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Comparison of Polymerization Shrinkage, Physical Properties, and Marginal Adaptation of Flowable and Restorative Bulk Fill Resin-Based Composites

JH Jung • SH Park

Clinical Relevance

A sufficient light-curing time should be applied to bulk fill resin-based composites as the depth of cure is dependent on the material used.

SUMMARY

Purpose: The purpose of this study was to compare the marginal adaptation of two flowable bulk fill resin-based composites (FB-RBCs), two restorative bulk fill resin-based composites (RB-RBCs), and one regular incremental-fill RBC in MOD cavities *in vitro*. Additionally, the influence of linear polymerization shrinkage, shrinkage force, flexural modulus, and bottom/top surface hardness ratio on the marginal adaptation was evaluated. Methods: A Class II MOD cavity was prepared in 40 extracted sound lower molars. In group 1 (control group), the preparation was filled with Filtek Z350 (Z3, 3M ESPE, St Paul, MN, USA) using the incremental filling technique. The FB-RBCs, SDR (SD, group 2) (Dentsply Caulk, Milford, DE, USA) and Venus Bulk Fill (VB, group 3) (Heraeus Kulzer, Dormagen, Germany), were placed in the core portion of the cavity first, and Z350 was filled in the remaining cavity. The RB-RBCs, Tetric N-Ceram Bulkfill (TB, group 4) (Ivoclar Vivadent, Schaan, Liechtenstein) and SonicFill (SF, Group 5) (Kerr, West Collins, Orange, CA, USA), were bulk filled into the preparation. Images of the magnified marginal area were captured under 100× magnification before and after thermomechanical loading, and the percentage ratio of the imperfect margin ($\%IM_{whole}$) was calculated. Gaps, cracks in the enamel layer, and chipping of composite, enamel, or dentin were all considered to be imperfect margins. Linear polymerization shrinkage, polymerization shrinkage force, flexural strength, flexural modulus, and bottom/top surface hardness ratio of were measured. Eight specimens were allocated for each material for each test. One-way analysis of variance with the Scheffé test

Ja-Hyun Jung, MS, Conservative Dentistry, Yonsei University, Seoul, Republic of Korea

*Sung-ho Park, PhD, Conservative Dentistry, Oral Science Research Center, Yonsei University, Seoul, Republic of Korea

*Corresponding author: 50, Yonsei-ro, Seodaemun-gu, Seoul 120-752, Republic of Korea; e-mail: sunghopark@yuhs.ac

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was used to compare the groups at a 95% confidence level. Results: Before thermomechanical loading, $\%IM_{whole}$ was in the order of group 3 ≤ groups 2 and 5 ≤ groups 1 and 4 (p=0.011), whereas after loading, it was in the order of group 4 ≤ group 5 ≤ group 1 ≤ groups 2 and 3 (p<0.001). The order of materials were Z3 < TB and SF < SD and VB (p<0.001) in polymerization shrinkage; SF ≤ TB ≤ Z3 < SD < VB (p<0.001) in polymerization shrinkage force; VB < SD < TB ≤ Z3 ≤ SF (p<0.001) in flexural modulus; SD, VB, and TB < Z3 and SF (p<0.001) in flexural strtength; and SF< Z3 < TB < VB and SD (p<0.001) in bottom/top surface hardness ratio. The Pearson correlation constant between $\%IM_{whole}$ and polymerization shrinkage, shrinkage force, elastic modulus, and bottom/top surface hardness ratio was 0.697, 0.708, −0.373, and 0.353, respectively, after thermomechanical loading. Conclusion: Within the limitations of this study, RB-RBCs showed better marginal adaptation than FB- RBCs. The lower level of polymerization shrinkage and polymerization shrinkage stress in RB-RBCs seems to contribute to this finding because it would induce less polymerization shrinkage force at the margin. FB-RBCs with lower flexural modulus may not provide an effective buffer to occlusal stress when they are capped with regular RBCs.

INTRODUCTION

The use of a resin-based composite (RBC) as a direct restorative material is increasing due to improved esthetics and adhesion to tooth structure. However, the volumetric polymerization shrinkage of RBC, being in the range of 2% to 3%, could cause various problems and may result in gaps between the tooth and the restorative material.[1] Such gaps may contribute to the formation of secondary dental caries or pathologic changes in the dental pulp.[2]

Kim and Park[3] reported that placing a composite into Class II cavities leads to the inward deformation of the cusp, and this cusp deflection was caused by the composites' cure. It was reported that restoring a cavity with the single bulk filling technique using a regular RBC resulted in more marginal leakage but less cuspal deflection compared with the incremental cure technique because bulk filling may result in an incomplete cure.[4] On the other hand, it was reported that the bulk filling technique resulted in more cuspal deflection than the incremental technique when RBCs are sufficiently polymerized by increasing the curing time up to 180 seconds.[3] Therefore, various methods, such as the incremental filling technique,[5] changing the curing mode,[6] using a stress-absorbing intermediate layer,[7] and using a sandwich technique with glass-ionomer,[8] have been suggested to increase marginal adaptation.

Flowable bulk fill resin-based composites (FB-RBCs), such as SDR and Venus Bulk Fill, have come onto the market, which claim to fill up to 4 to 5 mm thicknesses at once by improving the depth to which the RBCs can be light activated. According to the manufacturers of FB-RBCs, it is recommended to complete the restoration with a capping layer made of a regular incremental-fill RBC. It was reported that this step is imperative due to the lower flexural modulus and hardness of FB-RBCs compared to those of regular incremental-fill RBCs.[9]

Czasch and Ilie[10] compared SDR and Venus Bulk Fill and reported that Venus Bulk Fill showed, at all depths, a higher degree of conversion but was significantly lower in other physical properties than SDR. However, both materials showed a depth of cure of at least 6 mm.[10] In addition, Roggendorf and others[11] analyzed the marginal adaptation of MOD restorations with different RBCs while using SDR as the base material. This work showed that SDR did not have any negative impact on the marginal adaptation when used as a 4-mm-thick base material. According to Moorthy and others,[12] restorations with SDR showed the same level of microleakage in the cervical areas and a lower level of cuspal deflection compared to restorations without SDR. Kim and Park[13] recently compared the internal adaptation between RBCs and the cavity floor and also compared the linear polymerization shrinkage and the shrinkage force of RBCs. They reported that the internal adaptation was better when the cavity was filled in 2-mm increments with regular incremental-fill RBCs than when it was bulk filled with FB-RBCs. When the internal adaptation was correlated with the linear polymerization shrinkage and shrinkage force, they showed a high correlation.

Recently, restorative bulk fill resin-based composites (RB-RBCs) have been introduced to the market. According to the manufacturers, RB-RBCs have lower polymerization shrinkage stress than FB-RBCs; they need not be covered with regular incremental-fill RBCs and can themselves be used as filling materials.

Table 1: *Composite Materials Used in This Study and Their Composition*[a]

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

[a] *Composition of base resin and filler content are from manufacturer's information.*
Abbreviations: BIS-GMA, bisphenol A dimethacrylate; BIS-EMA, bisphenol A polyethylene glycol diether dimethacrylate; UDMA, urethane dimethacrylate; TEGDMA, triethyleneglycol dimethacrylate; EBPADMA, ethoxylated bisphenol A dimethacrylate; U, regular incremental fill resin-based composite; FB-RBC, flowable bulk filled resin-based composite; RB-RBC, restorative bulk filled resin-based composite.

It has been reported that flowable resins can be used as a stress-absorbing intermediate layer, which may result in the improved adhesion to dentin and absorb the stress of polymerization or functional loading.[14] According to Kwon and others,[15] the flexural modulus of base materials and the polymerization shrinkage of RBCs affect the marginal adaptation of the final restorations. The differences in the physical properties, polymerization shrinkage, and restoration technique between FB-RBCs and RB-RBCs likely affect the marginal adaptation differently. Clinicians would not be required to use the time-consuming layering technique if FB-RBCs or RB-RBCs functioned well. However, the scientific evidence of their function remains insufficient.

The purpose of this study was to compare the marginal adaptation of FB-RBCs, RB-RBCs, and regular incremental-fill RBCs in MOD cavities *in vitro*. Additionally, the influence of polymerization shrinkage (amount and force), flexural modulus, and bottom/top surface hardness ratio on the marginal adaptation was evaluated. The null hypothesis for this study was that there is no difference in the marginal adaptation of FB-RBCs, RB-RBCs, and regular incremental-fill RBCs.

METHODS AND MATERIALS

Materials

In this study, five different RBCs from different manufacturers were used. Filtek Z350 (3M ESPE, St Paul, MN, USA) was the regular incremental-fill RBC, SDR (Dentsply Caulk, Milford, DE, USA) and Venus Bulk Fill (Heraeus Kulzer, Dormagen, Germany) were the FB-RBCs, and Tetric N-Ceram Bulkfill (Ivoclar Vivadent, Schaan, Liechtenstein) and SonicFill (Kerr, West Collins, Orange, CA, USA) were the RB-RBCs. The types and composition of the RBCs used in this study are summarized in Table 1.

Measurement of the Linear Polymerization Shrinkage

Polymerization shrinkage was measured using a custom-made Linometer (R&B Inc, Daejon, Korea) following the previously described procedures by Kim and Park.[13] Glycerin gel was applied to a metallic disc and a piece of glass slide to prevent adhesion to the resin. RBCs were transferred to a Teflon mold to ensure that the same amount of composite was used for each linometer sample (39.25 mm^3). Then the RBC was placed on the thin metallic discs, covered with a 1-mm-thick glass slide, and, using a screw, positioned into place under constant pressure. An LED-type light-curing unit (Bluephase N, Ivoclar Vivadent) with a power density of 1140 mW/cm^2 was placed 1 mm above the glass slide, and the material was light cured for 30 seconds. The power density of the light-curing unit was calculated by dividing the integration power (mW) of the light-curing unit, measured using an integration sphere (Gigahertz-Optic GmbH, Puchheim, Germany), by the fiber bundle area (cm^2). As the RBC under the glass slide was cured, it moved the aluminum disk under the RBC upward. The amount of disk displacement, which was caused by the linear shrinkage of the RBC, was measured in μm using an eddy current sensor every 0.5 seconds for a period of 120 seconds, and the data were stored simultaneously in a computer. This was measured eight times for each material.

Measurement of the Polymerization Shrinkage Force

The polymerization shrinkage force of the RBC was measured using a custom-made device and software (R&B Inc) following the previously described procedures by Kim and Park.[13] The compliance of this device was 0.3 μm/N. The instrument was driven by a motor and was devised to move a tension rod up

and down. The RBC (145 mm^3) was transferred to an acrylic disc, and the upper tension rod, which was made of stainless steel and had a diameter of 8 mm, was set to ensure that the thickness of the specimen was 1 mm and the diameter was 8 mm. The c-factor was 4. The force between the tension rod and the RBC was set to zero using the software before light curing. Then the RBC was light cured with a light-curing unit (Bluephase N, Ivoclar Vivadent, 1140 mW/cm^2) for 30 seconds through the acrylic disc. The polymerization shrinkage force was measured in kgf using a load cell (model UM-K100,100-kgf capacity, Dacell, Chungcheongbuk-do, South Korea) connected to the tension rod, and the resulting data were stored in a computer every 0.5 seconds for a period of 180 seconds. This measurement was completed eight times for each material studied.

Measurement of Flexural Modulus

Specimens of each RBC were made using a metallic mold of $25 \times 2 \times 2$ mm in accordance with ISO 4049. The specimen was light cured along its length using a light-curing unit (Bluephase N, Ivoclar Vivadent, 1140 mW/cm^2) for three exposure times of 20 seconds for each surface. Thus, a 240-second curing time was needed for four surfaces. As the diameter of the curing tip was 9 mm, 2 mm of overlapping occurred during light curing. The specimens were stored in light-proof conditions for 24 hours. The specimens were slightly wet ground with 600-grit and 1200-grit SiCs on all four surfaces to remove flash. Then a universal testing machine (Instron, Norwood, MA, USA) was used to conduct three-point bending tests. Eight specimens were allocated for each material. The span length was 20 mm, and the crosshead speed was 0.75 mm/min. After the measurement, flexural moduli ($E_{flexural}$, flexural modulus) were calculated in GPa using the following equation. Deformation range between 0.6 and 1.0 mm was used for this calculation:

$$E_{flexural} = FL^3/4wh^3d$$

where F = maximum load, L = span length, w = width of the specimen, h = specimen height, and d = deflection.

Measurement of Microhardness and Calculating Bottom/Top Surface Hardness Ratio

An opaque polyacrylic mold (Dentsply Caulk), which had a hole 4 mm deep and 4 mm in diameter, was used to prepare the RBC specimens. After a glass slide and a celluloid strip were placed on a flat surface, the mold was placed on the top of the strip. RBCs were bulk filled into the mold for each material and covered with a celluloid strip and a glass slide. A slight digital force was applied to the glass slide to ensure that the celluloid covered the RBC surface tightly and to make the surface flat and smooth. The tip of the curing light was placed within 1 mm of the upper surface of the glass slide and then light cured for 30 seconds using a light-curing unit (Bluephase N, Ivoclar Vivadent, 1140 mW/cm^2). Eight specimens were allocated to each group. Each specimen was removed from the mold, and its upper and lower surfaces were slightly polished with 2000-grit SiC paper. The specimens were then stored in dark and dry conditions for 24 hours at room temperature. The Vickers microhardness of the top and bottom surfaces of each specimen was measured using a Micro Hardness Tester (HMV-2, Shimadzu, Kyoto, Japan). For these measurements, a 5-kgf force was applied for five seconds, and four points were measured for each surface. The bottom/top surface hardness ratio was calculated and compared.

Measurement of Marginal Adaptation

Preparation of the specimens—Human teeth, which were extracted for periodontal or orthodontic reasons within a month of the study, were collected and stored in distilled water. Forty lower molar teeth free of coronal cracks or caries were used as specimens. The bucco-lingual dimension of the specimens was between 10.1 and 10.6 mm, and the mesiodistal dimension was between 10.7 and 11.2 mm. Then a Class II preparation was made on each of the molar teeth using a high-speed diamond bur (959 KR 018, Komet GEBR Brasseler GmbH & Co KG, Lemgo, Germany), and the enamel margin was trimmed with a fine-grit diamond bur (862 EF +010, Komet GEBR Brasseler). The bur was replaced with a new one every 10 teeth. Measured from the central fossa, the depth of the cavity was 4.5 mm, and the bucco-lingual width was 3.5 mm. On one side of the proximal cavities, the cavity was extended just from the central cavity, and the cervical margin was located on the enamel (the shallow proximal box), while a box-shaped cavity was prepared on the other side, the cervical margin was located on the dentin 1 mm beneath the CEJ, and the cavity depth was 6.5 mm (the deep proximal box) (Figure 1).

The enamel and dentin of the specimens were etched with 34% phosphoric acid (Caulk 34% Tooth Conditioner, Dentsply Caulk) for 15 seconds and washed with distilled water. After blot drying the

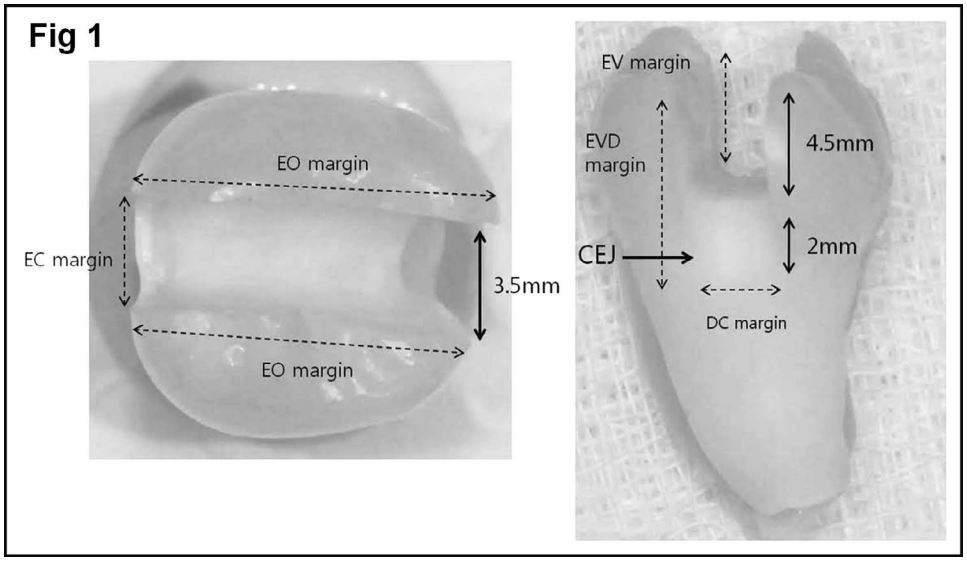

Figure 1. *Occlusal and proximal views of the cavity preparation.*

surface, the adhesive (XP Bond, Dentsply Caulk) was applied and light cured on the occlusal, mesial, and distal sides using an LED light-curing unit (Bluephase N, Ivoclar Vivadent, 1140 mW/cm^2) for 20 seconds at each position. The same curing light was used in the following curing process for the RBCs.

Forty specimens were randomly allocated into five groups. Then the cavities were filled and light cured as follows for each group:

• Control group (group 1)

After applying the Ivory retainer and matrix to the tooth specimen, the RBC (Z3) was applied. The first 2-mm increment was placed in the deep proximal box and was light cured for 20 seconds from the occlusal side. The second and third 2-mm increments were placed in the shallow to deep proximal side and light cured for 20 seconds each from the occlusal side. The fourth and fifth 2-mm increments were placed in the mesial and distal half of the remaining cavity and were light cured for 20 seconds each from the occlusal side. After removing the retainer and the matrix, additional light curing was applied from the buccal and lingual sides of the deep and shallow proximal cavities obliquely from the occlusal surface. Eighty seconds of additional light curing (20 seconds $\times$ 4) was applied in this process. Figure 2a shows a schematic diagram of the filling procedure.

• FB-RBCs: group 2 (SD + Z3) and group 3 (VB + Z3)

After applying an Ivory retainer and matrix to the tooth specimen, FB-RBCs (group 2: SD; group 3: VD) were placed in the core portion of the cavity. Then the FB-RBCs were light cured for 20 seconds from the occlusal direction. The thickness of the materials in the occlusal and deep proximal portions was calculated by subtracting the remaining depth of each portion after light curing from its original depth. Therefore, it was 3.5 and 5.5 mm in the occlusal and deep proximal portions, respectively. When the thickness of the material exceeded the criteria, the thickness was reduced using a high-speed fine-grit diamond bur (959 KREF 018, Komet GEBR Brasseler). In cases when the materials were not confined to the core portion and were not away from the margins, the extended portions were removed using a hand instrument. Z350 was added to the cavity (first in the deep proximal, then in the shallow proximal, then the mesial half, and then the distal half) and light cured for 20 seconds after each addition (Figure 2b). After removing the retainer and matrix, additional light curing was applied to the buccal and lingual sides of the deep and shallow proximal cavities obliquely from the occlusal surface; thus, a total of 80 seconds of additional light curing (20 seconds $\times$ 4) was applied.

• RB-RBCs: group 4 (TB) and group 5 (SF)

TB (group 4) and SF (group 5) were bulk filled in the cavity after applying the ivory retainer and matrix to the tooth specimen, followed by a 20-second photopolymerization. The filling process was carried out using hand instruments (group 4) or a sonically activated hand piece (group 5) as instructed by the manufacturer. After removing the retainer and matrix, additional light curing was applied from the buccal and lingual sides of the deep and shallow proximal cavity obliquely from the occlusal surface such that 80 seconds of additional light curing (20

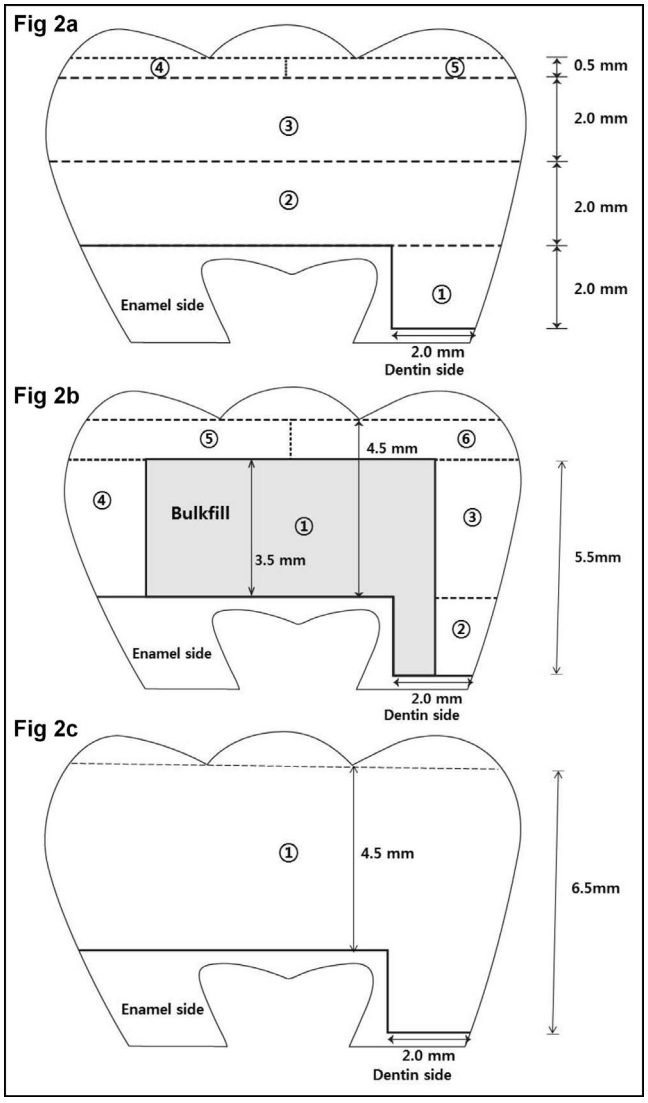

Figure 2a. *Schematic diagram of the resin placement of the control group (Z3).*
Figure 2b. *Schematic diagram of the bulk fill resin placement (SD, VB).*
Figure 2c. *Schematic diagram of the bulk fill resin placement (TB, SF).*

seconds × 4) was applied. Figure 2c shows a schematic diagram of this filling procedure. The calculated c-factor was about 2.1.

Stereomicroscope Imaging and Analysis of the Margin

All of the specimens were polished under a surgical microscope at 10× magnification (Carl Zeiss Surgical GmbH, Oberkochen, Germany) using a high-speed fine-grit diamond bur (863 EF, Komet GEBR Brasseler). Then they were polished with a flame-shaped silicone bur (Astropol F, P, and HP, Ivoclar Vivadent) in the order of Astropol F, P, and HP at 10,000 rpm.

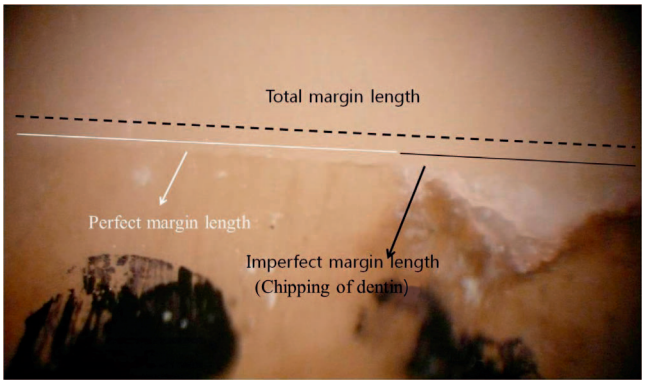

Figure 3. *Example of the margin analysis of the cavity.*

Finally, they were polished with a brush (Astrobrush, Ivoclar Vivadent) in which polishing paste was impregnated into the bristles. After polishing, the specimens were stored in 100% humidity for seven days. The specimens were positioned in a jig in which the specimens could be freely moved making it easy to observe the margin of the restoration. They were then observed using a stereomicroscope (Leica S8APO, Leica Microsystems, Wetzlar, Germany) at 100× magnification, and pictures of the whole margins were taken using a digital camera connected to the microscope. Using ImageJ software (version 1.46, National Institute of Mental Health, Bethesda, MD, USA), the lengths of the perfect and imperfect margins were calculated for each image. Adding the whole data of each image, the percentage of imperfect margin ($\%IM_{whole}$) (whole length of imperfect margin/[whole length of perfect margin + whole length of imperfect margin]×100) was calculated for each tooth specimen. Gaps between the restorations and cavity, cracks, and chippings of composites, enamel, or dentin were all considered to be imperfect margins (Figure 3). In addition, the cavity margins were categorized as the occlusal enamel margins (EO), the vertical enamel margins (EV), and the cervical enamel margins (EC) of the shallow proximal cavity as well as the vertical enamel margins (EVD) and the cervical dentin margins (DC) of the deep proximal cavity (Figure 1). The %IM was calculated in the EO, EV, EC, EVD, and DC as well.

Application of a Mechanical Load Using a Chewing Simulator

The CS-4.8 chewing simulator (SD Mechatronik, Feldkirchen-Westerham, Germany) was used under specific thermodynamic conditions to provide thermocycling (5°C to 55°C with a dwell-time of 60 seconds and a transfer time of 24 seconds) and mechanical load (49 N, 600,000 cycles, 1 Hz)

Table 2: *Polymerization Shrinkage, Shrinkage Force, Flexural Modulus, and Bottom/Top Surface Hardness Ratio*[a]

Materials	Linear Polymerization Shrinkage, μm / %	Polymerization Shrinkage Force, Kgf	Flexural Strength, MPa	Flexural Modulus, GPa	Bottom/Top Surface Hardness Value	
					VHN (Upper/Lower)	Ratio
Z3	11.98 (0.86) A /0.86	3.03 (0.16) B	128.05 (8.99) B	5.98 (0.66) CD	77.5/56.6	0.73 (0.03) B
SD	32.38 (1.27) C /2.31	4.00 (0.11) C	101.26 (11.39) A	3.29 (0.64) B	32.1/29.2	0.91 (0.02) D
VB	34.33 (3.14) C /2.45	4.94 (0.18) D	97.36 (5.63) A	2.35 (0.27) A	25.2/22.9	0.91 (0.02) D
TB	15.31 (0.86) B /1.09	3.01 (0.11) AB	100.21 (5.69) A	5.29 (0.41) C	49.3/40.4	0.82 (0.01) C
SF	16.43 (0.89) B /1.17	2.81 (0.19) A	136.67 (6.49) B	6.54 (0.50) D	70.5/47.94	0.68 (0.01) A

[a] *Different letters within a column indicate significantly different values* ($p<0.001$). *Figures in the parentheses are standard deviations.*

simultaneously. The specimens were embedded and fixed in chambers where thermocycling and mechanical loading were carried out. Chewing was simulated using a steel rod with a rounded conical end that pressed down on the center of the restorative material to apply a load from the top side. The rod moved 6 mm vertically and 0.3 mm horizontally. The rising speed was 55 mm/s, while the descending speed was 30 mm/s with a forward speed of 30 mm/s and a backward speed of 55 mm/s.

Analysis of the Marginal Adaptation

After mechanical loading, the margins of restorations were analyzed again, as described above.

Statistical Analysis

The linear polymerization shrinkage, the polymerization shrinkage force, the flexural modulus, and the bottom/top ratio of the microhardness of the RBCs were analyzed using one-way ANOVA, which was further verified using Tukey analysis at a 95% confidence interval. One-way ANOVA with Tukey was used to compare the $\%IM_{whole}$ of the groups at a 95% confidence interval. A paired *t*-test was used to compare the $\%IM_{whole}$ before and after thermomechanical loading in each group at a 95% confidence interval. The %IM between the groups at each part of the margins was analyzed using the Kruskal-Wallis and Mann-Whitney U-test method. Correlation analysis was performed to investigate the relationship between the %IM and linear polymerization shrinkage, shrinkage force, flexural modulus, and bottom/top surface hardness ratio.

RESULTS

Measurement of Polymerization Shrinkage

The linear polymerization shrinkage varied from 11.98 μm (Z3) to 34.33 μm (VB). The measured shrinkage levels were Z3 < TB and SF < SD and VB ($p<0.001$) (Table 2).

Measurement of the Polymerization Shrinkage Force

The polymerization shrinkage force was between 2.81 kgf (SF) and 4.94 kgf (VB). The measured levels were in the order of SF ≤ TB ≤ Z3 < SD < VB ($p<0.001$) (Table 2).

Measurement of the Flexural Strength and the Flexural Modulus

The flexural strength varied from 97.36 MPa (VB) to 136.67 MPa (SF). The measured values were in the order of VB, TB, and SD < Z3 and SF ($p<0.001$) (Table 2). The flexural modulus varied from 2.35 GPa (VB) to 6.54 GPa (SF). The measured values were in the order of VB < SD < TB ≤ Z3 ≤ SF ($p<0.001$) (Table 2).

Bottom/Top Surface Hardness Ratio

The bottom/top surface hardness ratio was between 0.68 (SF) and 0.91 (SD and VD). The measured values were in the order of SF < Z3 < TB < VB and SD ($p<0.001$) (Table 2).

$\%IM_{whole}$ and %IM

Before thermomechanical loading, $\%IM_{whole}$ was in the order of group 3 (VB + Z3) ≤ groups 2 (SD + Z3) and 5 (SF) ≤ groups 1 (Z3) and 4 (TB) ($p=0.011$), whereas after loading, it was in the order of group 4 (TB) ≤ group 5 (SF) ≤ group 1 (Z3) ≤ groups 2 (SD + Z3) and 3 (VB + Z3) ($p<0.001$). There were statistically significant differences between before and after mechanical loading in all groups ($p<0.001$) (Table 3). As for %IM in each cavity wall, no group showed a significant difference with the other groups in all of the margins before loading (Figure 4), whereas there was a significant difference between groups after thermomechanical loading. In EO and EV, %IM were group 5 (SF) ≤ groups 1 (Z3), 3 (VB + Z3), and 4 (TB) ≤ group 2 (SD + Z3) ($p = 0.044$ in EO, $p=0.015$ in EV) and group 5 (SF) ≤ groups 1 (Z3)

Table 3: *Mean Percentage of the Imperfect Margin Length to the Whole Cavity Margin Length (% IM) (Standard Deviation)*

Thermomechanical Loading Groups	$\%IM_{whole}$	
	Before	After
1	4.49 (2.92) B	20.44 (10.96) BC*
2	2.64 (1.62) AB	26.26 (5.24) C*
3	1.75 (1.51) A	22.05 (8.46) C*
4	4.07 (2.82) B	12.73 (3.94) A*
5	2.49 (1.83) AB	13.49 (1.87) AB*

*[a] Different letters indicate significantly different %IM levels among the different groups before ($p=0.011$) and after ($p<0.001$) thermomechanical loading. * indicates significant differences in the %IM between before and after thermomechanical loading ($p<0.001$). Group 1: Z3 (Control), Group 2: SD+Z3, Group 3: VB+Z3, Group 4: TB, Group 5: SF*

and 4 (TB) $\leq$ groups 2 (SD + Z3) and 3 (VB + Z3) in EC ($p=0.028$). There was no difference in %IM between the groups in DC and EDV (Figure 5).

Correlation Analysis

Before thermomechanical loading, the correlation coefficients (r) of the $\%IM_{whole}$ with linear polymerization shrinkage, shrinkage force, flexural modulus, and bottom/top surface hardness ratio were 0.362, 0.348, 0.360, and 0.285, respectively. After thermomechanical loading, they were 0.697, 0.708, −0.373, and 0.353, respectively.

DISCUSSION

The null hypothesis was partly rejected, as RB-RBCs showed better marginal adaptation than one of the two FB-RBCs following thermomechanical loading. RB-RBC showed smaller polymerization shrinkage and shrinkage force and higher flexural modulus than FB-RBC.

Gap formation in a restorative resin material was in proportion with the level of polymerization shrinkage.[16] A higher level of polymerization shrinkage stress may also result in a larger amount of microleakage.[17] In the present study, the correlation between $\%IM_{whole}$ and linear polymerization shrinkage and shrinkage stress was also relatively high. The %IM of RB-RBCs (TB and SF) was lower than FB- RBCs (SD and VB). This is consistent with a previous study.[18]

In this study, the correlation between $\%IM_{whole}$ and linear polymerization shrinkage and shrinkage

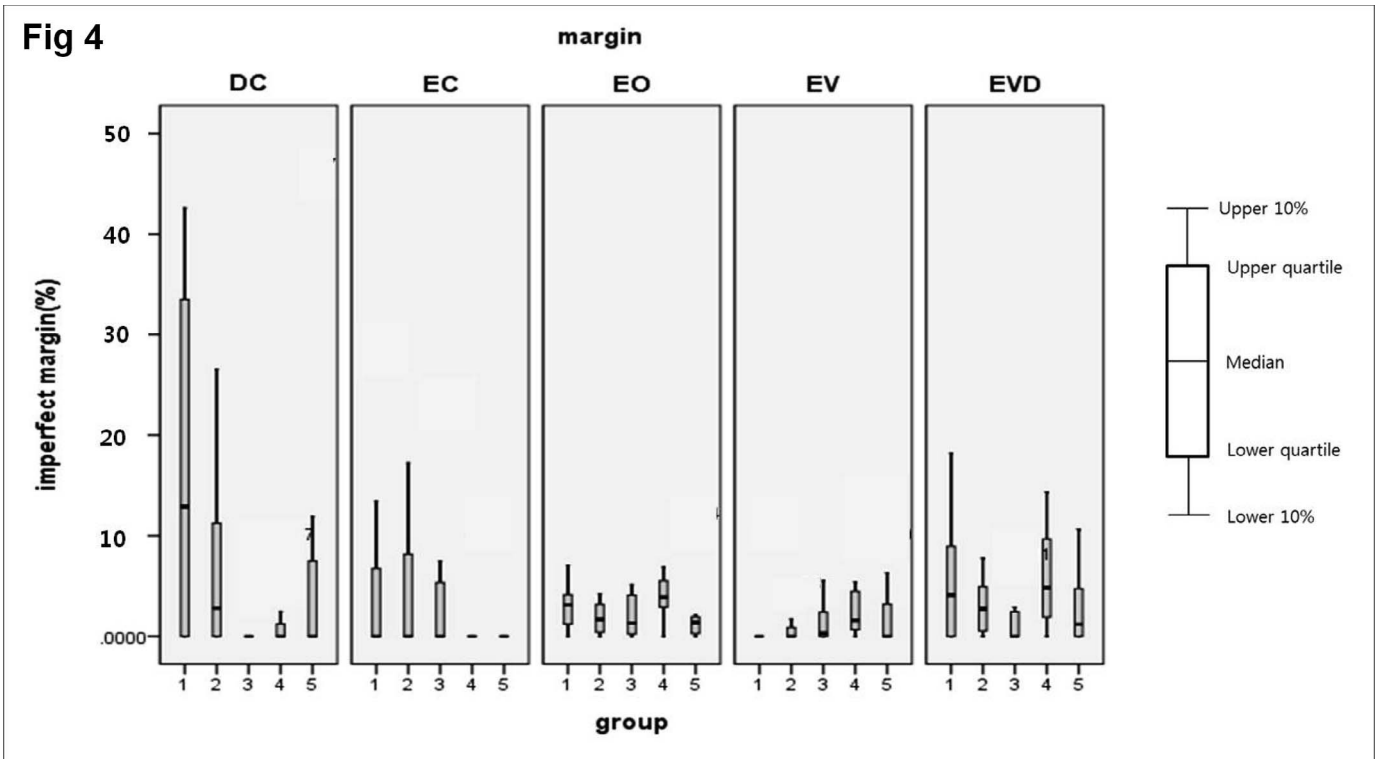

Figure 4. *The % ratio of the imperfect margin (%IM) in each tooth area before thermomechanical loading. EO, occlusal enamel margins; EV, vertical enamel margin; EC, cervical enamel margins of the shallow proximal cavity; EVD, vertical enamel margins; DC, cervical dentin margin of the deep proximal cavity. Group 1: Z3 (Control), Group 2: SD+Z3, Group 3: VB+Z3, Group 4: TB, Group 5: SF.*

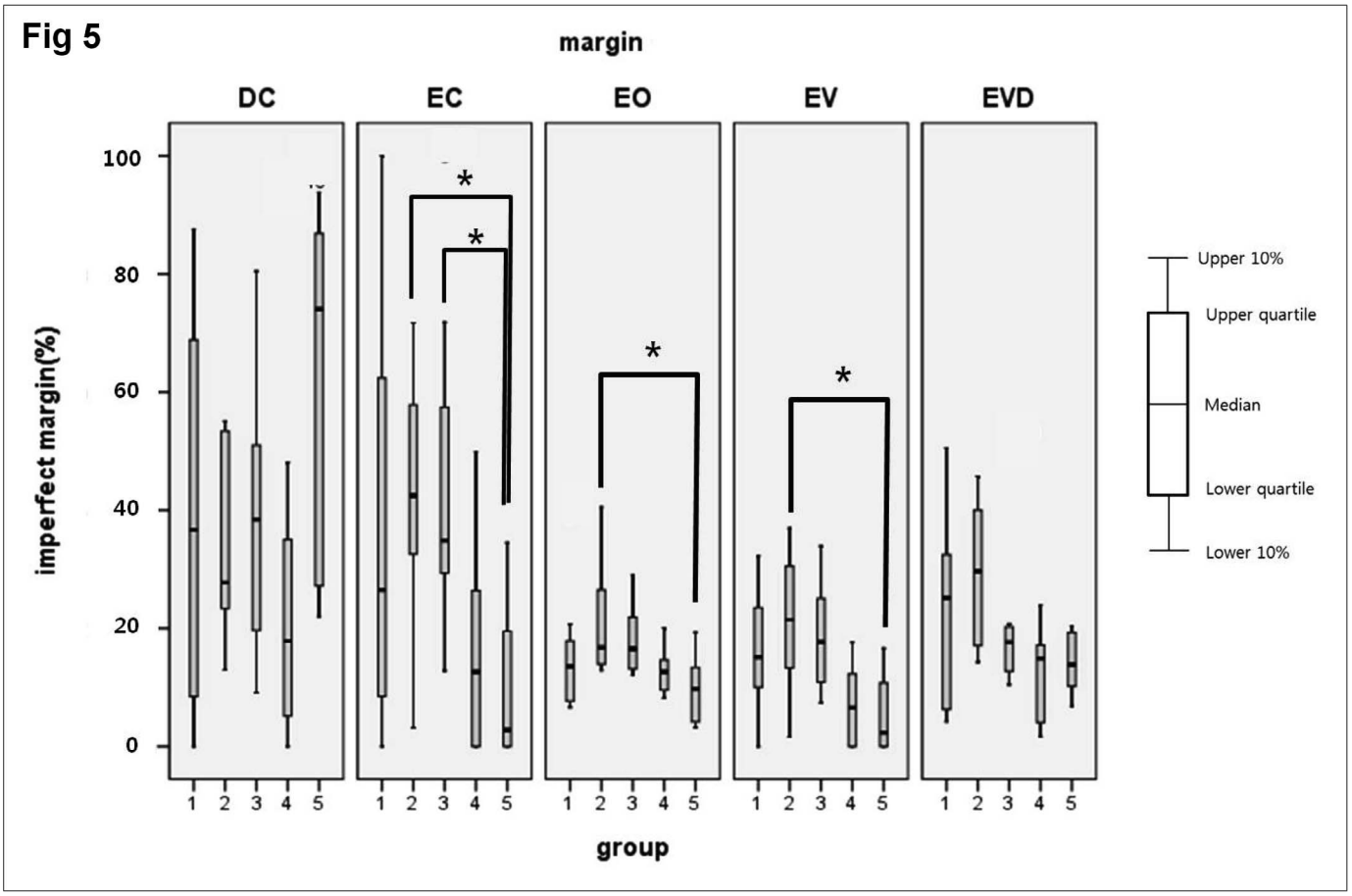

Figure 5. *The % ratio of the imperfect margin (%IM) in each tooth area after thermomechanical loading. * indicates significant differences in the %IM between groups (p = 0.028 in EC, 0.044 in EO, and 0.015 in EV). EO, occlusal enamel margins; EV, vertical enamel margin, EC: cervical enamel margins of the shallow proximal cavity, EVD, vertical enamel margins; DC, cervical dentin margins of the deep proximal cavity. Group 1: Z3 (Control), Group 2: SD+Z3, Group 3: VB+Z3, Group 4: TB, Group 5: SF.*

stress was higher in postloading (0.697 and 0.708) than in preloading (0.362 and 0348). In the preloading state, the influence of polymerization shrinkage and stress might be masked due to the tight bonding between the composites and the tooth, but their influence might remain in the margin as residual stresses. After loading, their influences might be shown more evidently when the bonding between composites and teeth is weakened through the loading process.

The higher volume percentage of the fillers RB-RBCs compared to FB-RBCs may affect the polymerization shrinkage, shrinkage stress, and flexural modulus. According to the manufacturer, the volume percentage of fillers in SD and VB are 44% and 38%, respectively, (Table 1), which are lower than those of TB and SF (55% and 68%, respectively). When the contents of the fillers increase, the contents of monomers decrease, resulting in a reduction of the total level of polymerization shrinkage and shrinkage stress and an increase in the flexural modulus of the material.[19,20]

FB-RBCs were placed only in a core portion of the cavity and Z3 was placed in the outer portion in groups 2 and 3. When the authors consider the core portion of this study as a base, they also consider that the flexural modulus of the core portion may affect the marginal adaptation. It was reported that base material with a lower flexural modulus, such as flowable resins, could absorb the impact that is applied during mechanical loading, and this may result in better marginal adaptation.[21,22] Kwon and others[15] reported that the marginal adaptation was different in the final restoration when the base or lining materials of a different flexural modulus were used. They reported that the optimal range of flexural modulus in flowable RBCs as base materials of 1 mm thick was 4 to 6 GPa, within which the base material can effectively buffer the occlusal stress, and that the moduli that were lower or higher than

this range resulted in a more imperfect margin. In their study, the flexural modulus of the experimental flowable RBC, which was 2 GPa, showed worse results than the other groups. In the present study, the flexural modulus in VB and SD was 2.35 and 3.29 GPa, respectively, and it seems that these low moduli negatively affect the marginal adaptation of the overlying final restoration. In addition, a relatively thick layer of core material was used in groups 2 and 3 (3.5 mm in the central area and 5.5 mm in the deep proximal area), and the thickness of Z3 was 1 mm or less in some areas due to the limitation of the cavity depth. The impact of thick, low modulus FB-RBCs under thin Z3 overlying restorations would be intensified to a greater degree.

According to research conducted by Watts and others,[23] an acceptable curing depth is achieved if the bottom hardness corresponds to at least 80% of the top surface hardness. In the present study, the bottom hardness exceeded 80% of surface hardness in all bulk fills except SF. This result is consistent with previous studies.[24,25] The lower bottom/top surface hardness ratio in SF may be related with its lower translucency than other bulk fill RBCs.[26] In the present study, the cavity depth was 6.5 mm in the deep proximal area. The relatively higher value in %IM in SF in the DC margin may be due to the insufficient cure of this material even though additional light curing was applied from the occlusal direction after the matrix band was removed from the proximal cavities. In clinical situations, care should be taken for the light-curing time in the deep proximal cavity, and additional light-curing time may be necessary. On the other hand, Alrahlah and others[27] reported that SF and TBF had higher depth of cure than VBF. Further studies are needed to clarify this.

It was reported that 30 seconds of curing time, which was longer than the manufacturer's recommendation for bulk fill RBCs (10 to 20 seconds), had positive effects on polymerization properties so that enhanced light curing of bulk fills in deep cavities was recommended.[28] In the present study, after 20 seconds of light curing for FB-RBC, 80 seconds of light curing was applied additionally for capping composite (groups 2 and 3). In groups 4 and 5, RB-RBCs were light cured for 20 seconds, and 80 seconds of additional light curing was applied after removing the retainer and matrix band. The sum of 100 seconds of light curing may have positive effects on the results of the present study.

According to the manufacturer, TB contains an initiator called Ivocerin. It is a germanium-based photoinitiator and has a higher photocuring activity than camphorquionone (CQ). It shows a higher absorption spectrum in the 350- to 470-nm range compared to CQ. It has the potential to reduce the curing time and increase the curing depth of composites.[29] As a result, it may enable even deeper polymerization in the present study, and it may be related to the higher bottom/top surface hardness ratio of TB (0.82) than SF (0.68) and Z3 (0.73) (Table 2). Ilie and others[30] reported that the influence of parameter irradiation time, distance away from the light tip, and depth on the elastic modulus, microhardness, and degree of conversion (DC) were material dependent. According to them, the strongest effect on all measured properties was exerted by the depth followed by irradiation time and distance away from light tip in TB.

Fok,[31] in his mathematical model, successfully predicted shrinkage stress's dependence on the interaction between the entire system's compliance and the material properties. In his model, the shrinkage stress decreased as the compliance of the system increased, and the faster the creep rate, the lower the shrinkage stress in zero compliance. When composites are cured in an MOD cavity, the cusps move inward and this cusp deflection could relieve shrinkage stress of composites in a cavity. Considering this, shrinkage force measurement allowing compliance of an instrument was recommended to simulate the situation in the MOD cavity.[32] In this study, the compliance of the testing machine for the shrinkage force measurement was 0.3 μm/N. As the recorded polymerization force was between 3 and 5 kgf in the present study, about 9 to 15 μm of movement of the testing machine occurred during measurement, which was consistent with the amount of cuspal deflection in the MOD cavity.[3]

In shrinkage force measurement, the c-factor is determined by the diameter and height of the specimens ($d/2h$, where d = diameter and h = height). In the present study, the c-factor of the composite specimens for shrinkage force measurement was 4, whereas it was 2.1 for the MOD restorations. It would have been more ideal if the former were 2.1, but the authors could not increase the height of the specimens as was wanted due to the flow of FB-RBC.

In a study using the Zurich wear testing method, a 5-kgf (49 N) load of 1,200,000 cycles and a themocycling of 5°C to 55°C was applied to mimic five years of service *in vivo*.[33] Considering the results of this study, the stress of thermomechanical loading of the present study would correspond to 2.5 years *in vivo*.

Traditionally, the marginal quality has been assessed with SEM at high magnification (200×).[34] However, stereomicroscopy has also been successfully used recently at lower magnification (6×, 20×, 40×, 100×).[15,35-38] It is simpler and easier to record. Heintze and others[38] pointed out that assessing the margin at 200× magnification would be clinically irrelevant because minor gaps of 2 to 5 μm and minor discrepancies would be recorded. They also indicated that semiquantitative evaluation by means of a stereomicroscope (6×) yielded a statistically significant lower defective margin value than did the SEM (200×) evaluation, but there was a strong correlation between the two evaluation methods. In the present study, 100× stereomicroscope was used according to the method by Kwon and others.[15] Further research is needed to determine clinical relevance.

CONCLUSION

Within the limitations of this study, RB-RBCs showed better marginal adaptation than FB-RBCs. The lower level of polymerization shrinkage and polymerization shrinkage stress in RB-RBCs seems to contribute to this finding because it would induce less polymerization shrinkage force at the margin. FB-RBCs with lower flexural modulus may not provide an effective buffer to occlusal stress when they are capped with regular RBCs.

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. The approval code for this study is #12-0149.

Conflict of Interest

The authors of this article 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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