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Original Article

Effects of wall compliance and light-curing protocol on wall deflection of simulated cavities in bulk-fill composite restoration

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Radiant emittance

Background/purpose: Cuspal deflections in composite restoration have been investigated with considering wall compliance of human tooth cavity and light-curing protocol. The purpose of this study was to investigate effects of mold wall compliance and radiant emittance of LED light on the wall deflection of simulated aluminum mold cavities restored with a bulk-fill composite.

Materials and methods: Sixty aluminum molds simulating a class II mesio-occluso-distal (MOD) cavity (6 W × 8 L × 4 D mm; W, width; L, length; D, Depth) were prepared and allocated to three groups with varying mold wall thicknesses of 1, 2, and 3 mm. The molds were bulk-filled with a bulk-fill composite and photo-cured. Four light-curing protocols were used: three duty ratios/exposure times: 100%/20 s, 50%/40 s, or an increasing mode (0 → 100%)/40 s with a pulse width modulated (PWM) LED curing light and one 20 s exposure time with a commercial LED light.

Results: Mean mold wall deflection at 2000 s decreased with increasing mold wall thickness (1, 2, and 3 mm) ($p < 0.05$). Wall deflections with 1- and 2-mm-thick molds exhibited no statistically significant differences among light-curing protocols ($p > 0.05$). However, in the 3-mm-thick mold, wall deflections with low radiant emittance were significantly lower than those with high radiant emittance ($p < 0.05$).

Conclusion: In composite restoration of class II MOD cavities, lowering the radiant emittance of LED light can reduce the mold wall deflection only in low compliance cavities.

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Introduction

Cuspal deflection results from polymerization shrinkage stress of composite during restoration of class II cavities, leading to post-operative hypersensitivity or enamel micro-fractures.[1,2] Cuspal deflection is the result of interactions between the polymerization shrinkage stress of composite and compliance of cavity walls, and should be investigated biomechanically.[3]

Compliance of cavity walls is defined as dimension change per force and is the opposite of stiffness.[4] Cuspal deflections during composite curing can be varied by changing the compliance of the cavity walls to which the composite is bonded. Also, previous studies have concluded that polymerization shrinkage stress varied with changing compliance.[5–11] Therefore, to obtain clinically relevant in vitro results, cuspal deflection measurements must be conducted with compliances similar to those of human teeth. However, differences in anatomical and histological structures among human teeth and the size and shape of prepared cavity can cause variations in measuring cuspal deflections.[12–14] Therefore, the use of standardized aluminum molds is recommended since their compliance can be easily altered by varying mold wall thickness and experimental errors can be reduced by using precisely milled cavities. In the present study, to control compliance quantitatively, aluminum blocks with different wall thicknesses simulating class II mesio-occluso-distal (MOD) cavities were used.

Polymerization shrinkage stress of composite can vary with light-curing protocol.[15–19] 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 also published.[20–22] However, precisely changing radiant emittance of LED curing light while maintaining a constant total energy is difficult.[20,22]

Pulse width modulation (PWM) refers to a technique for controlling an analog circuit by digital output from a microcontroller.[23] Unlike continuous analog signals, digital signals express analog signals by being turned on and off within a specific time period. The ratio of "on-time" to "off-time" within a single cycle is called the duty ratio. By using the PWM, the radiant emittance of LED light can be precisely controlled.[24]

Polymerization shrinkage stress increases with increasing radiant emittance of PWM-LED light at a constant radiant exposure.[24] However, in composite tooth cavities with embedding steel rods into the center of the buccal and palatal cusp, which was replicated from an MOD cavity on an artificial model tooth, no significant differences in cuspal deflection were observed when changing the radiant emittance of the PWM-LED light due to the high compliance of cavity walls.[25]

Therefore, the present study was aimed to evaluate the wall deflections of aluminum molds that simulate class II MOD cavities with varying mold wall compliance and different light-curing protocols. The radiant emittance of LED lights was precisely altered while maintaining a constant total energy (radiant exposure) using a custom-made PWM-LED light.

The hypotheses tested were (1) differences will exist in mold wall deflection based on variations in mold wall compliance and (2) differences in mold wall deflection will occur when changing the radiant emittance of LED light.

Materials and methods

Materials

The present study used a nano bulk-fill composite, Filtek™ Bulk Fill Posterior Restorative (BFP; 3M ESPE, St. Paul, MN, USA) (Table 1).

LED light-curing unit

To change light-curing protocols, a PWM-LED light (IB Systems, Seoul, Korea) and a commercial LED light (Elipar™ DeepCure-S (EDC), 3M ESPE, Neuss, Germany; wavelength 430–480 nm) were used. In the PWM-LED light, the digital output of an open source microcontroller (Arduino UNO, Arduino, Torino, Italy) turned on and off (f = 50 Hz, period = 20 ms) a NPN transistor to control the current supplied to the LED probe (B&Lite, B&L Biotech, Ansan, Korea) with an LED emitter (LZ4, LED Engin,Inc., San Jose, CA USA; maximum current: 1200 mA; mean wavelength: 460 nm), resulting in change of duty ratio and exposure time of the LED light (PWM) (Fig. 1a). Output signals of the duty ratios of the PWM-LED light were confirmed using a digital oscilloscope (TDS 220, Tektronix, Inc., Wilsonville, OR, USA) (Fig. 1b). The radiant emittances of the PWM-LED light were changed while maintaining a constant total energy (radiant exposure) (Fig. 1c). The details of duty ratio, radiant emittance, and exposure time of LED lights are shown in Table 2 and the radiant emittance was measured using the CheckMARC curing light testing service (BlueLight Analytics Inc., Halifax, Canada). The radiant emittance of the PWM-LED light was 902 mW/cm^2 at 50% duty ratio and 1793 mW/cm^2 at 100% duty ratio, and EDC was 1490 mW/cm^2 (Table 2).

Table 1 Composite used in this study.

Composite (Code, Shade, Lot No.)	Type	Filler	Resin matrix
Filtek™ Bulk Fill Posterior Restorative (BFP, A2, N710161)	Nano Bulk-fill Posterior	76.5 wt% (58.4 vol%) Non-agglomerated/ non-aggregated zirconia (4–11 nm)/ silica (20 nm) Aggregated zirconia/ silica cluster Agglomerated YbF_3 (100 nm)	AFM AUDMA DDDMA UDMA

Abbreviations: AFM, addition–fragmentation monomer; AUDMA, aromatic urethane dimethacrylate; DDDMA, 1,12-dodecanediol dimethacrylate; UDMA, urethane dimethacrylate

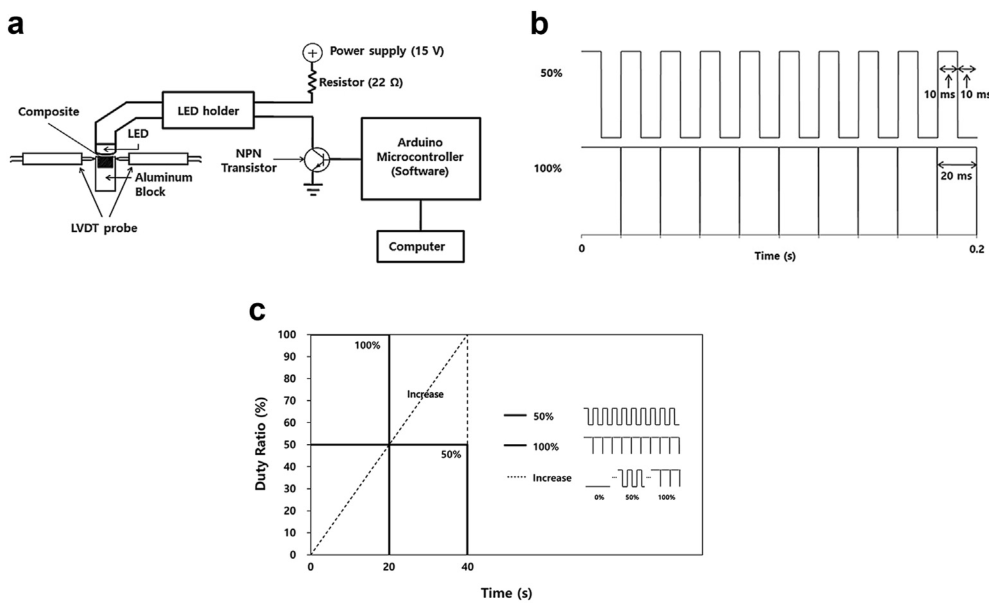

Figure 1 (a) Schematic diagram of a custom-made pulse width modulated (PWM) LED curing system, (b) PWM signals with different duty ratios (50 and 100%) at a frequency of 50 Hz (period = 20 ms), and (c) a diagram of changing duty ratio and exposure time with constant total radiant exposure (product of duty ratio and exposure time).

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

Light-Curing Protocol	Duty Ratio (%)	Radiant Emittance (mW/cm^2)	Exposure Time (s)
PWM-LED_100%/20 s	100	1793	20
PWM-LED_50%/40 s	50	902	40
PWM-LED_Increase/40 s	Increase (0 → 100)	0 → 1793	40
Elipar™ DeepCure-S (EDC)/20 s	100	1490	20

Abbreviations: PWM-LED, Pulse Width Modulated LED

Wall deflection measurement of aluminum molds during composite restoration

Sixty aluminum molds simulating class II MOD cavities (6 W × 8 L × 4 D mm; W, width; L, length; D, depth) were prepared and allocated to three groups with mold wall thicknesses of 1, 2, and 3 mm (Fig. 2a—c). The internal surfaces of aluminum molds were air-abraded with 50 μm Al_2O_3 powder (Basic Mobil, Renfert, Hilzingen, Germany), rinsed with water, and air-dried. The internal surface was treated with a metal primer (Reliance, Ortho Prod. Inc., Itasca, IL, USA) and an adhesive (Adper™ Scotchbond™ Multi-Purpose Adhesive, 3M ESPE, St. Paul, MN, USA) and photo-cured for 10 s with EDC (3M ESPE).

To prevent composite from being pushed out of proximal boxes during bulk-filling, a custom-made acrylic cap with two notches on the upper borders of both lateral walls was placed over and wrapped around the aluminum mold (Fig. 2d). The notches engraved on the acrylic cap allowed reproducible guidance of linear variable differential transformer (LVDT) probes (AX-1, Solartron Metrology, West Sussex, UK) with a sensitivity exceeding 0.1 μm over a range of ±1 mm to the center of the upper borders of the mold walls. The inner surface of the acrylic cap was lubricated with petroleum jelly to avoid adherence to the composite. The required weight of composite to restore the aluminum mold cavity was calculated from the density of composite and the volume (192 mm^3) of aluminum mold cavity.

To investigate the effects of mold wall compliance and light-curing protocol on mold wall deflection, aluminum molds with wall thicknesses of 1, 2, and 3 mm were bulk-filled with a bulk-fill composite (Bulk Fill Posterior Restorative (BFP), 3M ESPE) and photo-cured with the four light-curing protocols presented in Table 2.

Two LVDT probes in the cuspal deflection measurement module of a μ-BioMechanics (IB Systems, Seoul, Korea) were used to measure mold wall deflection in real time at 25 ± 0.5 °C during composite curing over a period of 2000 s (n = 5). The tip of the light-curing unit was positioned directly above and parallel to the upper surface of aluminum mold (Fig. 3). The displacement values measured by two LVDT probes and stored on a computer at a rate of 10 data points/s. Measurements of mold wall deflection were initiated 10 s prior to light exposure to obtain a baseline and was continued for 2000 s. Displacements of both walls were added to obtain the total amount of deflection.

Wall compliance measurement of aluminum molds

To measure mold wall compliance, an LVDT probe (AX-1, Solartron Metrology) was located on a metal cantilever

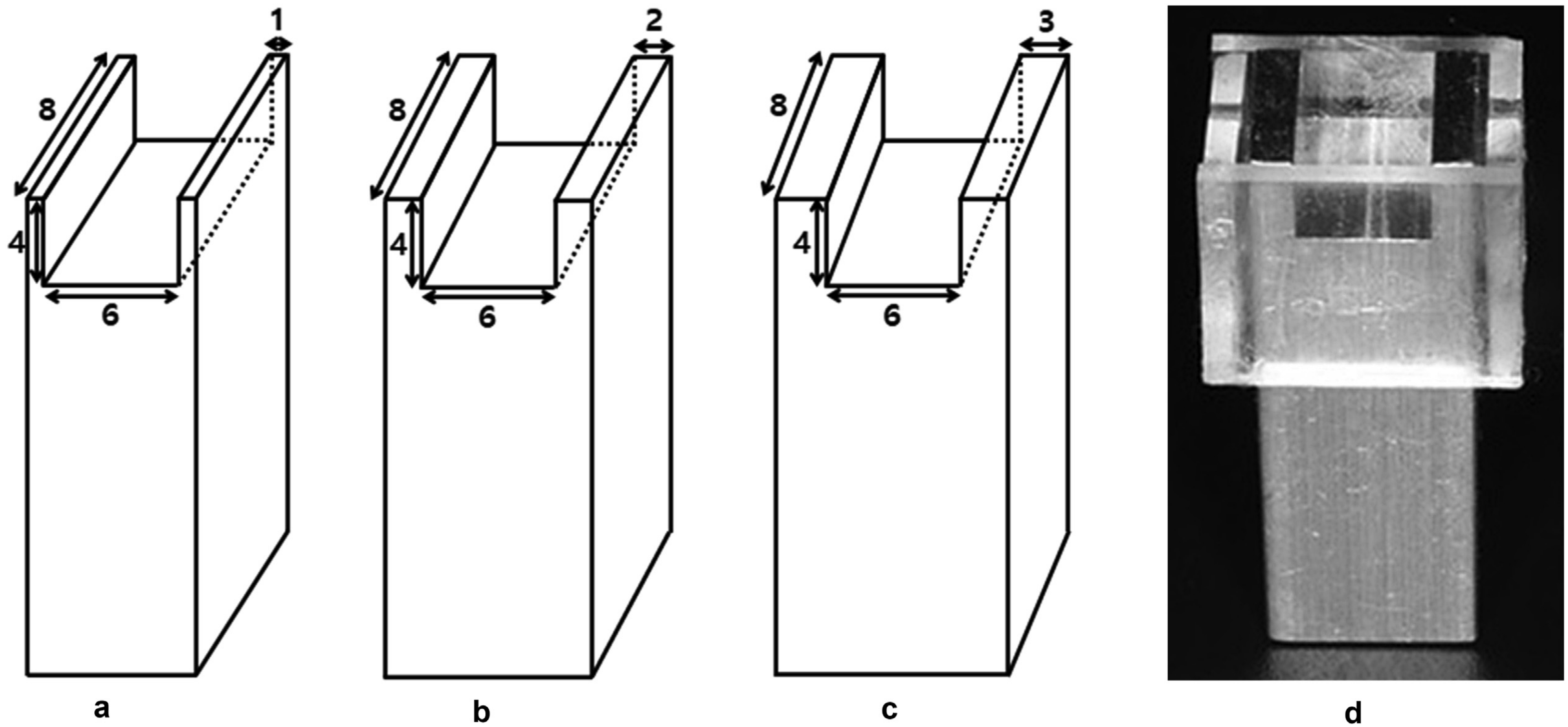

Figure 2 Dimensions (mm) of aluminum blocks with varying mold wall thicknesses: (a) 1 mm, (b) 2 mm, and (c) 3 mm. (d) Acrylic cap placed over the aluminum block.

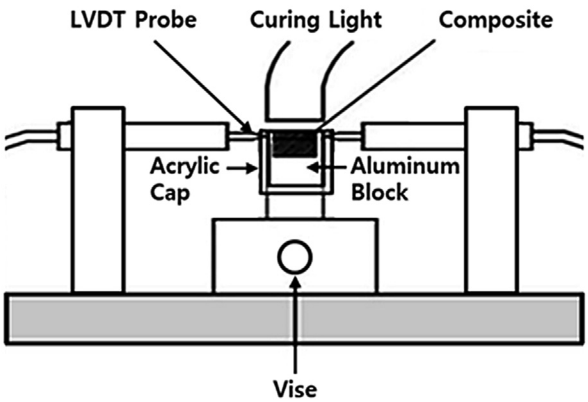

Figure 3 Schematic diagram of the instrument for measuring mold wall deflection.

beam connected to the ball bearing. The aluminum mold was fixed on a metal base, and the LVDT probe was positioned on the center of the upper border of the mold wall. A metal weight of 5 kgf was loaded onto the center of the metal cantilever beam (Fig. 4). After measuring wall displacement for both sides, mean wall displacement of an empty mold was divided by 2.5 kgf weight loading to obtain mold wall compliance (μm/N; n = 3).

Statistical analysis

Data were analyzed using one-way analysis of variance (ANOVA) followed by a post-hoc Tukey's test to evaluate statistical significance for mold wall deflections based on mold wall thickness and light-curing protocol. Analyses were conducted with SPSS software (version 23.0, SPSS Inc., Chicago, IL, USA) at $\alpha = 0.05$.

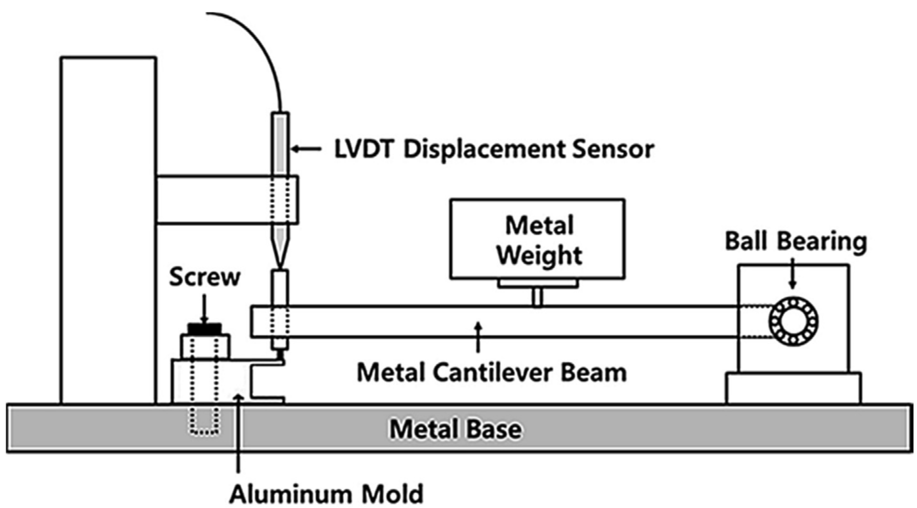

Figure 4 Schematic diagram of the instrument for measuring mold wall compliance.

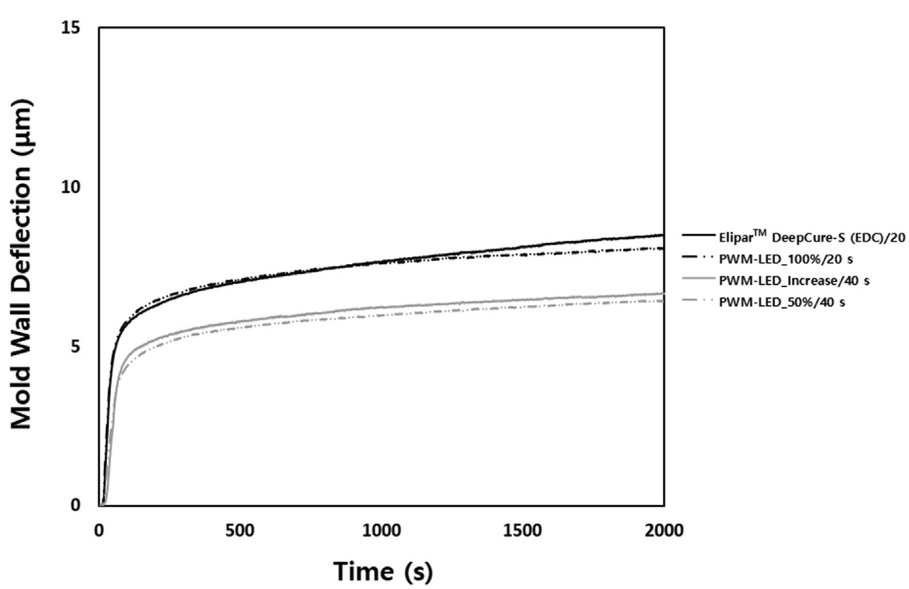

Figure 5 Representative curves of 3-mm-thick mold wall deflection as a function of time with varying light-curing protocols.

Table 3 Mean mold wall deflections (μm) of three mold wall thicknesses (1, 2, and 3 mm) restored with BFP composite with varying radiant emittance and exposure time of LED light.

Light-Curing Protocol	Aluminum Mold Wall Thickness		
	1 mm	2 mm	3 mm
	Deflection (μm)		
PWM-LED_100%/20 s	28.47 (2.43) ^{Aa}	12.84 (0.57) ^{Ba}	8.07 (0.89) ^{Ca}
PWM-LED_50%/40 s	27.95 (1.58) ^{Aa}	12.20 (0.36) ^{Ba}	6.42 (0.50) ^{Cb}
PWM-LED_Increase/40 s	27.98 (2.23) ^{Aa}	12.37 (0.84) ^{Ba}	6.63 (0.67) ^{Cb}
Elipar™ DeepCure-S (EDC)/20 s	28.14 (2.14) ^{Aa}	12.58 (1.07) ^{Ba}	8.44 (1.01) ^{Ca}

Different superscript upper-case letters indicate statistically significant differences among mold wall thicknesses with identical light curing protocols ($p < 0.05$).
Different superscript lower-case letters indicate statistically significant differences among light-curing protocols in identical mold wall thicknesses ($p < 0.05$).

Results

Wall deflection of aluminum molds during composite restoration

The representative curves of 3-mm-thick mold wall deflection as a function of time are shown in Fig. 5. Mean mold wall deflection of BFP filling decreased with increasing mold wall thickness (1, 2, and 3 mm) (Table 3; $p < 0.05$). No significant difference in mold wall deflection was observed among the four light-curing protocols at 1- or 2-mm wall thickness ($p > 0.05$). However, in the 3-mm-thick mold, wall deflections of PWM-LED_50%/40 s and PWM-LED_Increase/40 s were significantly lower than those of PWM-LED_100%/20 s and EDC/20 s ($p < 0.05$).

Wall compliance of aluminum molds

The mold wall compliances (μm/N) with 1-, 2-, and 3-mm thicknesses were 0.83 ± 0.16, 0.25 ± 0.01, and 0.17 ± 0.01 μm/N, respectively. The mold wall compliance decreased with increasing mold wall thickness.

Discussion

In the present study, to minimize errors due to differences in human tooth size and to simulate a class II MOD cavity, aluminum molds were used. The inner surface of the aluminum molds was air-abraded with Al_2O_3 powder and treated with an adhesive, promoting adhesion between composite and aluminum mold. There was no abrupt halt in movement on the continuous plot recording while the mold wall deflection measurement, so the bond strength was sufficient to produce measurable mold wall deflections during composite curing that could be detected by LVDT sensors.

The elastic modulus of aluminum was approximately 68.5 GPa between human dentin (20 GPa) and enamel (80 GPa).[26–31] Wall compliance of simulated aluminum molds ranged from 0.13 to 0.81 μm/N depending on wall thickness[4] and could be quantitatively and precisely adjusted. In addition, cuspal compliance of class II MOD tooth cavities has been measured in the range of 0.5–3.32 μm/N depending on size of the cavity.[2,25] Therefore, aluminum molds can simulate various clinical situations and allow investigation of wall deflections with minimal variations among specimens. In the present study, mold wall compliance decreased with increasing mold wall thickness and was comparable to findings from a previous study. In all light-curing protocols, the mold wall deflection of BFP fillings decreased with increased mold wall thickness, which was consistent with a previous study.[4] Assuming zero mold wall compliance, the adhesion interface will be separated when polymerization shrinkage stress of composite is greater than the bond strength between composite and mold wall.[5] In other words, if mold wall thickness increases (compliance decreases), polymerization shrinkage stress of composite can hardly be relieved and affect the adhesion interface. On the other hand, if mold wall thickness decreases (compliance increases), stress may be partially relieved by wall deflection, concluding that deflection increases as wall thickness decreases.

Mold wall deflection increased as a power function of mold wall compliance, where the order "b" of function $y = ax^b$ (x: mold wall compliance, y: mold wall deflection) was approximately 0.76 (Fig. 6). This value was comparable to the orders "b" of power function ranging from 0.46 to 0.93 in a previous study in which mold wall thickness was changed.[4] The "b" value depends on physical

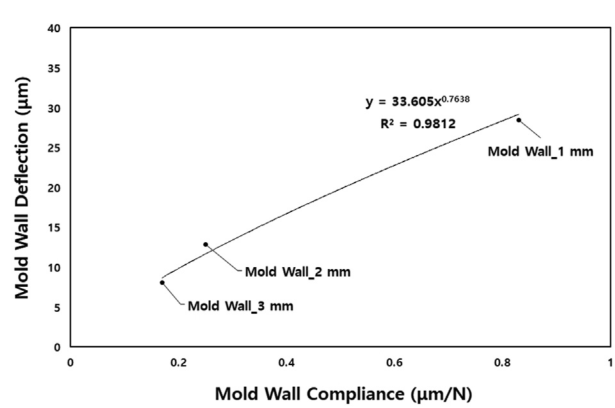

Figure 6 Mold wall deflection *versus* mold wall compliance with varying mold wall thickness (Mold Wall_1 mm, 2 mm, and 3 mm).

characteristics such as polymerization shrinkage and elastic modulus of the composite.

In high compliance cavities where the mold wall thickness was 1 or 2 mm, no significant difference in mold wall deflections was observed despite changing radiant emittance. By contrast, in the 3-mm-thick mold (i.e., low compliance cavity) mold wall deflection decreased with decreasing radiant emittance. Decreasing radiant emittance and increasing exposure time can partially relieve stress by lowering the initial polymerization shrinkage rate of composite and allowing a longer viscous flow of composite. The difference in amount of relief is reflected as the difference of mold wall deflection. In 1- or 2-mm-thick molds (i.e., high compliance cavity), considerable amounts of stress may be relieved by mold wall deflection rather than by viscous flow due to change of light-curing protocols at the initial part of the polymerization process.

Although the radiant emittance of the EDC curing light (1490 mW/cm^2) was lower than that of the PWM-LED light at 100% duty ratio (1793 mW/cm^2), no significant difference in mold wall deflection between the two light-curing units was observed. According to the manufacturer, since the EDC curing light exhibits homogeneous energy distribution and a uniform beam profile, the irradiance, which is referred to as the amount of radiant power incident on a composite surface of known dimensions at a certain distance, is reportedly similar to the radiant emittance at the end of the light-curing unit.[32] In the present study, since the irradiance (radiant power/flux on a surface of known dimensions) of the EDC may be similar to that of PWM-LED light at 100% duty ratio, no significant difference in mold wall deflection was observed between the two light-curing units.

According to the manufacturer, BFP is a high viscosity bulk-fill composite that is capable of bulk-filling up to 4 mm.[33] In the present study, mean mold wall deflections of BFP bulk-filling with 1-, 2-, and 3-mm wall thicknesses were 28.13, 12.50, and 7.39 μm, respectively. These were very similar to mean mold wall deflections of Z250 (micro-hybrid conventional type) incremental filling (1 mm: 28.4 μm, 2 mm: 14.2 μm, and 3 mm: 8.1 μm) and Tetric N-Ceram (high-viscosity bulk-fill type) bulk-filling (1 mm: 27.2 μm, 2 mm: 14.2 μm, and 3 mm: 8.7 μm) in a previous study.[4] Other studies have also reported that high-viscosity bulk-fill composites exhibited significantly lower cuspal deflections compared to conventional composites.[34,35] These results suggest that bulk-filling of high-viscosity bulk-fill composites can be clinically applied without harmful effects on composite restorations.

In the present study, mold wall deflection decreased with decreasing mold wall compliance, and the first hypothesis was accepted. Significance difference in mold wall deflections of 3-mm-thick molds when altering the radiant emittance of LED lights was observed. However, this same difference was not observed in 1- or 2-mm-thick molds, resulting in partial acceptance of the second hypothesis.

In clinical situations, compliance varies depending on size and shape of the cavity and type of tooth. Based on the present study, mold wall deflections vary with mold wall compliance. Therefore, in future studies, efforts will be required to measure compliance of various human tooth cavities to be restored, and investigation on wall deflections with changing the compliance based on mold wall thickness is necessary.

In conclusion, wall deflection of aluminum molds filled with bulk-fill composites decreased with decreasing mold wall compliance. Based on the results of this study, while restoring a tooth cavity with composites, clinicians can reduce cuspal deflection by lowering the radiant emittance of LED curing light in low compliance cavities. Reduced cuspal deflection will prevent complications or a failure and allow to ensure long-term prognosis of the composite restoration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

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