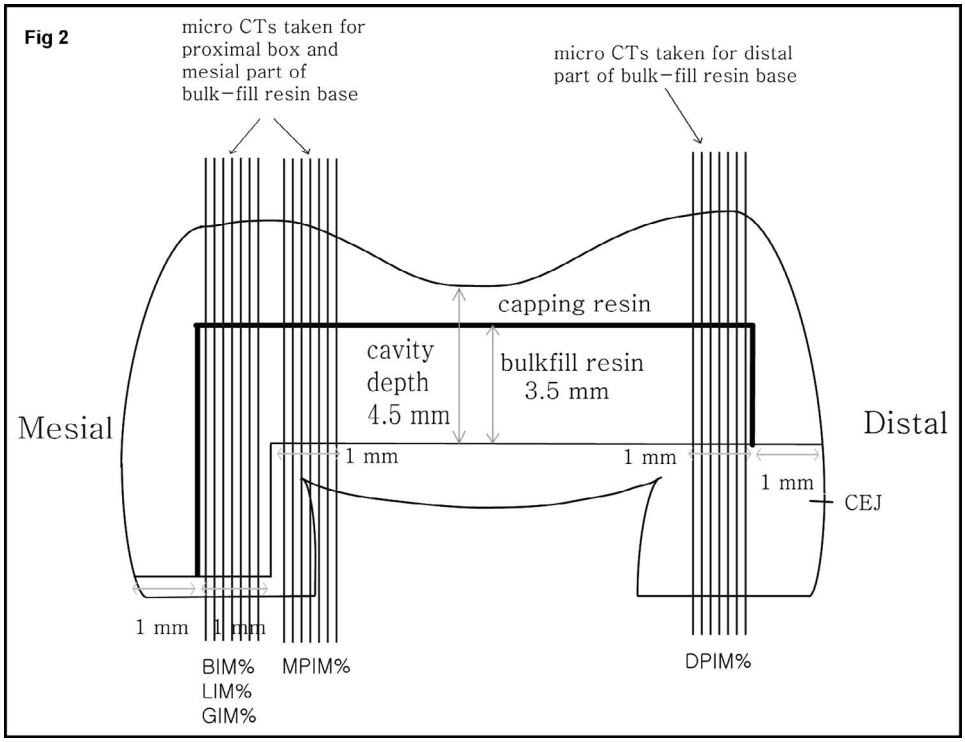

Figure 2. *Bulk-fill resin placement and locations where micro-CT images were taken. BIM%, buccal wall imperfect margin %; LIM%, lingual wall imperfect margin %; GIM%, gingival floor imperfect margin %; MPIM%, mesial pulpal floor imperfect margin %; DPIM%, distal pulpal floor imperfect margin %; CEJ, cemento-enamel junction.*

cured for 20 seconds each from the occlusal side. After removing the retainer and matrix, additional light-curing was applied from the buccal and lingual sides of the mesial and distal cavities (20 seconds × 2 for mesial side and 20 seconds × 2 for distal side).

Group 2 (SD, Flowable Bulk-fill Resin) and Group 3 (VB, Flowable Bulk-fill Resin)—After an ivory retainer and matrix band were placed on the specimen, flowable bulk-fill resin was used to fill the base portion of each cavity. For group 2, SDR (Dentsply Caulk) bulk-fill resin was placed on the mesial proximal box and light-cured. Resin was then placed on the pulpal floor at a thickness of 3.5 mm and light-cured (Figure 2). The base materials and cavity walls were refined with a fine diamond bur, hand instruments, and digital calipers to control the base thickness. After the refining process, the base surface was cleaned with cotton and dry air. Z350 composite was added to the remaining cavity: first on the mesial proximal, second on the distal proximal, third on the mesial cusp portion, and fourth on the distal cusp portion. Light-curing was performed for 20 seconds after each application. After removing the retainer and matrix, additional light-curing was performed from the buccal and lingual sides of the mesial and distal cavities (20 seconds × 2 for mesial side and 20 seconds × 2 for distal side). For group 3, Venus Bulk Fill (Heraeus Kulzer) was placed as the base material. The base dimension, refining, and light-curing processes were the same as for group 2. A capping layer of Z350 composite was added to the

Table 1: *Compositions of Resin Composites in This Study*[a]

Code	Product	Manufacturer	Base resin	Filler (wt/vol.%)
Z3	Filtek Z350	3M ESPE, St Paul, MN, USA	Bis-GMA/EMA, UDMA	78.5/59.5%
SD	SDR	Dentsply Caulk, Milford, DE, USA	Modified urethane dimethacrylate	68/44%
			EBPADMA/ TEGDMA	
VB	Venus Bulk Fill	Heraeus Kulzer, Dormagen, Germany	UDMA, EBPDMA	65/38%
TB	Tetric N-Ceram Bulk Fill	Ivoclar Vivadent, Schaan, Liechtenstein	Bis-GMA, UDMA	78/55% (including prepolymer)
			Dimethacrylate co-monomers	
SF	SonicFill	Kerr, West Collins, Orange, CA, USA	Bis-GMA, TEGDMA, EBPDMA	83.5/68%

[a] *Composition and filler percentages are from the manufacturers.*
Abbreviations: BIS-EMA, ethoxylated bisphenol A dimethacrylate; BIS-GMA, bisphenol A glycidyl methacrylate; EBPDMA, ethoxylated bisphenol A dimethacrylate; TEGDMA, triethyleneglycol dimethacrylate; UDMA, urethane dimethacrylate.

remaining cavity. Light-curing was performed for 20 seconds after each application. After removing the retainer and matrix, additional light-curing was performed from the buccal and lingual sides of the mesial and distal cavities (20 seconds × 2 for mesial side and 20 seconds × 2 for distal side).

Group 4 (TB, Packable Bulk-fill Resin) and Group 5 (SF, Packable Bulk-fill Resin)—After an ivory retainer and matrix band were placed on the specimen, packable bulk-fill resin was used to fill each cavity in groups 4 and 5. For group 4, Tetric N-Ceram Bulk Fill (Ivoclar Vivadent) was placed with hand instruments at the same dimensions as in groups 2 and 3, followed by light-curing for 20 seconds. Another layer of Tetric N-Ceram Bulk Fill composite was added to the remaining cavity and light-cured in the same way as with groups 2 and 3. For group 5, SonicFill (Kerr) was applied as filler with a sonically activated handpiece following the manufacturer's instructions. After SonicFill resin was filled to the full cavity depth, light-curing was performed for 20 seconds. After removing the retainer and matrix, additional light-curing was applied from the buccal and lingual sides of the mesial and distal cavities (20 seconds × 2 for mesial side and 20 seconds × 2 for distal side).

Thermo-mechanical Load Cycling

After storing in water for 24 hours, the specimens were mechanically loaded with a chewing simulator CS-4.8 (SD Mechatronik, Feldkirchen-Westerham, Germany). They were then simultaneously thermocycled under thermodynamic conditions (5-55°C, with a dwell-time of 60 seconds and a transfer time of 24 seconds) and a mechanical load of 5 kgf (49 N) for 600,000 cycles. A conical-shaped opposing plunger made of nickel-chromium was initially positioned at the center of the restoration. A 5-kgf load was applied from the top surface and pressed into the center of the tooth. In the Zurich wear testing study, a 5-kgf (49 N) load applied for 1,200,000 cycles with thermo-cycling of 5-55°C was equivalent to five years of service *in vivo*.[29] The rod moved 6 mm vertically and 0.3 mm horizontally. The rising speed was 55 mm/s, whereas the descending speed was 30 mm/s. After thermo-mechanical loading, the samples were stored in distilled water at room temperature.

Silver Nitrate Infiltration

Silver nitrate was used to fill microgaps.[24] Precipitated silver nitrate functioned as a contrasting medium on x-ray images.[30] The specimens were soaked in 17% EDTA for five minutes to remove the smear layer. Then they were rinsed with distilled water. The teeth were completely immersed in a 25% ammoniacal silver nitrate solution and placed under 3.75-kPa pressure, upside down, for 3 days. This step facilitated silver nitrate infiltration from the pulp chamber into the cavity floor. The specimens were then rinsed thoroughly with distilled water and kept in water at room temperature.

Micro-CT Imaging

Thirty cross-sectional micro-CT images were taken of each specimen. Ten micro-CT images of the proximal box were taken, extending from the mesial end of the bulk filled base to the axial wall of the proximal box at 90-μm intervals (Figure 2). Ten micro-CT images were taken at the mesial end of the bulk filled cavity floor. The last 10 micro-CT images were taken from the distal end of the bulk filled base toward the center of the cavity at the same interval (Figure 2). A high-resolution micro-CT (Model 1076, Skyscan, Aartselaar, Belgium) was used to obtain images. The imaging settings were as follows: acceleration voltage, 100 kV; beam current, 100 μA; Al filter, 0.5 mm; resolution, 18 μm; and rotation, 360° in 0.5° steps. Each tooth was mounted on a specially designed jig for uniform imaging. The 2D images were analyzed with image analysis software (ImageJ ver. 1.46, National Institutes of Health, Bethesda, MD, USA).

Evaluation of Internal Adaptation

To evaluate internal adaptation, the silver spots that were present between the tooth and restoration were measured on the micro-CT images. All the images were captured from the mesial point of view. Figure 3 shows an image at the mesial proximal box, and Figure 4 shows an image taken at a nonproximal box portion of the cavity. To evaluate internal adaptation, a previously reported method was applied.[30]

The imperfect margin percentage (IM%) was calculated by dividing total length where silver nitrate had penetrated the microgap by the entire length of the wall or floor. The local IM% was calculated for each image. On the proximal box images, the buccal wall imperfect margin percentage (BIM%), lingual wall imperfect margin percentage (LIM%), and gingival floor imperfect margin percentage (GIM%) were measured (Figures 2 and 3). Mesial pulpal floor imperfect margin percentage (MPIM%) was measured from micro-CT images captured from the mesial end of pulpal floor 1 mm toward the center of the cavity (Figures 2 and 4). Distal pulpal floor imperfect margin percentage

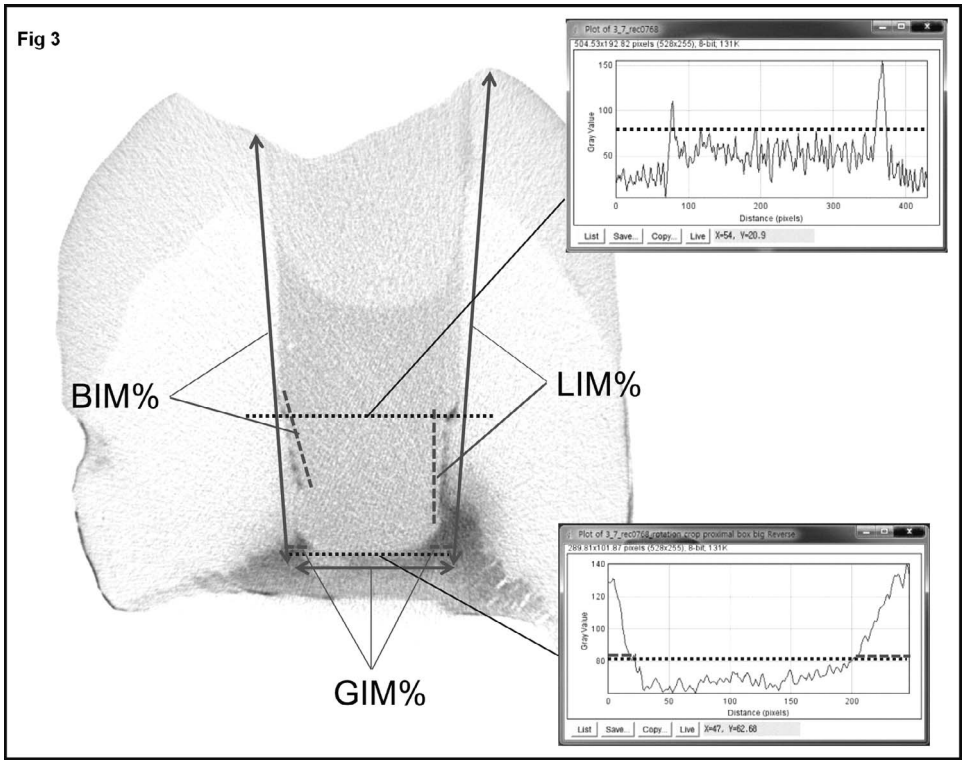

Figure 3. *Measurement of the imperfect margin for BIM%, LIM%, and GIM% on micro-CT. BIM%, buccal wall imperfect margin %; LIM%, lingual wall imperfect margin %; GIM%, gingival floor imperfect margin %. The plot profile shows the intensity of the pixels along the horizontal axis. The plot profile function in ImageJ shows a gray density of the selected line or area. Dentin exhibits a gray density of 20-40, bulk-fill resin has a gray density of 40-70, and the silver nitrate infiltrating gaps shows a gray density of >80 (upper right inset). Intensity >80 was regarded as a critical value for determining the imperfect area (lower right inset).*

(DPIM%) was measured on micro-CT images captured from the distal end of the bulk-filled base.

To verify any correlation between polymerization shrinkage and internal adaptation, the total imperfect margin percentage (TIM%) was calculated, defined as the total imperfect margins on the buccal wall, lingual wall, gingival floor, mesial pulpal floor, and distal pulpal floor divided by the sum of all internal margins in a specimen.

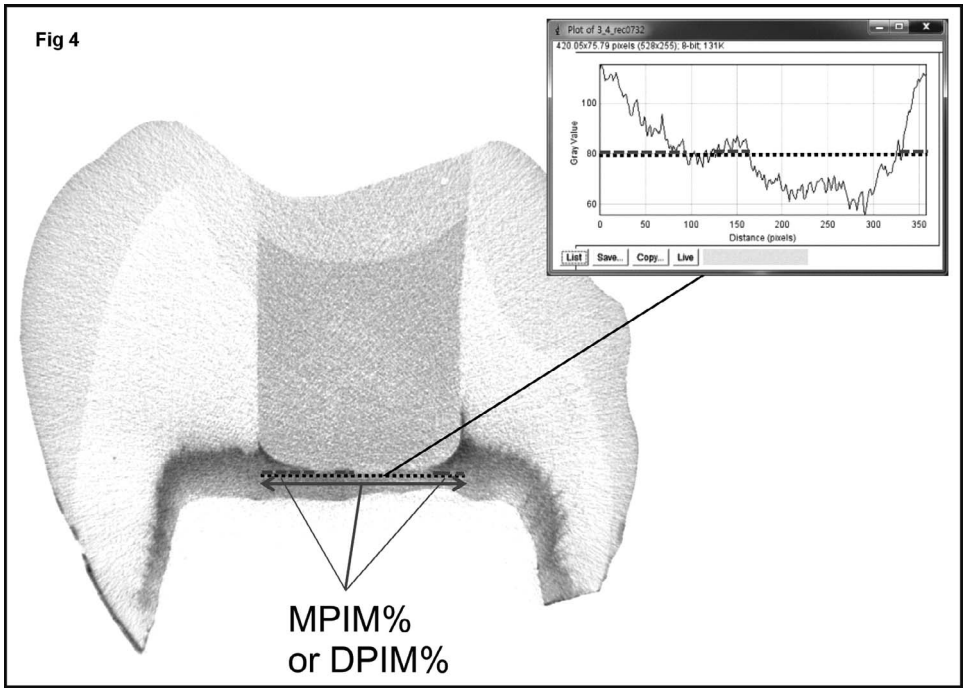

Figure 4. *Measurement of the imperfect margin for MPIM% and DPIM% on the pulpal floor of the cavity. MPIM%, mesial pulpal floor imperfect margin %; DPIM%, distal pulpal floor imperfect margin %. The plot profile shows the intensity of the pixels along the horizontal axis. Intensity >80 was regarded as a critical value for determining the imperfect area (upper right inset).*

Table 2: *Physical Properties of the Resin Composites Used in This Study*[a]

Group	Flexural modulus (GPa)[b]	Linear polymerization shrinkage (%)	Polymerization shrinkage stress (MPa)
1(Z3)	6.32 (0.65)^{D}	1.36 (0.10)^{A}	2.19 (0.12)^{A,B}
2(SD)	3.04 (0.63)^{B}	1.78 (0.12)^{B}	3.02 (0.17)^{C}
3(VB)	1.10 (0.15)^{A}	2.27 (0.11)^{C}	3.46 (0.18)^{D}
4(TB)	5.33 (0.43)^{C}	1.20 (0.09)^{A}	2.03 (0.12)^{A,B}
5(SF)	6.03 (0.45)^{C,D}	1.21 (0.12)^{A}	1.86 (0.15)^{A}

[a] *Polymerization stress was measured under a compliance-allowed condition. Numbers in parentheses are SDs. Identical letters within each column indicate no statistically significant difference among groups,* $p > 0.05$ *(compared vertically).*
[b] *Flexural modulus measurements were adopted from the literature.*

The definitions of the terms are as follows: BIM%, buccal wall imperfect margin percentage = (length of the buccal wall of the proximal box that was penetrated by silver nitrate/height of the buccal wall of the proximal box) × 100; LIM%, lingual wall imperfect margin percentage = (length of the lingual wall of the proximal box that was penetrated by silver nitrate/height of lingual wall of the proximal box) × 100; GIM%, gingival floor imperfect margin percentage = (length of the gingival floor of the proximal box that was penetrated by silver nitrate/width of gingival floor of proximal box) × 100; MPIM%, mesial pulpal floor imperfect margin percentage = (length of the mesial pulpal floor of the occlusal cavity that was penetrated by silver nitrate/width of pulpal floor of the cavity) × 100; DPIM%, distal pulpal floor imperfect margin percentage = (length of the distal pulpal floor of the occlusal cavity that was penetrated by silver nitrate/width of pulpal floor of the cavity) × 100; TIM%, total imperfect margin percentage = (sum of the imperfect margin measurements on the buccal wall, lingual wall, gingival floor, mesial pulpal floor, distal pulpal floor/total length of all internal margins) × 100.

Measuring Polymerization Linear Shrinkage of Resin Composite (LS)

Polymerization shrinkage strain was measured with a custom-made Linometer (R&B Inc, Daejon, Korea).[24] Glycerin gel was applied to a metallic disc and a portion of a glass slide to prevent adhesion to the resin. Resin composites were measured in a custom Teflon mold to ensure that the same amount of composite resin (0.07 g, 29.45 mm^2; 5 mm diameter x 1.5 mm high disc) was used for each linometer sample. The composite was then transferred to the thin metallic discs, covered with a glass slide, and positioned under constant pressure from a screw. An LED-type light-curing unit (Bluephase, Ivoclar Vivadent) with a power density of 800 mW/cm^2 was placed 1 mm above the glass slide, and the material was light-cured for 30 seconds. As the resin composite under the glass slide was cured, the aluminum disk moved upward. The disc displacement due to linear shrinkage of the resin composite was measured with an eddy current sensor every 0.5 seconds for 180 seconds. This measurement was repeated five times for each material, and the average was calculated (Table 2).

Measurement of Polymerization Shrinkage Stress Under a Compliance-allowed Condition (PS)

The polymerization shrinkage stress of the resin composite was measured with a custom-made device and software (R&B Inc). The instrument was driven by a motor and was devised to move a load bar up and down. The polymerization shrinkage stress applied to the bar was measured by a load cell (Model UM-K100, capacity 100 kgf, Dacell, Chungcheongbuk-do, South Korea) connected to the bar. The composite was placed between an acrylic disc, which was screwed to the load bar, and a transparent cylinder. Light to polymerize the resin composite was projected from beneath the transparent cylinder. The entire process was controlled by software by R&B Inc.

The surface of the acrylic disk was roughened with sandpaper before it was screwed to the load bar. The surface was coated with adhesive resin (Bond, Clearfil SE Bond, Kuraray Noritake Dental, Okayama, Japan) and light-cured for 20 seconds. To measure polymerization stress, a Teflon mold was used to measure a consistent amount of resin composite (0.03 g, 7.07 mm^2; 3-mm-diameter × 1-mm-high disc). The composite was placed on the acrylic disc, and the load bar screwed to the disk was moved so that the composite specimen formed a disk with a 1-mm thickness and a 3-mm diameter. Before measurements, the setup was switched to compliance-allowed mode in which the feedback system was not activated. The compliance of the system was 0.3 μm/N. The stress between the tension rod and the

Table 3: *Internal Adaptation Depending on Cavity Location (Result of One-Way ANOVA)*

Interface location	N	Subset[a]	
		1	2
Lingual wall (LIM%)	40	26.2175	
Buccal wall (BIM%)	40	26.6197	
Distal pulpal floor (DPIM%)	40		38.8276
Gingival floor (GIM%)	40		40.5827
Mesial pulpal floor (MPIM%)	40		41.6917

[a] *Subset 1 differed significantly from subset 2 (one-way ANOVA, p<0.05). In both subsets 1 and 2, there was no statistical difference between or among locations (p>0.05).*

Table 4: *Internal Adaptation of Groups (TIM%) (Results of One-Way ANOVA)*

Group	N	Subset[a]		
		1	2	3
5 (SF)	40	30.1221		
1 (Z3)	40	32.8954	32.8954	
4 (TB)	40	32.9378	32.9378	
2 (SD)	40		37.0317	37.0317
3 (VB)	40			40.9522

[a] *Subsets 1, 2, and 3 differed significantly (one-way ANOVA, p<0.05). In each subset, there was no statistical difference between or among groups (p>0.05).*

resin composite was set to zero before light-curing. Then the resin composite was light-cured with a light-curing unit (800 mW/cm^2, Bluephase, Ivoclar Vivadent) through the transparent disc for 20 seconds. Along with the load-cell signal, the displacement was continuously recorded by the computer every 0.1 seconds for 180 seconds. This measurement was repeated five times for each material, and the average was calculated (Table 2).

Statistical Analysis

Statistical analysis was conducted with PASW Statistics 18 software (SPSS for Windows, SPSS Inc, Chicago, IL, USA). To compare internal adaptation, two-way analysis of variance (ANOVA) was applied. To compare internal adaptations among different groups or those of different locations, one-way ANOVA with Scheffe analysis was used. Pearson correlation test was used to analyze the relationships between polymerization parameters and internal adaptation (IM%).

RESULTS

Table 2 shows physical properties of the resin composites used in the study. The linear polymerization shrinkages were 4(TB), 5(SF), and 1(Z3) < 2(SD) < 3(VB). The polymerization shrinkage stresses were 5(SF) and 4(TB) ≤ 1(Z3) < 2(SD) < 3(VB).

Two-way ANOVA results showed no interaction between filling materials and locations ($p>0.05$). One-way ANOVA with Scheffe analysis indicated that GIM% (gingival floor), MPIM%, and DPIM% (pulpal floor) were significantly higher than BIM% and LIM% ($p<0.05$; Table 3). There was no significant differences among GIM%, MPIM%, and DPIM% ($p>0.05$). The IM% values of the different groups were as follows: group 5 ≤ groups 1 and 4 ≤ group 2 ≤ group 3 (Table 4). The detailed results in Table 5 were compared by one-way ANOVA, horizontally (among different filling materials) and vertically (among different locations). Pearson correlation analysis showed that p was 0.006 between LS and IM% and 0.003 between PS and IM%, indicating that internal adaptation was significantly correlated with both polymerization shrinkage and stress ($p<0.05$).

DISCUSSION

GIM%, MPIM%, and DPIM% were significantly higher than BIM% and LIM%, and TIM% differed among groups. These findings indicate that the first and second null hypotheses were rejected. The third hypothesis was rejected due to the correlation between internal adaptation and polymerization shrinkage parameters.

GIM% was relatively higher than BIM% and LIM% in the proximal box. This difference might be due to the occluso-gingival height of the proximal box, which was longer than the bucco-lingual width of the box. The dimensions were approximately 6 mm for the occluso-gingival height and 3.5 mm for the bucco-lingual width. As the bulk resin polymerized, polymerization shrinkage could be greater in the occluso-gingival axis than in the bucco-lingual axis. This difference could lead to a higher IM% at the gingival floor interface. While measuring imperfect margins at the restoration interfaces, imperfections were often found around the axiofaciogingival or axiolinguogingival point-angles of the proximal box. This may be because these two point-angles are where more than two vectors of force are exerted: toward the occlusal surface and toward the buccal/lingual surface. Another explanation for the difference in IM% is that the buccal and lingual walls contained their own portions of the enamel margin. The enamel part of the cavity could bond more

Table 5: *Mean Percentage of Measured Imperfect Margin (IM%) of Each Cavity Wall or Floor*[a]

Location	Group 1	Group 2	Group 3	Group 4	Group 5
BIM%	27.8^{a,A,B} (4.24)	28.3^{a,B,C} (4.07)	29.9^{a,C} (4.52)	24.4^{a,A,B} (5.03)	23.4^{a,A} (4.24)
LIM%	25.2^{a,A,B} (5.94)	27.0^{a,B,C} (4.02)	29.7^{a,C} (3.48)	25.3^{a,A,B} (5.90)	23.9^{a,A} (3.6)
GIM%	37.7^{b,A,B} (4.98)	43.4^{b,B,C} (3.33)	48.5^{b,C} (3.28)	38.9^{b,A,B} (5.29)	34.5^{b,A} (3.51)
MPIM%	38.0^{b,A,B} (3.22)	45.1^{b,B,C} (3.11)	50.2^{b,C} (2.97)	40.1^{b,A,B} (2.85)	35.1^{b,A} (2.74)
DPIM%	36.5^{b,A,B} (3.77)	41.3^{b,B,C} (4.14)	46.4^{b,C} (5.06)	36.2^{b,A,B} (3.30)	33.7^{b,A} (2.73)
TIM%	32.9^{A,B} (6.07)	37.0^{B,C} (8.67)	40.9^{C} (10.3)	32.9^{A,B} (7.56)	30.1^{A} (5.93)

[a] *Numbers in parentheses are SDs. Lowercase superscripts represent differences in IM% among the locations where the imperfect margin was measured within each group at* $p<0.05$ *(compared vertically). Capital superscripts represent differences in IM% among the groups at each location at* $p<0.05$ *(compared horizontally). Identical letters represent no statistical difference at* $p>0.05$*. BIM%, buccal wall imperfect margin %; DPIM%, distal pulpal floor imperfect margin %; GIM%, gingival floor imperfect margin %; LIM%, lingual wall imperfect margin %; MPIM%, mesial pulpal floor imperfect margin %; TIM%, total imperfect margin %.*

strongly where little microleakage occurred along the enamel margin on the micro-CT images. After resin polymerization, the composite restoration might have produced a strong bond at the occlusal margin and a weak bond at the cervical margin. Intact enamel margins could have decreased the IM% of the buccal and lingual walls. Finally, dentinal tubules on a deep cavity floor have different characteristics from those of outer superficial dentin. The tubule diameters near the pulpo-dentinal junction (PDJ) are larger, the distance between tubule centers is half the distance between tubule centers at the dentino-enamel junction (DEJ), and peritubular dentin is either thinner or absent.[31] At the PDJ, the volume of the fluid-filled tubule lumens approaches 80%.[32] Therefore, the dentin at this area is more permeable and wetter than dentin at the DEJ.[33] These conditions are poor for dentin bonding, especially with an etch-and-rinse system like the XP-bond used in this experiment. Therefore, the gingival and pulpal floors might be less favorable to dentin bonding than are the occlusal portions of the buccal and lingual walls.

Polymerization shrinkage and stress are thought to be major factors for the difference in IM% among groups. The different resin composites seemed to have their own polymerization shrinkage characteristics. Groups 2 and 3 (SD and VB), which were flowable bulk-fill composite resins, had high linear polymerization shrinkage and stress. They also had higher IM%, indicating that internal adaptation and polymerization were significantly correlated. The composites with low filler content (wt/vol%) had higher IM% (Tables 1 and 4). Filler content appears to be one of the most important material properties affecting IM%.

The magnitude of shrinkage stress is influenced by numerous factors like shrinkage volume, elastic modulus, flow of the resin, filler contents, resin matrix formulation, adherence of the resin to the wall, compliance of the cavity wall, and C-factor.[34-36] The interplay between these factors can determine the shrinkage stress of the restoration. According to the linear elastic model, the change in shrinkage stress is proportional to the product of increase in volumetric shrinkage and change in elastic modulus.[3] In the present study, information on the flexural modulus was adopted from a previous study from our laboratory (Table 2). The flexural modulus increased as Group VB $<$ SD $<$ TB $\leq$ SF $\leq$ Z3, whereas the linear polymerization shrinkage increased in a different order: groups TB, SF, and Z3 $<$ SD $<$ VB. This difference could indicate that polymerization shrinkage stress depends much more on polymerization shrinkage than on elastic modulus. Compliance in the measuring system might offset the influence of the elastic modulus, and its effect on stress might be limited. Therefore, the polymerization stress of these flowable bulk-fill resins did not decrease due to low elastic modulus but demonstrated high shrinkage stress. Another report demonstrated that polymerization stress had a strong direct correlation with shrinkage and an inverse correlation with elastic modulus.[37]

There are two types of measurement systems for polymerization shrinkage stress measurement: a zero compliance (rigid) setup and a compliance-allowed (nonrigid) setup.[38,39] Because the nonrigid setup does not have a feedback system, composite resin can shrink relatively freely under the compliance-allowed condition. With the nonrigid setup, shrinkage stress can dissipate through the components of the system.[39] In the present study, polymerization stress was measured under compliance-allowed condition because some compliance was found in the MOD cavity due to the cuspal deflection.[5]

Light-curing of bulk-fill composites can be affected by several variables of the light source: distance, angle, output, and footprint. Depth of cure was

linearly correlated with distance.[40] Versluis and others used finite element analysis to show that polymerization shrinkage vectors differed depending on the incidence angle of the light source.[41] Peutzfeldt and Asmussen found that not only energy density (the product of output and exposure time), but also power density (output) had a significant influence on resin properties.[42] Sufficient light energy is needed to create sufficient double bonds for the composite to link to the adhesive layer.[42,43] Low irradiance generates a small number of free radicals, which results in longer polymeric chains with low cross-linking.[44] In this experiment, to minimize incomplete curing of the resin composite, additional light curing was performed after the matrix was removed.

In this study, the packable bulk-fill resins, TB and SF, had better internal adaptation than did the flowable bulk-fill resins. The TB manufacturer insisted that TB includes an initiator called Ivocerin that increases polymerization. They claim that TB also contains low-elastic modulus fillers that relieve shrinkage stress. SF uses sonic energy to place the composite. SF has a special modifier that can be activated by sonic waves. Once activated by sonic energy, SF viscosity decreases to obtain rheological properties for adaptation. When the polymerization shrinkage is similar, the material with the lower viscosity has better marginal adaptation.[45,46] In the SF group, however, small bubbles were found inside the resin restoration on micro-CT images. These bubbles could be due to the vibration of the resin composite by sonic energy. Although they might relieve stress, they could increase IM% if they were present at the interface between the composite and tooth.

The purpose of this paper was to compare the internal adaptation of bulk-fill composite restorations in class II cavities. Internal adaptation (IM%) was determined by a critical threshold of the gray value on micro-CT images. Setting a threshold level is somewhat subjective, so measurements of the imperfections do not represent absolute leakage. However, this method makes possible relative comparison. Bonding between the base and capping layer could have been affected by the refining process. To avoid removing the oxygen inhibition layer of the base material, the use of finishing burs was minimized. The capping layer was light-cured right after the refining process, which meant that the composites could continue to polymerize.[46] Even though the oxygen inhibition layer was reduced, the capping layer and bulk-fill base composites could have reacted because free radicals were present for polymerization.[47] To evaluate internal adaptation of the bulk-fill composite restoration, improved methods and further studies are needed.

CONCLUSION

Flowable bulk-fill composites had a higher IM% and polymerization shrinkage stress than did packable bulk-fill and hybrid composites. In class II composite restorations, the gingival floor of the proximal box and pulpal floor of the cavity had higher IM% than did the buccal and lingual walls of the proximal box. Polymerization shrinkage and stress, which were measured under compliance-allowed conditions, were significantly related to internal adaptation.

Regulatory Statement

This study was conducted in accordance with all the provisions of the local human subjects oversight committee guidelines and policies of Yonsei University Dental Hospital Institutional Review Board. The approval code for this study is number 12-0149.

Conflict of Interest

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

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