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치아 두께에 따른 광중합형 및 이중중합형 복합레진의 전환율 차이

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Differences in degree of conversion of light-cured and dual-cured composite resins depending on tooth thickness

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복합레진 수복은 종종 치아 구조를 통과하는 광중합이 요구되는데, 이로 인해 광 감쇠가 발생하여 중합이 저해될 수 있다. 이에 본 연구에서는 법랑질-상아질 시편을 통해 중합된 광중합형 및 이중중합형 복합레진의 전환율(DC)에 대한 치아 두께의 영향을 평가하였다. 사람 소구치를 절단하여 0.5, 1.0, 1.5, 2.0 mm 두께의 치아 시편을 제작하고, 시편 아래에 복합레진을 적용하여 광중합하였다. 라만 분광법을 이용하여 전환율을 정량화하였다. 광중합형 레진의 경우, 치아 두께가 1.0 mm 이상 증가함에 따라 전환율이 유의하게 감소하였다. 이중중합형 레진은 치아 두께가 1.5 mm까지는 전환율에 유의미한 변화가 없었지만, 2.0 mm에서는 전환율이 유의하게 감소하여 자가중합형 레진과 차이가 없었다. 이러한 결과는 치아 두께 증가로 인한 심각한 광 감쇠가 두 재료 모두에서 중합을 저해하며, 광 투과율이 감소할수록 이중중합의 이점도 줄어든다는 것을 시사한다.

색인단어 : 전환율, 광중합형 복합레진, 이중중합형 복합레진, 치아 두께, 라만 분광법

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Introduction

With the continuous advancement of adhesive dentistry, composite resin restorations have become widely utilized in clinical dentistry (1, 2). Composite resins are categorized based on their polymerization mechanisms into light-cured, dual-cured, and self-cured types. Dual-cure composite resin was developed to overcome the limitations of light-cure composite resin, particularly in clinical situations where light access is restricted, such as in deep cavities or areas with limited visibility. Dual-cured systems involve both a chemically initiated self-curing reaction triggered by the mixing of two components and light-induced polymerization mediated by photoinitiators (3). By combining these two systems, dural-cured resins allow rapid initial polymerization through light activation, followed by continued polymerization in deeper regions via chemical curing, thereby contributing to improved overall physical properties. Previous studies have reported that chemical curing alone may not provide sufficient mechanical properties in dual-cured resins, indicating that light activation remains essential even for dual-cured materials (4, 5).

The polymerization process of composite resins is a critical factor that affects the success and long-term clinical performance of restorations (6). The degree of conversion (DC), defined as the percentage of carbon-carbon double bonds (C=C) in monomers that are converted into single bonds (C–C), is commonly used as an indicator to assess polymerization efficiency (7-9). DC is closely related to the mechanical strength, wear resistance, and biocompatibility of composite resins (7, 8). A high DC enhances the durability and biological stability of restorations, while a low DC can lead to the presence of residual unpolymerized monomers, potentially causing discoloration, wear, microleakage, and secondary caries (6). Therefore, optimizing the polymerization conditions to maximize DC is essential for clinical success.

However, complete polymerization of composite resins is often difficult to achieve solely through light curing. In particular, when composite resins are placed in thicker increments, insufficient depth of cure may occur. For this reason, incremental layering techniques using a maximum thickness of approximately 2 mm have traditionally been recommended to ensure adequate polymerization (10). Beyond these material-related limitations, clinical conditions may further reduce effective light transmission. Difficulty in maintaining ideal light positioning and the presence of intervening tooth structure can attenuate light intensity reaching the resin, thereby compromising polymerization efficiency (8, 11). This transtooth illumination is particularly important in procedures such as the reattachment of fractured tooth fragments, where tooth structure lies between the curing light and the composite resin, potentially resulting in a reduced DC.

Although studies have investigated the extent of light attenuation through composite materials, relatively few have examined light attenuation through tooth structure. Among the limited number of previous studies, only a few have reported that increasing tooth thickness leads to greater light attenuation, thereby reducing the depth of cure and mechanical properties of light-cured composite resins (12, 13). However, most of these studies have assessed polymerization indirectly through changes in microhardness or mechanical properties, and quantitative evaluation of the degree of conversion (DC) remains limited. Although microhardness and mechanical properties are commonly used as indirect indicators of polymerization, they do not always correlate with the actual degree of monomer conversion. Moreover, systematic investigations addressing the effect of tooth thickness on the DC of dual-cured composite resins are still lacking.

Therefore, this study aimed to evaluate the effect of

tooth thickness on the degree of conversion of light-cure and dual-cure composite resins when polymerized through tooth structure, simulating clinically relevant conditions. The null hypotheses of this study were as follows: (i) There is no difference in the degree of conversion of the light-cured composite resin according to tooth thickness; and (ii) There is no difference in the degree of conversion of the dual-cured composite resin according to tooth thickness.

Materials and Methods

1. Materials and equipment used in this study

In this study, a light-cured composite resin (Filtek™ Supreme Flowable Restorative, 3M, St. Paul, MN, USA), a dual-cured composite resin (Luxacore Z Dual, DMG, Hamburg, Germany), and an LED light-curing unit (B&Lite S, B&L Biotech, Ansan, Korea) were used. Both composite resins were used in the A3 shade. Tooth specimens were prepared from sound maxillary and mandibular premolars extracted for orthodontic purposes in patients aged 18 to 30. The DC of the composite resins polymerized beneath the tooth specimens was measured using high-performance 3D imaging Raman spectroscopy (RAMANtouch, Nanophoton, Osaka, Japan).

2. Preparation of tooth specimens

The use of human teeth in this study was approved by the Institutional Review Board (IRB) of Jeonbuk National University Hospital (CUH 2025-03-044-003). A total of 10 extracted maxillary and mandibular premolars, free of caries, restorations, calcifications, resorptive defects, or any atypical hard tissue structures, were selected for specimen preparation. Each tooth was sectioned at the cementoenamel junction using a low-speed precision saw (Isomet, Buehler, Lake Bluff, IL, USA), and the cusps were flattened with a diamond bur to produce enamel-dentin discs with a diameter of 4.0 mm and a thickness of 2.0 mm. Pulp tissue within the crown was removed during specimen preparation. After conducting the experiment using specimens with a thickness of 2.0 mm, the thickness was sequentially reduced from the bottom using 600-grit sandpaper to prepare additional discs with thicknesses of 1.5 mm, 1.0 mm, and 0.5 mm (Figure 1). The ratio of enamel to dentin was measured using a scanning electron microscope, and the dentin ratio varied according to tooth thickness: 53.5% at 2.0 mm, 38.5% at 1.5 mm, 12.1% at 1.0 mm, and 3.86% at 0.5 mm.

3. Preparation of composite resin specimens

Custom metal molds were fabricated to accommodate

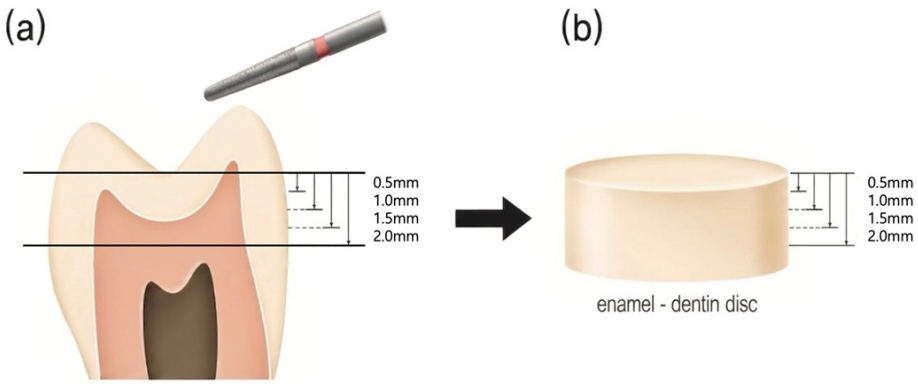


Figure 1. (a): Tooth sample preparation and (b): An enamel-dentin disc with different thicknesses.

each tooth thickness condition (Figure 2). Each mold consisted of an outer mold and a split-type inner mold. The outer mold, designed to hold the tooth specimen, was produced in thicknesses of 0.5 mm, 1.0 mm, 1.5 mm, and 2.0 mm, with a diameter of 4.0 mm to match the dimensions of the tooth specimens. However, in the self-cure composite resin group, the experiment was performed without the placement of a tooth specimen. The inner mold, also 4.0 mm in diameter and 2.0 mm in height, served as the cavity for composite resin placement and allowed easy removal of the cured specimen.

A Mylar strip was placed between the outer and inner molds, and either a light-cure composite resin (FiltekTM Supreme Flowable Restorative) or a dual-cure composite resin (Luxacore Z Dual) was injected into the mold in a single increment. Raman spectra were obtained prior to polymerization. The tooth specimen was then positioned in the outer mold, and light curing was performed for 40 seconds using an LED curing unit (B&Lite S) at an irradiance of 1140 mW/cm^2. During light irradiation, the head of the light-curing unit was fixed so that it contacted the tooth surface above the mold. The outer mold was exchanged according to tooth thickness.

All specimens were stored in distilled water at 37°C in a dark chamber for 24 hours. Five specimens were prepared for each group (n = 5). For the control group, composite resin was polymerized in the same inner mold without any intervening tooth specimen. In the self-cure group, polymerization was performed only through self-curing, without light irradiation.

4. Raman Spectroscopy

Raman spectra were obtained from the upper surface of each composite specimen using a Raman spectroscope. The system utilized a 532.06 nm laser (output power: 17.54 mW, irradiation density: 1.07 × 10^6 W/cm^2) and a 600 grooves/mm diffraction grating. Specimen surfaces were observed using a TU Plan Fluor objective lens (20×/NA 0.45), and the CCD detector was maintained at −70°C. The acquisition time was set at 60 seconds to optimize signal detection. Laser spot size and irradiation intensity were kept constant throughout all measurements. Prior to spectral acquisition, the Raman shift was calibrated using the silicon peak at 520.7 cm^{-1}. Each sample surface was scanned at three randomly selected locations. Raman spectra were collected both before and 24 hours after polymerization. The pre-cure spectrum was acquired by immediately scanning the uncured resin while positioned on a microscope slide. Post-cure spectra were obtained under identical conditions after 24 hours of polymerization. Spectra were collected in the range of 1000–2000 cm^{-1}. For each group, five specimens were

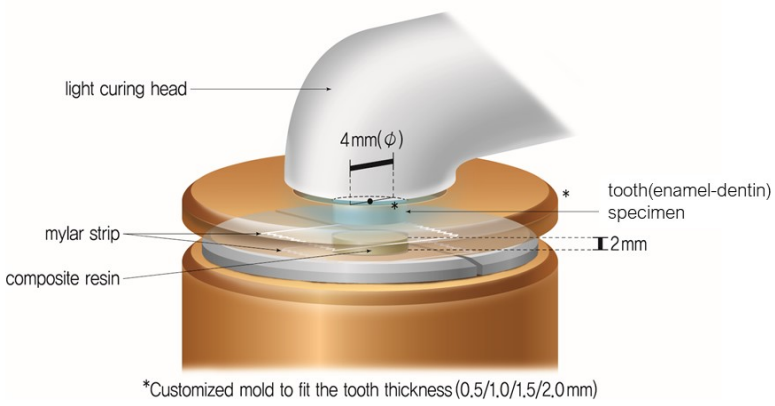


Figure 2. Schematic illustration of light curing of composite resin through tooth structure.

analyzed. Three Raman measurements were obtained from each specimen, and the mean value of the three measurements was used for statistical analysis. After normalization, peak intensities at 1609 cm^{-1}, 1637 cm^{-1}, and 1720 cm^{-1} were used to calculate the degree of conversion.

5. Calculation of degree of conversion (DC)

The degree of conversion was calculated based on the reduction in normalized peak intensity at 1637 cm^{-1} (C=C stretching band) between the pre- and post-polymerization spectra. For normalization, the 1609 cm^{-1} peak (aromatic C=C band) was used as the internal standard for the light-cured resin, while the 1720 cm^{-1} peak (C=O stretching band) was used for the dual-cured resin (7, 14, 15). The mean and standard deviation of the DC for each condition were calculated based on 15 measurements (3 per specimen × 5 specimens).

$$\text{Degree of conversion}(\%) = \left| 1 - \frac{\text{Abs}(1637\ cm^{-1})/\text{Abs}(\text{reference})_{\text{uncured}}}{\text{Abs}(1637\ cm^{-1})/\text{Abs}(\text{reference})_{\text{cured}}} \right| \times 100$$

6. Statistical analysis

All statistical analyses were conducted using SPSS version 29.0 (IBM Corp., Armonk, NY, USA). The normality was assessed using the Shapiro–Wilk test. For the light-cured groups, one-way analysis of variance (ANOVA) was performed, followed by Tukey post hoc tests. For the dual-cured groups, the Shapiro–Wilk test results did not satisfy normality, so the non-parametric Kruskal–Wallis test was applied. In addition, pairwise comparisons with Bonferroni correction were performed to check for differences between groups. The level of significance was set at p=0.05.

Results

1. Degree of conversion (DC) for the light-cured experimental groups

The results of the degree of conversion (DC) for the light-cured composite resins are summarized in Table 1. Representative Raman spectra of the light-cured composite resin before and after curing are shown in Figure 3, illustrating the reduction in the aliphatic C=C peak at 1637 cm^{-1} used for DC calculation. For the light-cured composite resin, the control group exhibited the highest DC at 73.52% (Table 1). In the experimental groups, the DC was 65.54% with a 0.5 mm tooth specimen, 57.80% with a 1.0 mm specimen, 56.61% with a 1.5 mm specimen, and 50.47% with a 2.0 mm specimen, demonstrating a decreasing trend in DC as tooth thickness increased. Statistically significant differences were observed between the control group and the 1.0 mm, 1.5 mm, and 2.0 mm groups (p<0.05), whereas no significant difference was found between the control and the 0.5 mm group (p>0.05). In addition, no significant difference was found between the 1.0 mm and the 1.5 mm group, or between the 1.5 mm and the 2.0 mm group (p>0.05).

Table 1. Degree of conversion of light-cure resin composite used in this experiment

Tooth Thickness (mm)	Polymerization Method	Degree of Conversion (%)
Control	Light cure	73.52 (0.94)^{A}
0.5	Light cure	65.54 (6.09)^{AB}
1.0	Light cure	57.80 (5.01)^{BC}
1.5	Light cure	56.61 (7.68)^{BC}
2.0	Light cure	50.47 (5.39)^{C}

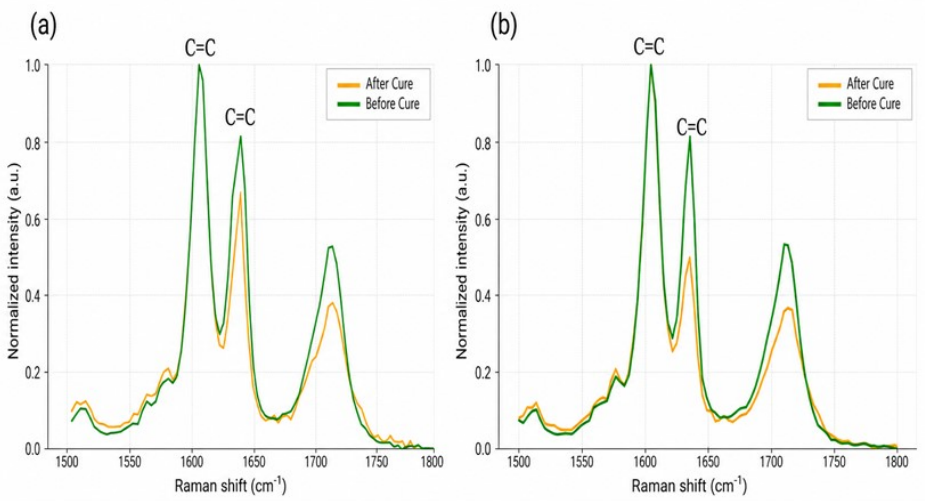


Figure 3. Representative Raman spectra of the light-cure composite resin. (a) The control group, and (b) the 2.0 mm group before and after light curing. The degree of conversion (DC) was calculated from the reduction in the normalized peak height of the 1637cm^{-1} band (aliphatic C=C stretching) between pre- and post-curing. For the light-cure composite resin, the 1609cm^{-1} band (aromatic C=C stretching) was used as an internal standard.

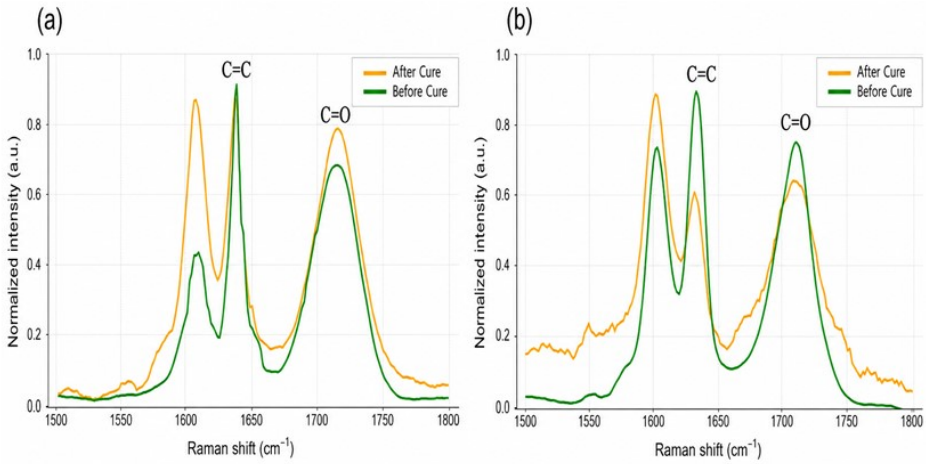


Figure 4. Representative Raman spectra of the dual-cure composite resin. (a) The control group, and (b) the 2.0 mm group before and after light curing. For the dual-cure composite resin, the 1720cm^{-1} peak (C=O stretching band) was used as an internal standard for normalization.

Table 2. Degree of conversion of dual-cure resin composite used in this experiment

Tooth Thickness (mm)	Polymerization Method	Degree of Conversion (%)
Control	Dual cure	69.08 (6.41)^{a}
N/A	Self-cure	35.83 (2.19)^{c}
0.5	Dual cure	61.43 (7.52)^{a}
1.0	Dual cure	55.79 (9.35)^{ab}
1.5	Dual cure	54.01 (1.41)^{ab}
2.0	Dual cure	46.53 (5.19)^{bc}

The control group underwent light-curing polymerization without the placement of a tooth specimen. Values having different superscript are significantly different (p<0.05). Data are presented as mean ± SD of five specimen-level values (n=5).

2. Degree of conversion (DC) for the dual-cured experimental groups

Representative Raman spectra of the dual-cured composite resin before and after curing are shown in Figure 4, demonstrating the change in the aliphatic C=C peak at 1637 cm^{-1} relative to the C=O peak at 1720 cm^{-1} used as the internal standard for DC calculation. For the dual-cured composite resin, the control group showed the highest DC at 69.08% (Table 2). The DC was 61.43% with a 0.5 mm tooth specimen, 55.79% with a 1.0 mm specimen, 54.01% with a 1.5 mm specimen, and 46.53% with a 2.0 mm specimen. No statistically significant differences were observed between the control and the 0.5 mm, 1.0 mm, and 1.5 mm groups (p〉0.05), while a significant difference was found between the control and the 2.0 mm group (p〉0.05). The self-cure group showed a DC of 35.83%, which was significantly lower than that of the control group (p〉0.05), but not significantly different from the 2.0 mm group (p〉0.05). In addition, no significant difference was found between the 1.0 mm and the 1.5 mm group, or between the 1.5 mm and the 2.0 mm group (p〉0.05).

The control group underwent dual-curing polymerization without the placement of a tooth specimen. In the self-cure group, polymerization was performed only through chemical curing, without light curing. Values having different superscript are significantly different (p〉0.05). Data are presented as mean ± SD of five specimen-level values (n=5).

Discussion

Composite resins are the most commonly used materials in restorative dentistry. The degree of conversion (DC) significantly influences the physical properties, durability, and biocompatibility of restorations. Inadequate polymerization leaves residual monomers, which may compromise long-term stability and esthetics and can diffuse into dentinal tubules, potentially causing pulpal irritation and reducing the mechanical and color stability of restorations (16-18).

In this study, Raman spectroscopy was used to quantify the effect of intervening tooth thickness on the DC of composite resins. Both light-cured and dual-cured resins showed decreased DC with increasing tooth thickness, thereby rejecting both null hypotheses. In the light-cured group, DC significantly decreased at tooth thicknesses of 1.0 mm or more (p〉0.05), likely due to insufficient light penetration through the tooth specimens. As tooth thickness increases, the number of photons available to activate camphorquinone in light-cured composite resins decreases due to absorption and scattering of light. Consequently, both the mean irradiance transmitted through the tooth structure and the effective depth of cure are reduced. Moreover, because light transmission through dentin follows a pattern of decreasing in proportion to its thickness, even small increases in specimen thickness can result in a disproportionate reduction in transmitted light energy, which may adversely affect the DC of resin composites (12, 19). In contrast, in the dual-cured group, a significant decrease in DC was observed only at 2.0 mm. Notably, at this thickness, the DC was not significantly different from that of the self-cure group in which no light curing was performed (p〉0.05), suggesting that under severe light attenuation, the dual-cure resin behaves similarly to a self-cured material. These findings highlight that dual-cure resin may not achieve optimal polymerization when tooth thickness exceeds 2.0 mm, as self-curing alone is insufficient to compensate for the loss of light in deeper regions.

Various methods exist for evaluating DC, including Fourier-transform infrared spectroscopy (FTIR), microhardness testing, and Raman spectroscopy (20-23). Raman spectroscopy, used in this study, offers a nondestructive, accurate, and rapid method for analyzing polymerization without the need for complex sample

preparation. The selection of internal reference peaks in Raman spectra is critical and must consider material-specific characteristics. For the light-cured resin, the 1609 cm^{-1} aromatic C=C band provided stable signals pre- and post-cure and was selected as the internal standard. However, in the dual-cured resin, the intensity of this peak was inconsistent. Therefore, the 1720 cm^{-1} C=O band, which exhibited greater stability, was used for normalization instead. These differences reflect the influence of material composition and curing behavior on Raman signal stability (9, 24-26). Because different internal reference bands were used for the two materials, their absolute DC values should not be directly compared.

The light-cured resin in this study (Filtek™ Supreme Flowable Restorative) exhibited a DC of 73.52% in the control group, decreasing to 50.47% at 2.0 mm. This finding is consistent with previous reports, which have documented DC ranges from 45% to 77% immediately post-cure and up to 93% after 24 hours (6, 9, 26-28). For the dual-cured resin (Luxacore Z Dual), the DC was 69.08% in the control and remained statistically unaffected up to a thickness of 1.5 mm. However, at 2.0 mm, DC decreased significantly to 46.53%, indicating that chemical curing component alone could not fully compensate for insufficient light activation. These findings align with prior studies that reported reductions in both DC and mechanical properties when light exposure was inadequate in dual-cured systems (4, 5, 25).

A novel clinical approach for light curing through tooth structure has also been introduced and is commonly referred to as transtooth illumination. This technique involves bulk placement of composite resin followed by light curing from the buccal and lingual directions through the tooth structure, and has been proposed as a means to overcome certain limitations associated with incremental filling techniques. Because light transmitted through tooth structure is attenuated, the polymerization rate of the resin is reduced, allowing continued resin flow at the bonded interface prior to vitrification. This delayed vitrification may help relieve polymerization shrinkage stress at the bonded interface, thereby improving interfacial integrity (29, 30). However, from the perspective of degree of conversion, transtooth illumination may be disadvantageous, as also demonstrated in the present study. When tooth structure is interposed between the curing light and the composite resin, light attenuation can compromise polymerization efficiency. Under such conditions, additional strategies—including extended curing time, increased irradiance, or optimization of light angulation—should be considered to compensate for reduced light transmission. Lempel et al. & de Mendonça et al. reported that doubling the curing time from 10 to 20 seconds significantly increased the DC of bulk-fill resin composites (27, 31). Collectively, these findings emphasize the importance of adjusting curing protocols according to clinical conditions in order to maximize polymerization effectiveness.

This study has several limitations. Only one light-cured and one dual-cured resin were tested; therefore, the findings may not be directly generalizable to other composite systems and may have been influenced by the specific formulations of the materials used. This limitation is particularly relevant because previous studies have shown that resin matrix composition, filler content, and initiator systems can affect DC (32). Additionally, this was an in vitro study conducted under controlled conditions. Variables present in the oral environment, such as moisture, light access angle, and cavity geometry, which are known to influence light transmission and polymerization, were not replicated. Further studies under more clinically relevant conditions and with a broader range of materials are warranted. The influence of individual variations in extracted teeth (ratio of curvature of the enamel-dentin interface, dentinal tubule density, and degree of mineralization) on light transmission is also a limitation of this study that was not considered. In addition, limitations are considered to include the statistical independence limitations due to the sequential reuse of the same tooth specimen, the optical asymmetry of pre-/post-cure

measurement conditions, and the fact that long-term post-cure polymerization changes were not evaluated because only a single 24-hour measurement was performed.

Conclusion

This study demonstrated that increasing intervening tooth thickness significantly reduced the degree of conversion (DC) of both light-cured and dual-cured composite resins when polymerized through tooth structure. The light-cured composite resin exhibited a progressive decrease in DC as tooth thickness increased, whereas the dual-cured resin showed a significant reduction in DC only at a thickness of 2.0 mm, at which point its polymerization behavior was comparable to that of a self-cured material. Limited to the products and experimental conditions used in this study, these findings indicate that severe light attenuation caused by increased tooth thickness compromises polymerization in both light-cured and dual-cured composite resins, and that chemical curing alone does not adequately compensate under such conditions. From a clinical perspective, conventional curing approaches may result in reduced polymerization efficiency when light transmission is substantially attenuated.

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Research Article

Differences in degree of conversion of light-cured and dual-cured composite resins depending on tooth thickness

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Composite restorations often require light curing through intervening tooth structure, which may compromise polymerization due to light attenuation. This study evaluated the effect of tooth thickness on degree of conversion (DC) of light-cured and dual-cured composites polymerized through enamel-dentin specimens. Human premolars were sectioned to obtain tooth specimens of 0.5, 1.0, 1.5, and 2.0 mm thickness, and composite resins were light-cured beneath the specimens. DC was quantified using Raman spectroscopy. For the light-cured resin, DC decreased significantly with increasing tooth thickness from 1.0 mm onward. The dual-cured resin showed no significant change in DC up to a tooth thickness of 1.5 mm compared to the control group; however, at 2.0 mm, DC was significantly reduced and was not different from that of the self-cured group. These findings indicate that severe light attenuation caused by increased tooth thickness compromises polymerization in both materials, and that the advantage of dual-curing diminishes when light transmission is reduced.

Keywords : Degree of conversion, Light-cured composite resin, Dual-cured Composite resin, Tooth thickness, Raman spectroscopy