INTRODUCTION

Stress at the tooth-restoration bonding interface caused by polymerization shrinkage of composite can cause enamel micro-cracks, cuspal deflection, and debonding, which leads to several clinical problems such as detachment of the restoration, micro-leakage, secondary caries, and post-operative hypersensitivity\(^1,2\). The cuspal deflection results from the interaction between polymerization shrinkage stress of composite and cavity wall compliance, and should be understood biomechanically. The biomechanical factors can be classified into three main categories\(^3,4\): (1) Material factor, which relates to the physical properties, such as polymerization shrinkage, flowability, viscosity, and elastic modulus of composites\(^5-11\); (2) Geometric factor, such as the cavity shape and size and the compliance of cavity wall\(^2-4,12\); (3) Clinical factor that is technically changeable in clinical situations, such as bulk or incremental filling\(^1,13-17\), direct or indirect restoration\(^3,18\), and light-curing protocols\(^19-23\).

To date, studies on cuspal deflection have been compared and analyzed with variations of the aforementioned three factors. However, these studies have some limitations. Differences in anatomical and histological structures of extracted human tooth specimens and the size and shape of prepared cavity can cause variations in the cuspal deflections\(^12,14,17\). In an effort to reduce these deviations, several studies using aluminum molds have been reported, however, the shape and size of aluminum molds are somewhat different from the human tooth cavity\(^1,2,10,14\). In other studies, typodont teeth were used to obtain a standardized tooth model, however, these artificial alternatives were difficult to provide appropriate compliance due to difference of properties between the human tooth and artificial one\(^16,24\).

In addition, studies in which cuspal deflection was reduced by relieving stress while changing initial polymerization shrinkage rate and controlling flow of composite using different light-curing protocols have been published\(^10,22,23\). However, precisely changing radiant emittance of LED curing light while maintaining a constant total energy is difficult\(^19,20,23\).

In the present study, geometric factors (shape and size of cavity) and cuspal compliance could be controlled by replicating the mesio-occluso-distal (MOD) cavity of an artificial model tooth to the composite tooth and embedding steel rods into the center of the buccal and palatal cusp. The aim was to investigate the effects of cuspal compliance and radiant emittance of LED light on the cuspal deflection of replicated tooth cavities during composite restoration.

The following hypotheses were tested: (1) differences will exist in cuspal deflection based on variations in cuspal compliance, (2) the differences in cuspal deflection will occur when changing radiant emittance of LED light, and (3) differences will occur in cuspal deflection depending on composite type.

MATERIALS AND METHODS

Materials

A micro-hybrid composite, Filtek Z250 Universal Restorative (Z250; 3M ESPE, St. Paul, MN, USA), and a nano bulk-fill composite, Filtek Bulk Fill Posterior Restorative (BFP; 3M ESPE) were used (Table 1).
Table 1 Composites used in the present study

<table>
<thead>
<tr>
<th>Composite</th>
<th>Type</th>
<th>Filler</th>
<th>Resin matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filtek™ Z250</td>
<td>Micro-hybrid</td>
<td>82 wt% (60 vol%) Zirconia/silica</td>
<td>Bis-GMA</td>
</tr>
<tr>
<td>Universal Restorative (Z250, A2, N783064)</td>
<td>Conventional</td>
<td>Zirconia/silica (0.01–3.5 μm, average 0.6 μm)</td>
<td>UDMA</td>
</tr>
<tr>
<td></td>
<td>Universal</td>
<td></td>
<td>TEGDMA</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bis-EMA</td>
</tr>
<tr>
<td>Filtek™ Bulk Fill</td>
<td>Nano</td>
<td>76.5 wt% (58.4 vol%) Zirconia/silica</td>
<td>AUDMA</td>
</tr>
<tr>
<td>Posterior Restorative (BFP, A2, N710161)</td>
<td>Bulk-fill</td>
<td>Non-agglomerated/non-aggregated zirconia (4–11 nm)/silica (20 nm)</td>
<td>AFM</td>
</tr>
<tr>
<td></td>
<td>Posterior</td>
<td>Aggregated zirconia/silica cluster</td>
<td>DDDMA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Agglomerated YbF₃ (100 nm)</td>
<td>UDMA</td>
</tr>
</tbody>
</table>

Bis-GMA, bisphenol A diglycidyl ether dimethacrylate; UDMA, urethane dimethacrylate; TEGDMA, triethylene glycol dimethacrylate; Bis-EMA, bisphenol A polyethylene glycol diether dimethacrylate; AUDMA, aromatic urethane dimethacrylate; AFM, addition-fragmentation monomer; DDDMA, 1,12-dodecanediol dimethacrylate; YbF₃, ytterbium trifluoride.

PWM-LED curing light
To prepare PWM-LED curing light, an LED probe (B&Lite, B&L Biotech, Ansan, Korea) with an LED emitter (LZ4, LED Engin, San Jose, CA USA; maximum current: 1,200 mA; mean wavelength: 460 nm) was used. The digital output of a microcontroller (Arduino UNO, Arduino, Torino, Italy) turned on and off (frequency=50 Hz, period=20 ms) the NPN transistor to control the current supplied to the LED probe, leading to change of the duty ratio and exposure time of LED curing light (PWM) (Fig. 1a). Output signals of the duty ratios of the PWM-LED light (IB Systems, Seoul, Korea) were confirmed using a digital oscilloscope (TDS 220, Tektronix, Wilsonville, OR, USA) (Fig. 1b). Table 2 showed three different light-curing protocols of the PWM-LED light changed while maintaining a constant total energy (Fig. 1c). A checkMARC curing light testing service (BlueLight Analytics) was used to measure the radiant emittance of the PWM-LED light. The radiant emittance was 902 mW/cm² at 50% duty ratio and 1,793 mW/cm² at 100% duty ratio (Table 2).

Tooth specimen preparation
An MOD cavity was prepared on an artificial upper premolar composite tooth (A5AN-500, Nissin, Kyoto, Japan) using a high-speed handpiece (Ti-Max A600L, NSK, Tokyo, Japan) with water coolant and a flat-end tapered diamond bur of 106–125 μm grit size (Dia-burs TF-43, Mani, Tochigi, Japan). The bucco-lingual width and depth of the occlusal cavity were equal to 1.5 mm, and the bucco-lingual width, mesio-distal length, and depth of the proximal box were 2.5, 1.0, and 2.0 mm, respectively (Fig. 2). The prepared tooth with MOD cavity was replicated into the same shape and size composite tooth using a polyvinyl siloxane (Honigum Light, DMG, Hamburg, Germany) impression and a flowable composite (SDR, Dentsply Caulk, Milford, DE, USA). To change the compliance of the cusp, steel rods (SK drill pin, SuperTools, Paju, Korea; diameter: 1.0, 1.5, or 2.0 mm) were placed in the impression mold parallel to the long axis of the tooth in buccal and palatal cusps (Fig. 2). Four compules of SDR were injected and photo-cured for 20 s with Elipar™ DeepCure-S (EDC; 3M ESPE, Neuss, Germany; wavelength: 430–480 nm) after each compule injection. The radiant emittance of EDC measured using a checkMARC curing light testing service (BlueLight Analytics) was 1,490 mW/cm². The composite tooth without steel rod and extracted human tooth specimen were also made. Five human upper premolars extracted for orthodontic treatment with dimension similar to the replicated composite tooth and without caries, restoration, or visible cracks were selected, and prepared with the MOD cavity dimension similar to the replicated composite tooth cavity.

Cuspal compliance measurement of tooth specimens
To measure cuspal compliance, an LVDT probe was located on a metal cantilever beam connected to a ball bearing. The replicated composite tooth or extracted human tooth was tightened on a metal base and the LVDT probe was positioned on the tip of cusp. A metal weight of 5 kgf was loaded onto the center of the metal cantilever beam (Fig. 3). After measuring displacement of the buccal and palatal cusps, mean cusp displacement of an empty cavity was divided by 2.5 kgf weight loading to obtain the cuspal compliance (μm/N; n=3).

Cuspal deflection measurement of tooth specimens
The internal surface of replicated composite tooth cavity was air-abraded under 0.4 MPa pressure with 50 μm Al₂O₃ powders (Basic Mobil, Renfert, Hilzingen, Germany), treated with a dentin adhesive (Adper Scotchbond Multi-purpose Adhesive, 3M ESPE), and photo-cured for 10 s with EDC (3M ESPE). To prevent the composite from being pushed out of proximal boxes during bulk-filling, an orthodontic metal band (Seamless Band, Tomy, Tokyo, Japan) was placed over the tooth specimen and wrapped around it. The linear variable differential transformer (LVDT) probes (AX-1, Solartron...
Fig. 1 (a) Schematic diagram of a custom-made pulse width modulated (PWM) LED curing system, (b) PWM signals with different duty ratios (50 and 100%) at a frequency of 50 Hz (period=20 ms), and (c) diagram of changing duty ratio and exposure time with constant total radiant exposure (product of duty ratio and exposure time).

Table 2 Four light-curing protocols and the radiant emittance and exposure time

<table>
<thead>
<tr>
<th>Light-Curing Unit</th>
<th>Duty Ratio (%)</th>
<th>Radiant Emittance (mW/cm²)</th>
<th>Exposure Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWM-LED</td>
<td>100</td>
<td>1,793</td>
<td>20</td>
</tr>
<tr>
<td>PWM-LED</td>
<td>50</td>
<td>902</td>
<td>40</td>
</tr>
<tr>
<td>PWM-LED Increase (0→100)</td>
<td>0→1,793</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>EDC</td>
<td>100</td>
<td>1,490</td>
<td>20</td>
</tr>
</tbody>
</table>

PWM-LED, pulse width modulated LED; EDC, Elipar™ DeepCure-S.
extracted human tooth cavities were bulk-filled with Z250 and photo-cured for 20 s with the 100% duty ratio mode of the PWM-LED light. The internal surface of human tooth cavity was acid-etched for 15 s with 32% phosphoric acid (Scotchbond Universal Etchant, 3M Deutschland), treated with dentin adhesive (Adper Scotchbond Multi-purpose Primer and Adhesive, 3M ESPE), and photo-cured for 10 s with EDC (3M ESPE).

To investigate effects of light-curing protocol and composite type, the replicated composite tooth cavities with steel rods (diameter: 2.0 mm) were restored with bulk-filling of Z250 or BFP and photo-cured. The four different light-curing protocols are shown in Table 2. Three different modes of the PWM-LED light (IB Systems) and one commercial LED light (EDC, 3M ESPE) were used.

Two LVDT sensors were used to detect cusp displacement in real time over a period of 2,000 s at 25±0.5°C (n=5). The tip of the light-curing unit was positioned parallel to the occlusal surface directly above the buccal cusp tip (Fig. 4a). The displacement detected by two LVDT sensors were recorded 10 data points per second using a microcontroller (Arduino UNO, Arduino) and software (Processing, MIT Media Lab., Cambridge, MA, USA). Measurement of cuspal deflection was started 10 s before light-curing to acquire a baseline and kept for 2,000 s. The displacements of both cusps were added to acquire the total deflection.

**Flexural modulus measurement of composites**

Bar-shaped specimens (3 W×3 T×30 L mm) were made by bulk-filling and compressing the composites (Z250 or BFP) between an acryl mold and a slide glass. The specimens were divided into five parts and photo-cured with overlapping exposures of EDC (3M ESPE) for 40 s each (total 200 s). The width and thickness of specimens were confirmed using a micrometer. The cured specimens were polished with abrasive paper (OSA, Changwown, Korea) of 10–20 μm grit size and stored under dry and dark conditions for 1 day at 25±0.5°C. The flexural modulus was measured using the three-point bending method with a universal testing machine (LF Plus, Lloyd Instruments, West Sussex, UK) at a crosshead speed of 0.5 mm/min (supporting span length=20 mm; n=5).

**Statistical analysis**

Data were analyzed using one-way analysis of variance (ANOVA) to evaluate statistical significance for cuspal deflections according to changing cuspal compliance, and two-way ANOVA to evaluate statistical significance for cuspal deflections based on light-curing protocol and composite type. Post-hoc analysis was performed.
using Tukey’s test. Independent t-test was conducted to compare flexural modulus between composite types. Normality and homogeneity of variance of data were checked with Shapiro-Wilk and Levene tests. Analyses were conducted with SPSS software (version 21.0, SPSS, Chicago, IL, USA) at $\alpha=0.05$.

**RESULTS**

*Cuspal compliance of tooth specimens*

The cuspal compliance decreased with increasing the diameter of embedded steel rod, and the cuspal compliance of extracted human tooth was the lowest among five different cusp types (Table 3).

*Cuspal deflection of tooth specimens*

The mean cuspal deflection of a micro-hybrid composite (Z250) filling was the highest in the replicated composite tooth without steel rod (Composite_No rod), followed by the composite tooth with 1.0 (Composite_1.0 rod), 1.5 (Composite_1.5 rod), 2.0 mm steel rods (Composite_2.0 rod), and the extracted human tooth (Table 3). The mean cuspal deflection of extracted human tooth was the lowest ($p<0.05$).

The mean cuspal deflection of the Composite_2.0 rod with varying light-curing protocols and composite types are presented in Table 4. The cuspal deflections were not different among light-curing protocols ($p>0.05$). The cuspal deflections in the micro-hybrid composite (Z250) were higher than in a nano bulk-fill composite (BFP) ($p<0.05$). There was no significant interaction between light-curing protocol and composite type ($p>0.05$).

**Flexural modulus of composites**

The flexural modulus (GPa) of the micro-hybrid composite (Z250; 7.88±0.69) was higher than the nano bulk-fill composite (BFP; 6.61±0.57) ($p<0.05$).

**DISCUSSION**

To reduce errors due to difference in tooth cavity size, the artificial composite tooth with MOD cavity was replicated with a flowable composite and steel rods. After the internal surface of the replicated composite tooth cavity was air-abraded and treated with a dentin adhesive, the composite was filler into the cavity andcuspal deflection was measured. There was no abrupt halt in movement on the continuous plot recording while the cuspal deflection measurement, so the bond strength between composite and cavity wall was enough to generate measurable deflection detected by LVDT sensors.

<table>
<thead>
<tr>
<th>Cusp Type</th>
<th>Cuspal compliance (μm/N)</th>
<th>Cuspal deflection (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composite_No rod</td>
<td>1.28 (0.36)</td>
<td>18.29 (1.00)$^a$</td>
</tr>
<tr>
<td>Composite_1.0 mm rod</td>
<td>1.17 (0.05)</td>
<td>16.98 (0.48)$^{ab}$</td>
</tr>
<tr>
<td>Composite_1.5 mm rod</td>
<td>1.01 (0.05)</td>
<td>15.62 (0.54)$^{bc}$</td>
</tr>
<tr>
<td>Composite_2.0 mm rod</td>
<td>0.77 (0.05)</td>
<td>14.56 (0.86)$^c$</td>
</tr>
<tr>
<td>Extracted Human Tooth</td>
<td>0.50 (0.05)</td>
<td>10.46 (1.51)$^d$</td>
</tr>
</tbody>
</table>

Different lower-case superscript letters indicate statistically significant differences among different cusp types ($p<0.05$).

<table>
<thead>
<tr>
<th>Light-Curing Protocol</th>
<th>Composite</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Z250</td>
<td>BFP</td>
</tr>
<tr>
<td>PWM_100%/20 s</td>
<td>14.56 (0.86)$^{aa}$</td>
<td>13.59 (1.29)$^{ab}$</td>
</tr>
<tr>
<td>PWM_50%/40 s</td>
<td>14.73 (0.63)$^{aa}$</td>
<td>13.17 (1.01)$^{ab}$</td>
</tr>
<tr>
<td>PWM_Increase/40 s</td>
<td>14.41 (1.20)$^{aa}$</td>
<td>13.34 (1.14)$^{ab}$</td>
</tr>
<tr>
<td>Elipar™ DeepCure-S (EDC)/20 s</td>
<td>14.22 (1.64)$^{aa}$</td>
<td>13.09 (1.70)$^{ab}$</td>
</tr>
</tbody>
</table>

Identical upper-case superscript letters indicate no statistically significant differences among different light-curing protocols ($p>0.05$).

Different lower-case superscript letters indicate statistically significant difference between composites ($p<0.05$).
To compensate for the low elastic modulus of flowable composite used for tooth replication, steel rods (diameter: 1.0, 1.5, or 2.0 mm) were embedded in the center of the buccal and palatal cusps parallel to the long axis of the tooth, resulting in change of cuspal compliance. The cuspal compliance of the replicated composite tooth decreased as the diameter of steel rods increased, however, was larger than the extracted human tooth. The elastic modulus of human tooth was reported approximately 80 GPa for enamel and 20 GPa for dentin. In contrast, the elastic modulus of flowable composite (SDR) used for replicating tooth in the present study was approximately 6 GPa and the steel rod 200 GPa. Because the elastic modulus of flowable composite was much lower than in the human tooth, embedding steel rods into both cusps of replicated composite tooth was not enough to reduce the cuspal compliance similar to the extracted human tooth. In addition, an absence of chemical bonding between steel rods and flowable composite may have impeded the reduction of cuspal compliance by embedding steel rods into the cusps.

In the present study, when the same size cavity was restored with a micro-hybrid composite (Z250) and photo-cured with the identical light-curing protocol, cuspal deflection increased with increasing cuspal compliance, which was consistent with previous studies. In addition, cuspal deflection increased as a power function of cuspal compliance, where the order "b" of function in the form of \( y = ax^b \) (x: cuspal compliance, y: cuspal deflection) was approximately 0.56 (Fig. 5). This value was similar to the order (0.52) of power function in a previous study in which aluminum mold thickness was changed. Theoretically, if there is no cuspal compliance, when polymerization shrinkage stress of composite is greater than bonding strength between composite and cavity wall, the adhesion interface will be separated. In case of increased cuspal compliance, the polymerization shrinkage stress of composite at the adhesion interface could be relieved by cuspal deflection.

In clinical situations, the cuspal compliance can vary based on the size and shape of cavity to be restored. In the present study, the composite tooth with 2.0 mm steel rods representing the closest cuspal compliance to the extracted human tooth cavity was selected to measure cuspal deflection with varying light-curing protocols and composite types.

In several studies, changes of the light-curing protocol (e.g., pulse-delay or soft-start) reportedly decreased cuspal deflection and the polymerization shrinkage stress increased with increasing radiant emittance of a PWM-LED light. However, in the present study, significant difference in cuspal deflection was not observed among different light-curing protocols, which might have been caused by cuspal compliance. In a previous study, the polymerization shrinkage stress was measured without instrument compliance by applying a negative feedback system, thus, the polymerization shrinkage stress offset the stress-relieving effect by viscous flow of the composite as a result of photo-curing with low radiant emittance.

Conversely, the cuspal deflection was significantly different between composite types. If the elastic modulus of composite by polymerization increases greater than the prepared cavity wall, polymerization shrinkage stress causes cuspal deflection and can be relieved. Therefore, when the elastic modulus of the prepared cavity wall is constant, the higher elastic modulus and polymerization shrinkage of the composite can generate a larger cuspal deflection and a positive correlation exists between cuspal deflection and elastic modulus. The elastic modulus of a micro-hybrid composite (Z250) was higher than a nano bulk-fill composite (BFP). Moreover, according to the manufacturer, BFP contains aromatic urethane dimethacrylate (AUDMA) monomers and addition-fragmentation monomers (AFM). In a previous study, the polymerization shrinkage of the nano bulk-fill composite (BFP) was proven lower compared with the conventional composite (Z250). Based on this result, the reason why cuspal deflection of the micro-hybrid composite (Z250) filling was higher than the nano bulk-fill composite (BFP) filling can be explained by the higher polymerization shrinkage and elastic modulus of the micro-hybrid composite (Z250). However, no clear relationship between flexural modulus of composite and cuspal deflection was also reported. Therefore, multiple types of composite need to be investigated to ensure accurate and consistent results.

![Fig. 5 Cuspal deflection versus cuspal compliance with varying cusp types (Composite_No rod, Composite_1.0 mm rod, Composite_1.5 mm rod, Composite_2.0 mm rod, and Extracted Human Tooth).](image)

\( y = 15.85z^{0.56} \)

\( W = 0.8715 \)
evaluate the relationship between elastic modulus and cuspal deflection in consideration of compliance and polymerization shrinkage.

In the present study, the cuspal deflection of the replicated tooth increased with increasing cuspal compliance, and the first hypothesis was accepted. Difference was not observed in cuspal deflection when changing the radiant emittance of light, however, significant difference between composite types was observed, thus, the second hypothesis was rejected and the third hypothesis accepted, respectively.

Since the compliance change is an important variable in studies on cuspal deflection, an effort to adjust the compliance similar to the human tooth should be required in the future. Consequently, embedding thicker diameter steel rods into the cusp of replicated composite tooth or fabricating ceramic tooth specimens using a 3D printer or CAD/CAM device can be considered. Therefore, due to reduced cuspal compliance similar to a human tooth, future studies on cuspal deflection during composite polymerization with varying light-curing protocols are necessary.

CONCLUSION

Geometric factors of the prepared cavity could be controlled by replicating the cavity and embedding steel rods into the cusps. To reduce cuspal deflection when restoring the MOD cavity with high compliance, selecting the proper composite based on physical properties such as polymerization shrinkage and elastic modulus is more important than changing the light-curing protocols.

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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