Light-attenuating Effect of Dentin on the Polymerization of Light-activated Restorative Resins

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The light-attenuating effect of dentin on the mechanical properties of light-activated composite resins was evaluated using a simple experimental filter. The filter was designed to simulate the light transmittance and light diffusion characteristics of 1.0-mm thick dentin. The depth of cure, surface hardness, and flexural strength for 13 shades of three light-activated restorative resins were examined. These resins were cured either using direct irradiation with a light source, or indirect irradiation through the filter. The attenuation of light intensity by 1.0-mm thick dentin reached 85-90% in the 400-550 nm wavelength region. For all materials, the values of depth of cure, surface hardness on the top and bottom surfaces, and flexural strength of specimens irradiated indirectly through the simulated 1.0-mm thick dentin filter decreased by 37-60%, 16-55%, 50-83%, and 44-82% in comparison with those by direct irradiation, respectively. Recovery from mechanical properties' reduction was achieved when materials were irradiated 1.5-4 times longer than the standard irradiation time.

Key words: Dentin, Optical properties, Resin composite

INTRODUCTION

Light-activated composite resins have been widely used as direct filling restorative materials because of beneficial features such as easy handling, improved esthetics, and enhanced physical and mechanical properties. However, a major drawback of light-activated composite resins is that the entire material must be exposed to sufficient light to achieve thorough polymerization. A material's degree of polymerization depends on the intensity of light by which it is irradiated1-3. Less-than-optimal light intensity would provide lower polymerization efficiency, hence leading to diminished physical and mechanical properties.

In clinical situations, such as in some Class III restorations and others with undercut retentive areas, it is impossible to place a light source's guide tip directly on the top of light-activated restorative resin. This is because tooth structure blocks direct access of the light to all portions of the restoration4. Similarly, metallic bonding appliances such as orthodontic brackets, acid-etch fixed partial denture retainers, and splints with light-activated composite resins require exposing the resin indirectly through tooth structure5,6. In such cases, enamel and dentin as the tooth structure would attenuate intensity of light irradiated to the material, depending on their optical properties such as light transmittance and light diffusion characteristics5,6. Some studies have described the effects of light irradiation through enamel on light-activated restorative resins. They reported that the light-attenuating effect of enamel significantly diminished the depth of cure and hardness of resins9-10. Dentin is more opaque and thicker than enamel, and therefore might further inhibit the polymerization of light-activated resins9,10. However, studies concerning the light-attenuating effect of dentin are rarely available9.

Difficulties in examining the light-attenuating effect of dentin lie in two key areas. The first difficulty is in preparing a die of adequate size to be used as natural filter for experiments – which usually require large-size specimens. The second difficulty stems from unstable optical properties due to water in dentin being dehydrated during experiment. Against this backdrop, it is necessary to use a simple yet substantial filter that simulates the optical properties of human dentin.

In this study, a simulated dentin filter was prepared. Then, the depth of cure, surface hardness, and flexural strength of light-activated restorative resins cured directly or indirectly through the filter were examined with the aim of investigating the light-attenuating effect of dentin.

MATERIALS AND METHODS

Materials
Three commercial light-activated composite resins (Silux Plus, 3M, St. Paul, MN, USA; Palfigue Estelite, Tokuyama Dental Co., Tokyo, Japan; Lite-Fil II A, Shofu, Kyoto, Japan) used in this study are
listed in Table 1 together with their shade and code. Four or five shades of each composite resin were evaluated.

**Light transmittance and diffusion characteristics of dentin**

To determine the light transmittance and light diffusion characteristics of dentin, 10 molar teeth — which were extracted due to periodontal disease — were used. Dentin discs, 1.0 mm in thickness and approximately 6-10 mm in diameter, were sectioned transversely to the tooth axis from each tooth using a micro-slicing cutter (MC-201, Maruto Instrument Co. Ltd., Tokyo, Japan)\(^\text{10}\). Both sides of the disc were polished with #1500 emery paper and a soft polisher with 1-μm alumina suspensions. The discs were stored in a physiological saline (Otsuka Pharmaceutical Co. Ltd., Tokyo, Japan) at 5°C in preparation for measurement.

Light transmittance and its wavelength distribution were measured using a spectral transmittance meter (TM-1, Topcon Co., Tokyo, Japan)\(^\text{10,16}\). In this apparatus, CIE \(D_65\) standard light from a pulse xenon lamp passing through the specimen was detected with an integrating sphere and a photoconductive line sensor with resolving power less than 5 nm. Measurements were recorded at 5-nm intervals in the wavelength region of 380 nm to 550 nm, which covers the range of absorption wavelengths of the catalyst system of conventional light-activated resins\(^\text{17}\). Light transmittance (\%) of specimen at each wavelength was then calculated as the ratio of intensities of the incident light and transmitted light passing through the specimen.

Light diffusion characteristics were examined using a gonio photometer (GP-1C, Optec Co., Tokyo, Japan). This apparatus consisted of a metal halide lamp as a light source and an angular goniometer. The incident light was collimated and focused on the specimen, and the intensity of scattered light in the material was measured using an optical power meter (TQ82017, Advantest Co., Tokyo, Japan) rotated around the fixed specimen at different angles to the specimen's surface, as shown in Fig.1. Light transmittance angular distributions were then recorded at 5° intervals from diffusion angle of +70° to −70°.

Once specimen was removed from the physiological saline, measurements were carried out immediately to avoid dehydration.

**Simulated dentin filter**

The filter was designed such that its optical properties, such as light transmittance and light diffusion

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**Table 1** Materials used

<table>
<thead>
<tr>
<th>Material</th>
<th>Shade</th>
<th>Code</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silux Plus</td>
<td>Light</td>
<td>SP-L</td>
<td>3M(^1)</td>
</tr>
<tr>
<td></td>
<td>Universal</td>
<td>SP-U</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gray</td>
<td>SP-G</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dark Gray</td>
<td>SP-DG</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Yellow Brown</td>
<td>SP-YB</td>
<td></td>
</tr>
<tr>
<td>Palfique Estellite</td>
<td>A2</td>
<td>PE-A2</td>
<td>Tokuyama(^2)</td>
</tr>
<tr>
<td></td>
<td>A3</td>
<td>PE-A3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B4</td>
<td>PE-B4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C3</td>
<td>PE-C3</td>
<td></td>
</tr>
<tr>
<td>Lite-Fil II A</td>
<td>A3</td>
<td>LF-A3</td>
<td>Shofu(^3)</td>
</tr>
<tr>
<td></td>
<td>A3.5</td>
<td>LF-A3.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B3</td>
<td>LF-B3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C3</td>
<td>LF-C3</td>
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</tr>
</tbody>
</table>

\(^1\)St. Paul, MN, USA;
\(^2\)Tokyo, Japan;
\(^3\)Kyoto, Japan.
characteristics, were similar to those of 1.0-mm thick dentin. A mixture of two light-activated composite resins, 5 wt% of Silux Plus (Universal, 3M, St. Paul, MN, US) and 95 wt% of Lite-Fil II A (A3, Shofu, Kyoto, Japan), served as a suitable and convenient translucent material for the filter. Although some composite resins were used for the simulated enamel filters reported in a previous study\(^{18}\), the composition of the filter used in this study was entirely different from those, which composed of 95 wt% of Silux Plus and 5 wt% of Lite-Fil II A. The mixture paste was then packed into Teflon molds (\(\phi 12 \times 2.0\) mm and \(8.0 \times 30 \times 2.0\) mm). After curing, the filter was removed from the mold and polished with \#1500 emery paper and 1.0-\(\mu\)m soft polisher. Two filters with different circular and rectangular shapes of 1.59 mm thickness were prepared. Filter's thickness was determined from dentin's measurement result. The circular filter was used for depth of cure and surface hardness tests, and the rectangular filter for flexural strength test.

**Depth of cure**

The depth of cure for all light-activated composite resins was examined in accordance with ISO specification No. 4049\(^{18}\). The test material was packed into a cylindrical stainless steel mold (\(\phi 4.0 \times 6.0\) mm) open at both ends. A thin glass plate was applied to each open end, and any excess material was expressed using finger pressure. A white backing was placed beneath the mold. The material was irradiated at the top surface for 30 seconds with a light source (Luxor, ICI, London, UK) through the thin glass plate. The spectrum emitted by the light source ranges approximately between 400 nm and 500 nm in wavelength\(^{19}\), and emission outside this range is considered to be ineffective. Therefore, by eliminating radiation from the infra-red region will help to reduce heat generated by irradiation. After curing, specimens were removed from the mold. The remaining length of unprocessed hard material was then measured using a slide gauge.

**Surface hardness**

Specimens were packed into a Teflon cylindrical mold (\(\phi 12 \times 1.0\) mm), which was slightly overfilled with resin paste. Each specimen was covered by a thin glass plate, and light source was activated on the material for 30 seconds. All specimens were stored in air at 37°C for 60 minutes before testing. Knoop hardness number (KHN) measurements were taken both at the top surface (which was exposed to the light) and the bottom surface under a 100-g load for 15 seconds with a micro-hardness tester (MVK-E, Akashi Seisakusho Ltd., Tokyo, Japan).

**Flexural strength**

Flexural strength was measured in accordance with ISO No. 4049 by means of a three-point flexural support and a mechanical testing machine (TCM-IKNB, NMB Co. Ltd., Tokyo, Japan). The test material was packed into a stainless steel mold (\(2.0 \times 2.0 \times 25\) mm) and pressed with a thin glass plate. After clamping tightly, the material was irradiated at the top surface for 60 seconds with a light source (Triad, Dentsply International Inc., York, PA, US) and then removed from the mold. At 24 hours after preparation, the rectangular specimen was supported on two cylinders and loaded on the top surface with another cylinder at a cross-head speed of 0.5 mm/min until fracture occurred. Flexural strength \((\sigma)\) of specimen in MPa was calculated from the equation:

\[
\sigma = \frac{PL}{2bd^2}
\]

where \(P\): applied load (N); \(L\): distance between the two supports (mm); \(b\): width of specimen (mm); \(d\): thickness of specimen (mm).

**Prolonging irradiation time**

To investigate the effect of irradiation time on the light-attenuating effect of dentin, irradiation times for specimens irradiated indirectly through the filter were prolonged. In addition to the standard 30-second irradiation time for depth of cure and surface hardness tests, irradiation time was further prolonged to 60 seconds and 120 seconds. In addition to the 60-second irradiation time for flexural strength test, irradiation time was further prolonged to 90 seconds and 120 seconds. To facilitate measurements for the three properties with different irradiation times, both types of specimen were prepared: specimens to be irradiated directly by light source, and those irradiated indirectly through a filter placed on top of the specimen.

**Statistical analysis**

Twenty specimens divided into four groups were prepared for each material. One group of five specimens as a control was irradiated directly by light source, while the other three groups were irradiated indirectly through the filter with different irradiation time. The mean values of the three measured properties among each group were multiply compared with Student's t-test at significance level of \(p=0.05\).

**RESULTS**

**Light transmittance and diffusion characteristics of dentin and filter**

Fig. 2 shows the light transmittance distribution spectra as a function of wavelength of 1.0-mm thick dentin and the simulated dentin filter in the wavelength region of 380 nm to 550 nm. The light transmittance of dentin was the mean value of 10 specimens measured. The light transmittance of dentin increased with increasing wavelength and
showed a small broad peak around 430 nm. Both spectra of dentin and filter agreed well with each other in the region of 420 to 500 nm. Linear regression analysis between light transmittance of dentin and filter through 420 nm to 500 nm was 0.98, which was significant ($p<0.05$).

Fig. 3 shows the angular intensity distribution of the transmitted light as a function of diffusion angle of dentin and the simulated dentin filter. In the figure, the changing ratio of transmittance was the ratio of light transmittance value at each diffusion angle to the value at 0° (Fig. 1). Although dentin showed large light transmittance component around 0°, strong diffusion in sideward directions was also observed. This was because diffused light intensity decreased slowly with increasing diffusion angle, and relatively high intensities were kept at large angles.

Fig. 4 shows the values of depth of cure for all materials irradiated directly or indirectly through the filter with different irradiation time. The depth of cure at direct irradiation (Cont.-30 s) ranged from 2.5 mm for SP-YB to 5.0 mm for LF-A3, and those by indirect irradiation through the filter with standard irradiation time (Filter-30 s) ranged from 1.2 mm for SP-YB to 2.4 mm for PE-A2. The values at indirect irradiation through the filter were 40-63% lower compared with those at direct irradiation, but increased with increasing irradiation time (Filter-60 and -120 s). For all materials except SP-L, SP-U, SP-DG, and LF-A3.5, there were no significant differences between the values at direct irradiation and those through the filter with prolonged irradiation time of 120 seconds.

The values of KHN at the top and bottom surfaces of all materials were shown in Figs. 5(a) and (b). The KHN at the top surface at direct irradiation ranged from 28.1 for SP-YB to 49.4 for LF-A3, and those at indirect irradiation with standard irradiation time ranged from 17.4 for SP-U to 31.7 for LF-A3.5. The values at indirect irradiation through the filter were 45-84% lower compared with those at direct irradiation. For all materials except SP-U and PE-C3, there were no significant differences between the values at direct irradiation and those through the filter with prolonged irradiation time of 120 seconds. On the other hand, the KHN of the bottom surface at direct irradiation ranged from 15.0 for SP-YB to 47.7 for LF-A3, and those at indirect irradiation ranged from 3.5 for SP-DG to 24.4 for LF-A3. The values at indirect irradiation through the filter were 17-50% lower compared with those at direct irradiation. SP-YB, when irradiated through
the filter with standard irradiation time, was not sufficiently polymerized for measurement.

Fig. 5 shows the flexural strength values of all materials. The flexural strength at direct irradiation ranged from 30.6 MPa for SP-YB to 95.2 MPa for PE-A2, whereas those through the filter ranged from 8.4 MPa to 58.7 MPa for the same materials respectively. The values at indirect irradiation through the filter were 18-56% lower compared with those at direct irradiation. Materials with darker shade, such as SP-YB, exhibited relatively larger changing ratio than the other shades of the same material. For all materials, when the specimens were irradiated through the filter with prolonged irradiation time of 90 or 120 seconds, the values were significantly equal to or larger than those at direct irradiation.

**DISCUSSION**

In the present study, the light transmittance characteristics of the filter, including its dependence on wavelength, well simulated those of dentin — especially in the wavelength region of 420 nm to 500 nm (Fig. 2). Commercial visible light sources usually have a peak wavelength range between 440 nm and 500 nm, and this is the region required for the catalyst system of light-activated restorative resins. Dentin showed strong light diffusion characteristics, which could be due to scattering in the thick dentin specimen (Fig. 3). The light diffusion characteristics of both dentin and filter were also similar to each other, although there were small differences in their diffusion patterns.

Human dentin is a complex structure composed of collagen-based organic matrix, small inorganic hydroxyapatite crystals, and dentinal tubules permeating the entire volume. The filter — a mixture of two composite resins — was also made of volume-permeating resin with small particles as filler. When a substance is composed of different materials, its optical properties are determined by its architectonics (such as arrangement of its constituent elements) and composition. Moreover, dentin shows optical anisotropy with respect to the orientation of dentinal tubules. Therefore, the exact optical behavior in both dentin and filter may be different from each other. However, based on the good agreement in both the light transmittance and light diffusion characteristics, the efficiency of the filter in attenuating light intensity could be considered to be approximately the same as that of 1.0-mm thick dentin — but within the limited wavelength region of 420 nm to 500 nm. This study was aimed at investigating the light-attenuating effect of dentin on the physical and mechanical properties of light-activated composite resins. Nevertheless, a substitutional filter was used instead of natural dentin to overcome the latter’s limitations in terms of size, shape, and unstable optical properties.

When irradiated with standard irradiation time, all materials within the two groups — one group of specimens was irradiated directly by light source and the other irradiated indirectly through filter — showed significant changes in their values for depth

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**Fig. 6** Comparison of flexural strength for 13 shades of three materials irradiated directly and indirectly through the simulated dentin filter with different irradiation time.
of cure, surface hardness, and flexural strength (Figs. 4-6). When irradiation time was 30 seconds, the depth of cure values of resins irradiated indirectly were 37-60% lower than those irradiated directly by light source. Likewise, the KHN values of the top and bottom surfaces and flexural strength – which are important mechanical properties of a material – also greatly decreased by 16-55%, 50-83%, and 44-82% respectively. In the overall wavelength range of 380 nm to 550 nm, light transmittance of 1.0-mm thick dentin measured only 12.0±2.6%. This means that a 1.0-mm thick dentin attenuates almost 85-90% of the original incident light’s intensity in this wavelength region. Strong light diffusion characteristics would encourage the light-attenuating effect of dentin. It can be seen that the marked reduction of light intensity by dentin brought down the extent of polymerization, and hence brought low the mechanical properties of resins. It has been reported that decrease in a material’s mechanical properties is closely correlated to some clinical problems of restorations, such as staining, marginal fracture, loss of anatomic form, and marginal leakage.

Nevertheless, when irradiation time was prolonged, this study showed that reduced mechanical properties could be improved significantly. All measured properties of the groups irradiated through the filter improved with increasing irradiation time. For most of the materials tested, reduced depth of cure, hardness, and flexural strength could be recovered if they were irradiated 1.5-4 times longer than the standard irradiation time. For LF, the increases in flexural strength at prolonged irradiation time were significantly greater than those for depth of cure. This indicates that the mechanical properties of a material may be more sensitive to light intensity reduction, arising from the light-attenuating effect of dentin.

In clinical situations, the maximum thickness of dentin that shadows the restoration from irradiation light would be approximately 2 mm and more. This study was conducted using 1.0-mm thick dentin. Hence, values of all measured properties would further reduce as the thickness of dentin increased. From the results, the magnitude of decrease in properties varied with different materials and shades. But on the overall, the light-attenuating effect of dentin reduced the intensity of the original light, and thereby significantly reduced the mechanical properties of light-activated restorative resins. Therefore, in clinical situation, if light-activated restorative resin is used in such a situation where light intensity might be attenuated by dentin, special care for clinical performance would have to be undertaken to minimize reduction of restoration’s mechanical properties. Although prolonging irradiation time could compensate the light-attenuating effect of dentin, it might require irradiation time longer than 30-90 seconds and might cause undesirable temperature rise. Moreover, the effects of dentin thicker than 1.0 mm must be ascertained in further investigations. To avoid restorations with poor mechanical properties due to the above-mentioned constraints, the advantages of auto-activated restorative resin may be realized again.

The simulated dentin filter used in this study could simulate the light transmittance and light diffusion characteristics of dentin of various thicknesses, and could be simply customized to any size and shape required for the tests. Moreover, the filter was free from any unstable optical properties arising from dentin dehydration or deterioration. This technique might indeed be a simple and useful method for examining the light-attenuating effect of dentin.

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