

Influence of light-curing units on the polymerization of low-shrinkage composite resins

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This study examined the effect of various light-curing units (LCUs) on the polymerization of low-shrinkage composite resins. Two different types of low-shrinkage composite resins (silorane-based and methacrylate-based) were light cured using a quartz-tungsten-halogen (QTH) (HX) unit, a single-peak light-emitting diode (LED) (DM) unit, and a dual-peak LED (GL) unit, respectively. Among the tested LCUs, HX showed the lowest light attenuation within the specimens. Among the specimens, Aelite LS and Venus Diamond showed the highest and lowest light attenuation, respectively. Silorane-based Filtek LS showed the highest degree of conversion both on the top and bottom surfaces. On the bottom surface, Grandio and Aelite LS showed the lowest (4.5–7.1%) and highest (25.0–40.0%) decrease in the degree of conversion compared to their top surface. For different LCUs, within the same resin product, the microhardness was significantly different. The silorane-based composite resin showed significantly less polymerization shrinkage than the methacrylate-based nanofiller-containing composite resins.

Keywords: Light-curing unit, Polymerization shrinkage, Degree of conversion, Microhardness, Silorane-based

INTRODUCTION

Since the development of methacrylate-based Bis-GMA, several light-curing composite resins have been developed or are under development based on the complex combinations of monomers and fillers. However, regardless of the diversity and complexity of the constituting components in the composite resins, most light-curing composite resins are polymerized by the activation of photoinitiators followed by the transformation of monomers to polymers through a chain reaction by forming cross-linking networks between molecules. As a result, paste-like viscous monomer commixtures become a solid polymer.

During the polymerization process, van der Waals forces that hold the monomer molecules convert to stronger covalent bonds with a concomitant decrease in molecular distance and free volume. This reduction causes polymerization shrinkage that induces stress and marginal discrepancies along the bonded interfaces of the restorations^{1–5}. In many cases, polymerization shrinkage causes clinical problems, such as restoration fractures, incidence of recurrent caries, marginal leakage, and postoperative sensitivity^{6–8}.

Regarding polymerization shrinkage, several causative factors associated with material formation have been identified, including the filler content, monomer chemistry, monomer structure, and additives⁹. To reduce the polymerization shrinkage and contraction stress of the composite resins, considerable efforts have been made mainly in two different areas: restoration-related and material-related. Regarding the restoration techniques, the development of new curing protocols

(soft-start, pulse, and ramping curing), incremental placement techniques, and the use of low-modulus intermediate layers have been tested^{10,11}. To develop low-shrinkage materials, efforts have been focused on increasing the filler content. Generally, the mechanical properties of the materials can be improved by increasing the filler content. Furthermore, the filler size and content in methacrylate-based composite resins have been significantly improved by introducing nanotechnology¹². Nevertheless, a high filler content can increase the elastic modulus of a material, which cannot effectively absorb shrinkage stress. Several alternatives to conventional Bis-GMA, such as modification of the monomer matrix (from typical dimethacrylate monomers to methacrylate with reduced reactive group), development of liquid crystal monomers and ring-opening systems, have been introduced. However, they still do not overcome the limitations posed on Bis-GMA-based composite resins¹³.

Recently, a low-shrinkage and tooth-colored silorane-based resin was introduced. Silorane is a hybrid compound of siloxane and oxirane molecules^{14–16}. Siloxane imparts high hydrophobicity to the silorane, so siloranes have lower water sorption and solubility than conventional methacrylate-based composites¹⁷. Oxiranes have lower polymerization shrinkage and higher strength through a cationic ring-opening mechanism^{18,19}. The key advantages of the two components (siloxane and oxirane) may impart many favorable properties to silorane.

Light-curing composite resins contain camphorquinone (CQ) as a primary photoinitiator. To activate CQ for the free radical-mediated

polymerization process, irradiation of blue external light is essential. To supply light, thus far, quartz-tungsten-halogen (QTH), light-emitting diodes (LEDs), plasma arc (PAC) units, and laser were introduced²⁰⁻²²⁾. Among them, QTH and LED units are mostly widely accepted in dental clinics. The advantage of QTH units is its broad emission spectral range, which matches well with the whole absorption spectrum of CQ. On the other hand, LED units emit much narrower light than that of QTH units. The emitted light matches with mainly at its absorption peak. Initially, the LED units did not emit light in the UV (ultraviolet) region. However, some of the recently developed LED units emit UV light in order to cure composite resins that contain any coinitiator in addition to CQ²³⁾.

Since the polymerization process is initiated by the light, understanding the light-composite resin interaction is always fundamental for the better use of composite resins in dental restoration. The purpose of the present study was to test how the different light-curing units (LCUs) affect the polymerization of low-shrinkage composite resins. For the study, light transmission, degree of conversion, microhardness, and polymerization shrinkage of the methacrylate-based and silorane-based composite resins were examined. The hypothesis to be tested is that LCUs are consistently correlated to the polymerization of low-shrinkage composite resins.

MATERIALS AND METHODS

Composite resins, LCUs, and photon count

Six commercially available low-shrinkage composite resins were selected as outlined in Table 1: one

silorane-based [Filtek LS (LS)] and five conventional methacrylate-based [Aelite LS Posterial (AL), Grandio (GD), Premise (PR), Estelite Sigma Quick (QU), Venus Diamond (VE)]. The materials were selected based on the manufacturers' claim that the products are low shrinkage.

For light curing, one quartz-tungsten-halogen (QTH) LCU [Hilux 601 (HX), First Medica, Greensboro, NC, USA] and two light-emitting diodes (LEDs) [L.E.Demetron 1 (DE), Kerr, Danbury, CT, USA; G-light (GL), GC Corp., Tokyo, Japan] were used. The emission spectra of the LCUs (Fig. 1) and the absorption spectrum of CQ were measured using a photodiode array detector (M1420, EG&G PARC, Princeton, NJ, USA) connected to a spectrometer (SpectroPro-500, Acton Research, Acton, MA, USA). The output light intensity of each LCU was approximately 900 mW/cm², as measured using a radiometer built in HX.

The abovementioned detector and spectrometer were used to measure the number of photons transmitted through the specimens of different thicknesses. Light-cured specimens with different thicknesses (diameter: 7 mm, thickness; 1, 2, and 3 mm) were placed over a stage (thickness: 1 mm) with a hole of diameter 6.6 mm. Light was irradiated from the above the hole. The detector was placed in a fixed position under the hole to count the photons with consistency.

Through the study, all the specimens were prepared at 22±2°C room temperature and 60±5% humidity conditions under a fluorescent lamp.

Degree of conversion (DC)

To evaluate the DC of the specimens, a thin slide glass (200-μm thick) was placed on the table. A metal mold

Table 1 Composition of low-shrinkage composite resins tested in the study

| Brand | Composition | Filler type/filler size | Filler content vol%/wt% | Manufacturer |
|----------------------|--------------------------|---|----------------------------|-------------------------------------|
| Grandio | Bis-GMA, TEGDMA, UDMA | Ba-Al-Borosilicate glass filler, SiO ₂ nanofillers | 71.4/87 | VOCO, Cuxhaven, Germany |
| Premise | Bis-EMA, TEGDMA | Ba-Al-Borosilicate glass filler, barium glass, silica nanofiller, prepolymerized filler (PPF) | 71/84 | Kerr, Orange, CA, USA |
| Aelite LS | Bis-GMA, Bis-EMA, TEGDMA | Glass frit, amorphous silica | 74/88 | Bisco, Inc., Schaumburg, IL, USA |
| Estelite Sigma Quick | Bis-GMA, TEGDMA | Silica-zirconia filler, composite filler | 71/82 | Tokuyama, Tokyo, Japan |
| Filtek LS | Silorane | Silanized quartz, yttrium fluoride | 55/76 | 3M ESPE, St. Paul, MN, USA |
| Venus Diamond | TCD-DI-HEA, UDMA | Ba-B-F-Al-silicate glass, SiO ₂ , nanofiller | 64.3/81.2 | Heraeus Kulzer GmbH, Hanau, Germany |

Bis-EMA: bisphenol-A-glycidyl methacrylate; Bis-GMA: bisphenol-A-glycidyl methacrylate; TCD-DI-HEA: 2-Propenoic acid, (octahydro-4,7-methano-1H-indene-5-diyl) bis(methyleneiminocarbonyloxy-2,1-ethanediyl) ester; TEGDMA: triethyleneglycol dimethacrylate; UDMA: urethane dimethacrylate.

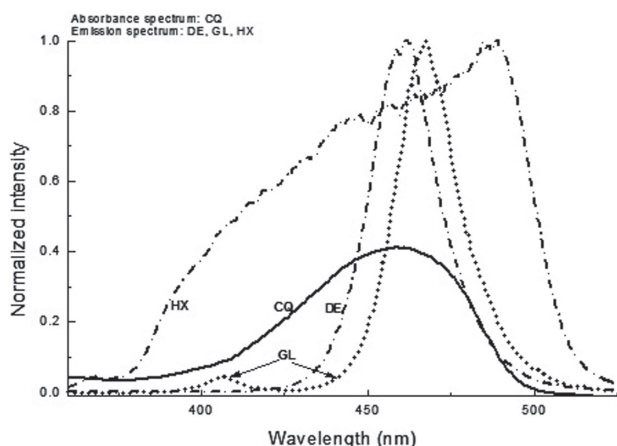


Fig. 1 Emission spectra of the LCUs used and the absorption spectrum of camphorquinone.

(inner space: 4×2×3 mm) was placed over the glass and filled with resin. The top surface of the resin-filled metal mold was covered with a thin slide glass, pressed firmly, and light cured for 40 s by contacting the light guide to the top surface of the slide glass. The light-cured specimen was removed from the mold and kept in a 37°C dark chamber for 24 h. After that, both top and bottom surface of the specimen (a thickness of 100–150 µm) were scratched using a scalpel to obtain the powder. The collected powder was dissolved in ethanol for transmission FTIR spectroscopy (Nicolet 6700, Thermo Fisher Scientific Inc., Waltham, MA, USA). The spectra were taken from 7,800–350 cm⁻¹ after thirty two scans. The resolution of the spectrophotometer was 0.09 cm⁻¹. The DC of the cured specimens was evaluated ($n=5$) using a baseline technique. For the methacrylate-based composite resins, the peak from the aliphatic C=C bonds (at 1,636 cm⁻¹) and the reference C-C aromatic ring bonds (at 1,608 cm⁻¹) were chosen. For the silorane-based composite resin (LS), the stretching vibrations of the epoxy rings C-O-C (883 cm⁻¹) and the reference CH bond (1,257 cm⁻¹) were chosen. A paste of uncured resins was also similarly tested.

Microhardness measurement

To evaluate the surface microhardness, specimens were prepared as described above in DC. After aging for 24 h in the dark chamber, the microhardness of the top ($z=0$ mm) and bottom ($z=3$ mm) surfaces were measured using a Vickers hardness tester (MVK-H1, Akashi Co., Tokyo, Japan). Microindentations ($n=15$ for each test condition) were made on each surface under a 200-gf load and a 10-s dwell time.

Polymerization shrinkage measurement

A linometer (RB 404, R&B Inc., Daejeon, Korea) was used to measure the polymerization shrinkage ($n=5$) during the light-curing process. A resin of cylinder

shape (diameter: 4 mm, thickness: 2 mm) was placed over the aluminum disc (the specimen stage of the measurement system) and secured its top surface using a slide glass²⁴. The end of the light guide was placed in contact with the slide glass. Before light curing, the initial position of the aluminum disc was set to zero. The light was irradiated from the light-curing unit for 40 s. As the resin polymerized, it shrank and the aluminum disc under the resin moved toward the light source. The amount of disc displacement that occurred due to polymerization shrinkage was measured automatically for 130 s using an inductive sensor. This shrinkage sensor was a non-contacting type and stationed below the aluminum disc. The resolution and measurement range of shrinkage sensor were 0.1 µm and 100 µm, respectively.

Statistical analysis

The results of each test were analyzed using two-way ANOVA for the LCU and resin product. A *post-hoc* Tukey test followed the multiple comparison. All tests were analyzed at $p<0.05$.

RESULTS

The number of the detected photons and the attenuation coefficient of the incident photons after curve fitting are shown in Table 2. Within the specimens, the number of incident photons decreased exponentially. Among the LCUs, HX showed the least (lowest) photon loss (attenuation coefficient) within the specimens. Among the specimens, AL and VE showed the highest and lowest attenuation, respectively, regardless of LCUs.

Table 3 shows the results of DC (%). On the top surface, LS and QU showed the highest (74.9–82.8%) and lowest DC (47.3–60.4%), respectively. On the bottom surface, GD and AL showed the lowest (4.5–7.1%) and highest (25.0–40.0%) decrease in DC, respectively, compared to that of the top surface. The specimens light-cured using the QTH unit (HX) showed a consistent and significantly different DC compared to those light-cured using the LED (DE, GL) units ($p<0.05$) both on the top and bottom surfaces. However, such significant difference did not mean any consistent superior or inferior DC values in all specimens. An inverse linear correlation was observed between the filler content and DC of the top surface at $R=0.61$ – 0.85 (for vol%) and $R=0.55$ – 0.66 (for wt%).

Table 4 shows the microhardness of the specimens on the top and bottom surfaces. Within the same resin product, the microhardness was significantly different for the LCUs ($p<0.05$), but the difference showed no consistency. Among the specimens, AL showed the highest microhardness (88.9–108.1 Hv) on the top surface. On the other hand, it showed the lowest microhardness (30.1–34.1 Hv) on the bottom surface. The linear correlation between the filler content and microhardness on the top surface was $R=0.80$ – 0.85 for wt% and $R=0.52$ – 0.59 for vol%. Among the specimens,

Table 2 Photons detected from the LCUs and estimated attenuation coefficient (AC, mm⁻¹) of the incident photons

| | | HX | | DE | | GL | |
|----|------|--------------|-------------------|--------------|-------------------|--------------|-------------------|
| | | Photon count | AC/R ² | Photon count | AC/R ² | Photon count | AC/R ² |
| GD | NS | 13813±204 | | 13915±229 | | 13805±231 | |
| | 1 mm | 7598±62 | -0.711/0.99 | 3410±28 | -1.118/0.978 | 4255±39 | -0.999/0.98 |
| | 2 mm | 3211±21 | | 1344±11 | | 1696±16 | |
| | 3 mm | 1614±15 | | 571±4 | | 781±9 | |
| PR | NS | 13859±220 | | 13859±236 | | 14070±253 | |
| | 1 mm | 6190±48 | -0.793/0.99 | 2990±19 | -1.159/0.964 | 2656±16 | -1.218/0.958 |
| | 2 mm | 2706±16 | | 1182±9 | | 1090±9 | |
| | 3 mm | 1330±13 | | 533±4 | | 458±5 | |
| AL | NS | 13653±225 | | 13704±221 | | 14015±245 | |
| | 1 mm | 2188±20 | -1.326/0.95 | 889±8 | -1.717/0.861 | 767±9 | -1.867/0.89 |
| | 2 mm | 799±11 | | 280±4 | | 250±4 | |
| | 3 mm | 342±5 | | 151±3 | | 88±2 | |
| QU | NS | 13754±242 | | 14015±252 | | 13590±235 | |
| | 1 mm | 5495±46 | -0.735/0.98 | 2626±23 | -1.106/0.927 | 3106±31 | -1.013/0.93 |
| | 2 mm | 3222±23 | | 1474±12 | | 1527±18 | |
| | 3 mm | 1590±10 | | 630±4 | | 844±9 | |
| LS | NS | 13704±227 | | 14011±245 | | 13589±227 | |
| | 1 mm | 8268±74 | -0.646/0.98 | 3944±29 | -1.021/0.972 | 4498±39 | -0.91/0.96 |
| | 2 mm | 3410±31 | | 1539±14 | | 1795±16 | |
| | 3 mm | 2015±18 | | 795±5 | | 1087±11 | |
| VE | NS | 14015±247 | | 13927±233 | | 13595±232 | |
| | 1 mm | 7715±69 | -0.632/0.99 | 4482±32 | -0.943/0.988 | 5555±49 | -0.862/0.99 |
| | 2 mm | 3960±32 | | 1997±11 | | 2310±18 | |
| | 3 mm | 2084±21 | | 906±8 | | 1070±12 | |

NS: no specimen;

HX: Hilux 601; DE: L.E.Demetron; GL: G-Light;

Table 3 Degree of conversion (DC, %) of low shrinkage composite resins for different LCUs

| | | LCU | | | <i>p</i> -value | |
|----------------|-----------------|-----------------|-----------------|-----------------|---|---|
| | Product | HX ^A | DE ^B | GL ^C | | |
| Top surface | GD ¹ | 57.4±3.1 | 63.6±2.7 | 62.9±3.2 | α <0.001 β <0.001 $\alpha\times\beta$ <0.001 | |
| | PR ² | 61.4±1.3 | 73.7±3.0 | 69.4±3.2 | | |
| | AL ¹ | 60.7±4.3 | 58.9±3.8 | 61.1±2.7 | | |
| | QU ³ | 47.3±2.6 | 58.3±2.2 | 60.4±2.8 | | |
| | LS ⁴ | 81.3±2.8 | 82.8±3.9 | 74.9±2.8 | | |
| | VE ¹ | 65.3±3.7 | 61.7±2.7 | 58.4±2.8 | | |
| | | Product | HX ^A | DE ^B | GL ^B | α <0.001 β <0.001 $\alpha\times\beta$ <0.001 |
| Bottom surface | GD ¹ | 53.3±4.9 | 59.6±1.7 | 60.1±1.6 | | |
| | PR ¹ | 52.0±2.9 | 65.3±4.3 | 57.8±4.5 | | |
| | AL ² | 38.8±3.4 | 44.2±3.9 | 36.6±3.0 | | |
| | QU ³ | 44.9±2.3 | 43.4±4.1 | 50.8±3.1 | | |
| | LS ⁴ | 72.8±3.9 | 72.8±6.3 | 69.1±1.5 | | |
| | VE ⁵ | 50.0±4.7 | 46.6±3.7 | 57.0±2.6 | | |

* Statistically significant difference on LCU is shown by superscript letters^{A,B,C}, on coinitiator-containing products by superscript numbers^{1,2,...}. Same letters or numbers are not significantly different ($p > 0.05$).

* On p -values, the letters α and β denote resin product and LCU, respectively.

Table 4 Microhardness (Hv) of low shrinkage composite resins for different LCUs

| | Product | HX ^A | LCU | | <i>p</i> -value |
|----------------|------------------|-----------------|-----------------|-----------------|--|
| | | | DE ^B | GL ^C | |
| Top surface | GD ¹ | 97.3±5.2 | 99.2±4.5 | 93.4±3.9 | $\alpha < 0.001$ $\beta < 0.001$ $\alpha \times \beta < 0.001$ |
| | PR ² | 66.5±3.4 | 68.2±3.1 | 63.5±2.8 | |
| | AL ³ | 103.8±3.9 | 88.9±3.1 | 108.1±2.6 | |
| | QU ⁴ | 54.8±1.0 | 50.2±0.5 | 52.4±1.1 | |
| | LS ⁵ | 59.1±1.6 | 51.2±1.2 | 55.4±1.1 | |
| | VE ² | 72.8±1.1 | 64.3±1.5 | 64.2±1.5 | |
| | Product | HX ^A | DE ^B | GL ^A | <i>p</i> -value |
| | | | | | |
| Bottom surface | GD ¹ | 82.1±3.5 | 95.2±2.9 | 83.4±2.5 | $\alpha < 0.001$ $\beta < 0.001$ $\alpha \times \beta < 0.001$ |
| | PR ² | 51.6±2.7 | 60.6±3.4 | 51.2±3.8 | |
| | AL ³ | 34.1±2.6 | 30.1±3.6 | 30.3±2.9 | |
| | QU ⁴ | 46.1±2.5 | 45.3±2.3 | 48.3±1.6 | |
| | LS ⁴⁵ | 42.3±1.4 | 46.0±2.2 | 46.9±1.2 | |
| | VE ⁵ | 46.6±1.3 | 46.2±2.1 | 41.1±1.8 | |

* Statistically significant difference on LCU is shown by superscript letters^{A,B,C}, on coinitiator-containing products by superscript numbers^{1,2,...}. Same letters or numbers are not significantly different ($p > 0.05$).

* On *p*-values, the letters α and β denote resin product and LCU, respectively.

Table 5 Polymerization shrinkage (μm) of low shrinkage composite resins for different LCUs

| Product | HX ^{AB} | LCU | | <i>p</i> -value |
|-----------------|------------------|-----------------|-----------------|---|
| | | DE ^A | GL ^B | |
| GD ¹ | 12.58±0.75 | 11.68±0.67 | 13.23±0.62 | $\alpha < 0.001$ $\beta = 0.06$ $\alpha \times \beta < 0.001$ |
| PR ² | 11.07±0.42 | 10.32±0.46 | 11.95±0.33 | |
| AL ² | 10.40±1.68 | 9.98±0.26 | 10.33±0.30 | |
| QU ³ | 13.13±0.21 | 13.73±0.31 | 14.10±0.37 | |
| LS ⁴ | 7.52±0.45 | 8.07±0.49 | 8.81±0.58 | |
| VE ² | 11.02±0.53 | 11.18±0.24 | 9.63±0.43 | |

* Statistically significant difference on LCU is shown by superscript letters^{A,B}, on coinitiator-containing products by superscript numbers^{1,2,...}. Same letters or numbers are not significantly different ($p > 0.05$).

* On *p*-values, the letters α and β denote resin product and LCU, respectively.

GD and AL showed the smallest (3.9–15.9%) and largest (66.1–72.0%) difference in microhardness, respectively, between the top and bottom surfaces.

The polymerization shrinkage of the specimens was shown in Table 5. Among the specimens, LS and QU showed the least (7.52–8.81 μm) and greatest (13.13–14.10 μm) polymerization shrinkage. However, within the same specimen, polymerization shrinkage was similar regardless of the used LCUs. There was a linear correlation between the filler content and polymerization shrinkage: $R=0.59$ – 0.77 for vol% and $R=0.36$ – 0.59 for wt%. The correlation between the polymerization shrinkage and DC was not consistent. In case of HX, for the top surface DC, the correlation was high and negative ($R=-0.95$, $p=0.003$), but with regard

to GL, it was much low ($R=-0.36$, $p=0.48$). On the bottom surface, the correlation was -0.18 to -0.68 depend on the LCU.

DISCUSSION

In the present study, various LCUs were used to evaluate their efficiency in the polymerization of low-shrinkage composite resins. Since the polymerization process is initiated by the light (photons), the characteristics of the incident light, such as emission spectrum, number of photons, transmission within the spectrum, are important for the preparation of the clinically acceptable dental restoration^{25,26}.

HX, the conventional QTH LCU, shows the widest

spectral distribution as that of CQ. On the other hand, LED LCUs shows a concentrated light on the absorption peak of CQ. The apparent difference between QTH and LED is the light lower than 430 nm. The advantage of QTH will be in its overall excitation of CQ molecules through the whole emission spectral range. However, the efficiency can be diminished due to photons of lower wavelength. According to the Raleigh scattering, photons of lower wavelengths will have high chance to be scattered by the fillers that have dimension greater than the wavelength of incident photons, consequently the transmission to the subsurface can be decreased²⁷. In case of LED, it may react reversely to that of QTH. Since the LED units emit no (DE) or weak light (GL) in the lower wavelengths, LED units cannot effectively activate CQ in the lower wavelengths. Among the LCUs tested, HX showed the least attenuation within the specimens. Also, among the specimens, AL attenuated the incident light most greatly: the estimated attenuation coefficient (AC) was almost double to that of VE, which had the lowest AC regardless of LCUs. The high AC implies exponentially low light transmission into the subsurface of the specimen.

There was no specific and consistent correlation among the AC, DC, microhardness, and polymerization shrinkage of the specimens in conjunction with the LCUs, which was apparent in the case of AC. In conjunction with DC, the attenuation characteristics of the incident light within the specimens do not match consistently with the DC of the top and bottom surfaces. The highest and lowest DC on the bottom surface of LS and AL, respectively, matched well with the AC values. The highest DC in LS may be related both to the lowest AC and the cationic ring-opening process, which is insensitive to the existence of oxygen. In the free-radical-mediated polymerization process, oxygen inhibits further polymerization because it can inactivate free radicals by converting them into stable species (peroxides)^{28,29}. In this process, fillers are also important. Fillers can hinder the oxygen diffusion from the atmosphere into the bulk structure, but, they can also adsorb oxygen onto their surface^{30,31}. The surface can act as pathway for diffusion. In this study, during light curing, the specimen surfaces were covered by thin slide glasses, so the oxygen supply from the atmosphere might not be easy in both specimens (methacrylated-based and silorane-based).

The highest DC on the top and bottom surfaces in LS was not reflected on the microhardness. LS showed one of the lowest microhardness both on the top and bottom surfaces despite the least light attenuation among the specimens. Such lowest microhardness, even with a high DC and low light attenuation, may be attributable to the lowest filler content. In case of AL, it showed the highest microhardness on the top surface and the lowest microhardness on the bottom surface. Such extreme microhardness would be related with the highest filler content and the greatest light attenuation among the specimens, respectively. Densely distributed

fillers within the resin matrix may attenuate the light transmission due to the frequent scattering, so photon delivery to the bottom surface and the subsequent polymerization will be diminished. In case of VE, on the bottom surface, the significant decrease in microhardness (28.1–35.9%) and change in DC (23.4/24.4%) for HX and DE compared to the top surface does not reflect the lowest light attenuation within its structure. GD showed the lowest decrease in DC, but the decrease in AC was not the lowest among the specimens examined. Overall, the DC of the specimens on the top and bottom surfaces was not consistent in conjunction with the attenuation pattern of the LCUs and specimens, and was more product-specific. Generally, greater conversion results in higher surface hardness and wear resistance, as well as better fracture resistance^{32–34}. Whereas, the mechanical properties including microhardness depend much on polymer network formation which is not always linearly correlated with conversion. Since polymers with similar conversion rates may have different crosslinking densities, conversion alone may not be a solid indicator of the resulting mechanical properties including microhardness^{35,36}. Therefore, many other factors, such as the combination and chemistry of the commixtures as well as the degree of crosslink, should be complicatedly related. However, the investigation of their complicated relationship is beyond the scope of the present study.

Polymerization shrinkage is an inevitable drawback in the current methacrylate-based monomers moiety. There are several causative factors for polymerization shrinkage, among which are material formulation factors and material polymerization factors⁹. The filler content, monomer chemistry, monomer structure and additives are examples of material formulation factors. The curing method, placement technique, and catalyst and inhibitor concentration are examples of material polymerization factors³⁷. In many cases, the filler content is related directly to polymerization shrinkage and contraction stress in dental composite materials³². Many resin products, which were claimed to have low shrinkage, have a higher filler content than ever by the introduction of nanofillers. In the present study, the shrinkage of the nanofiller-based composite resins ranged from approximately 9.6–14.1 μm for a 2-mm thick specimen depends on the resin product and LCU. These values were significantly higher than that of LS. The shrinkage of LS ranged 7.5–8.8 μm . As claimed, such low shrinkage was achieved by the ring-opening system of oxirane molecules despite the lowest filler content among the specimens examined^{18,19}. From the result, a further decrease in polymerization shrinkage from the most nanofiller-containing composite resins seems not simple because the filler content of most nanofiller-containing composite resins is so high that there is less available margin for increasing the filler content. In case of LS, it is unclear whether the shrinkage can be reduced further and the mechanical properties can be

enhanced by increasing the filler content.

CONCLUSIONS

Within the limitation of the present study, the incident light of each LCU showed a significantly different but consistent attenuation nature within the specimens. However, the DC, microhardness, and polymerization shrinkage of the specimens which reflect the degree of polymerization showed no consistent correlation with tested LCUs, as was consistently observed in the case of AC. These properties depended not more on the used LCUs, but the tested products themselves.

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