Effect of Inhomogeneity of Light from Light Curing Units on the Surface Hardness of Composite Resin

Hiroyuki ARIKAWA¹, Takahito KANIE¹, Koichi FUJII¹, Hideo TAKAHASHI² and Seiji BAN¹
¹Department of Biomaterials Science, Graduate School of Medical and Dental Sciences, Kagoshima University, 8-35-1
Sakuragaoka, Kagoshima 890-0075, Japan
²Department of Electronics Engineering, Faculty of Engineering, Shibaura Institute of Technology, 3-7-5 Toyoasu, Koto-ku,
Tokyo 135-8548, Japan
Corresponding author, Hiroyuki ARIKAWA; E-mail: hiro@dentb.hal.kagoshima-u.ac.jp

Received June 17, 2007/Accepted July 25, 2007

This study investigated the characteristics of output light from different types of light curing units, and their effects on polymerization of light-activated composite resin. Three quartz-tungsten-halogen lamps, one plasma arc lamp, and one LED light curing unit were used. Intensity distribution of light emitted from the light guide tip was measured at 1.0-mm intervals across the guide tip. Distribution of Knoop hardness number on the surface of resin irradiated with the light curing units was also measured. For all units, inhomogeneous distribution of light intensity across the guide tip was observed. Minimum light intensity values were 19–80% of the maximum values. In terms of surface hardness, inhomogeneous distribution was also observed for the materials irradiated with the tested units. Minimum values were 53–92% of the maximum values.

Our results indicated that markedly inhomogeneous light emitted from light curing unit could result in inhomogeneous polymerization in some areas of the restoration below the light guide tip.

Keywords: Light curing unit, Light intensity, Knoop hardness number

INTRODUCTION

Light-activated composite resins are widely used as direct filling restorative materials because of their easy handling, good aesthetics, and improved physical and mechanical properties. However, a persistent disadvantage besets the light-activated composite resins: all parts of the material must be exposed to sufficient light to achieve thorough polymerization. The degree of polymerization of the material depends on the intensity of light emitted from the light curing unit with which it is irradiated. A suboptimal light intensity results in lower polymerization efficiency, which might cause diminished physical and mechanical properties and color stability of the material. Therefore, numerous studies have investigated the light characteristics of light curing units (including wavelength distribution and light intensity) and the curing conditions (such as fluctuations in line voltage and degradation of light bulb and guide)¹⁰⁻¹⁷.

Most studies on radiation characteristics and resin polymerization have assumed that light curing units always emits homogeneous, uniform light across the light guide tip, and that polymerization of the resin surface is homogeneous. However, industrial light units used for xerographic printers and facsimiles—which need extremely homogeneous light—tend to emit somewhat inhomogeneous radiation⁹. In the same connection, dental light curing units that use quartz-tungsten-halogen lamps, plasma arc lamps, or light-emitting diodes (LEDs) may also emit inhomogeneous radiation. Intensity distribution of output light from a light curing unit depends on the shape of the light bulb and the optical system, including the optical filter and light guide in the light curing unit. Inhomogeneous radiation could cause incomplete polymerization, resulting in inhomogeneous physical and mechanical properties affecting the restoration. Although a few studies⁸⁻¹⁰ have suggested that differences exist in light intensity at different points over the face of the guide tip, little information is available on the homogeneity of radiated light and its effect on polymerization efficiency.

Against this backdrop of information scarcity, this study was undertaken with twofold objectives to investigate: (1) the characteristics of output light from different clinical light curing units, in particular the distribution of light intensity across the light guide tip; and (2) the effect of radiation inhomogeneity on polymerization efficiency, as determined by the surface hardness of light-activated composite resin.

MATERIALS AND METHODS

Light curing units
Table 1 lists the details and codes of the light curing units used in this study: three quartz-tungsten-halogen (QTH) lamps, one plasma arc (PAC) lamp, and one LED light curing unit.

The QTH lamps contained halogen light bulbs with a quartz-tungsten filament and reflector as the light source. QTH-J (Jetlite 1000, J. Morita USA, Tustin, CA, USA) and QTH-W (Wite Lite, Takara
Belmont Corp., Osaka, Japan) were handpieces that contained 75 W (Osram GmbH, Munich, Germany) and 35 W (Philips, Eindhoven, The Netherlands) bulbs respectively, a low bandpass optical filter for limiting the wavelengths that cause heating, and a curved light guide tip (φ11 × 90 mm long). The guide tips of both units consisted of many hexagonal glass fibers fused together into a solid bundle. QTH-L (Luxor Model 4000, ICI, Macclesfield, UK) comprised a 150 W bulb (GE Co., Cleveland, OH, USA), an optical bandpass filter, and a long light guide of randomly bundled fine glass fibers (φ8 × 1300 mm long).

The LED (Translux Power Blue, Heraeus-Kulzer GmbH & Co., Hanau, Germany) light curing unit comprised a single 5 W blue LED device, an aspheric condenser lens, and a curved light guide tip of glass fibers fused into a bundle (φ8 × 90 mm long) in a handpiece.

The PAC (Credi II, 3M Health Care Ltd., Tokyo, Japan) was equipped with a 300 W xenon plasma arc bulb with reflector (3M) and bandpass filter, and a long light guide consisting of randomly bundled acrylic fibers (1400 mm long) with a curved light tip of glass fibers fused into a bundle (φ10 × 90 mm long).

The LED and PAC were brand new. Although other units have been used for several experiments in recent years, old light bulbs were replaced with new bulbs for this study. Similarly, optical filters and ends of light guide were cleaned and confirmed to be free from contamination by light microscopy. All the light units were used in standard mode in this study, as recommended by their manufacturers. Figure 1 shows a photograph of the light emitted from the guide tip of the PAC.

### Inhomogeneity of radiated light

**Table 1 Light curing units used in this study**

<table>
<thead>
<tr>
<th>Light curing unit</th>
<th>Code</th>
<th>Light bulb</th>
<th>Light source</th>
<th>Size of bulb</th>
<th>Guide tip diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jetlite 1000</td>
<td>QTH-J</td>
<td>75 W Halogen lamp</td>
<td>8.5×9.5 mm oval, φ31 mm reflector</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>Luxor Model 4000</td>
<td>QTH-L</td>
<td>150 W Halogen lamp</td>
<td>10×11 mm oval, φ42 mm reflector</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Wite lite</td>
<td>QTH-W</td>
<td>35 W Halogen lamp</td>
<td>φ8.5 mm, φ29 mm reflector</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>Translux Power Blue</td>
<td>LED</td>
<td>5 W Blue LED</td>
<td>φ6 mm</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Credi II</td>
<td>PAC</td>
<td>300 W Plasma-arc lamp</td>
<td>φ8.0 mm, φ74 mm reflector</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

**Radiated light intensity distribution**

Intensity distributions of light emitted from the light guide tip of all the light curing units were measured using an acrylic optical fiber (φ1.0 × 300 mm long) and a high-precision optical power meter with an optical demodulation sensor (TQ8210 and TQ82017, Advantest Co., Tokyo, Japan), as shown in Fig. 2. Sensor sensitivity was compensated at a wavelength of 470 nm. Light radiating from the guide tip was conducted through the optical fiber, and light intensity was measured in a dark room using the power meter. The end of the optical fiber was mounted on a miniature X-Y axis stage, and was scanned manually from the center to the edge at 1.0-mm intervals across the face of guide tip. Light intensity was measured at each point across the light guide tip as shown in Fig. 3. Light intensity was evaluated as the relative intensity to the maximum value for each light curing unit. The inhomogeneity ratio of light intensity was defined using the ratio of minimum (I_min) to maximum (I_max) for all the measured values, and was calculated as follows:

\[
\text{Inhomogeneity ratio} = 1 - \frac{I_{\text{min}}}{I_{\text{max}}}
\]

**Surface hardness test**

One commercial light-activated restorative composite resin (Lite-Fil II A, A3, Shofu, Kyoto Japan) was used as the test material. The material contained 82.4% microfiller particles by weight and camphorquinone as the photoinitiator. Specimens were packed into a

---

Fig. 1 Representative image of inhomogeneous light emitted from the light guide tip of a dental light curing unit (PAC). The light was attenuated by the ND filter.
stainless steel mold with a cylindrical hole (ϕ 12 × 1.0 mm) on a glass plate. The resin paste was covered by a thin glass plate, and then a second glass plate was placed over the thin glass plate. Finger pressure was exerted to extrude excess material.

After the upper plate was removed, the material was irradiated through the thin glass plate for a total of 30 seconds with the QTHs and LED, and for five seconds with the PAC, with the light guide tip at 0.1 mm from the material, according to the manufacturers' recommendations. Distribution of Knoop hardness number (KHN) on the top surface of the specimen, which was exposed to the light, was measured under a 100-g load with a dwell time of 30 seconds using a microhardness tester (MVK-E, Akashi Co., Tokyo, Japan). Measurements were made at 1.0-mm intervals from the center to the edge — which corresponded with the edge of guide tip of the light unit — across the surface of the specimen, in the same manner that light intensity distribution was measured (Fig. 3). All specimens were stored in air at 37°C for 24 hours before testing. Five specimens were used for each test, and three readings were made at each measurement point. Surface hardness was evaluated as the relative hardness to the maximum value of KHN for each light curing unit. The inhomogeneity ratio of KHN was defined using the ratio of KHN minimum (H_{min}) to KHN maximum (H_{max}) for all measurement points, and was calculated as follows:

\[
\text{Inhomogeneity ratio} = 1 - \frac{H_{\text{min}}}{H_{\text{max}}}
\]

**Statistical analysis**

Multiple comparisons of the mean values of the measured properties of light intensity and KHN were made using Student's t-test at a significance level of \( p = 0.05 \).

**RESULTS**

**Radiated light intensity distribution**

Figure 4 shows the intensity of radiated light across the guide tip at 0.1 mm distance from the tips of the five light curing units. In the figures, light intensity at each measurement point was normalized using the maximum light intensity (I_{max} = 1) of each light curing unit. Light intensity differed from location to location across the light guide tip for all units. The distribution pattern also differed among the units. For all the QTHs and PAC, a markedly inhomogeneous distribution of radiated light intensity was observed. By contrast, the LED showed a more homogeneous distribution in comparison with the other units.

Table 2 shows the maximum (I_{max}) and minimum
Table 2  Maximum and minimum values of light intensity at measurement points across the face of the guide tip for all the light curing units tested and KHN of specimens irradiated with the light curing units

<table>
<thead>
<tr>
<th>Light-curing unit</th>
<th>Light intensity (μW)</th>
<th>KHN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max</td>
<td>Min</td>
</tr>
<tr>
<td>QTH-J</td>
<td>1873.3(18.6)</td>
<td>589.3(50.0)</td>
</tr>
<tr>
<td>QTH-L</td>
<td>2193.5(8.4)</td>
<td>689.3(53.3)</td>
</tr>
<tr>
<td>QTH-W</td>
<td>1987.9(26.5)</td>
<td>541.7(72.1)</td>
</tr>
<tr>
<td>LED</td>
<td>1413.7(24.3)</td>
<td>1126.3(60.8)</td>
</tr>
<tr>
<td>PAC</td>
<td>4721.5(62.7)</td>
<td>890.3(32.5)</td>
</tr>
</tbody>
</table>

Mean value with standard deviation in parentheses

Fig. 4  Comparison of intensity distributions of radiated light across the guide tip at 0.1 mm distance from the guide tips of five light curing units: (a) QTH-J; (b) QTH-L; (c) QTH-W; (d) LED; (e) PAC.

Fig. 5  Comparison of the inhomogeneity ratios of light intensity at 0.1 mm distance from the light guide tip to the sensor. Bracket-connected groups mean that they do not differ statistically (p>0.05).

Fig. 6  Variation of inhomogeneity ratios of light intensity with distance from the light guide tip to the sensor.
values \( I_{\text{min}} \) of light intensity at 0.1 mm distance from the tip at measurement points across the face of the guide tip for all the light curing units. PAC had significantly higher maximum light intensity in comparison with the other units. For all units, minimum light intensity values were 19–80% of the maximum values.

Figure 5 shows the inhomogeneity ratios of light intensity at 0.1 mm distance from the tip. A higher value of inhomogeneity ratio implied greater inhomogeneity in the distribution of light intensity. The obtained inhomogeneity ratios were 0.69 for QTH-J, 0.70 for QTH-L, 0.73 for QTH-W, 0.20 for LED, and 0.81 for PAC.

Figure 6 then shows the inhomogeneity ratios with distance between the face of the guide tip and the optical fiber. For all the light curing units except QTH-W and PAC at 5.0 mm distance from the tip, no significant differences in inhomogeneity ratio were observed among the values obtained at different distances from the guide tip.

**Surface hardness distribution**

Figure 7 shows the KHN distributions on the top surfaces of specimens exposed to the light curing units at 0.1 mm distance from the tip. In the figures, KHN at each measurement point was normalized using the maximum value \( H_{\text{max}} = 1 \) of each light curing unit. The distribution patterns corresponded roughly with those of light intensity for all units. The maximum \( H_{\text{max}} \) and minimum values \( H_{\text{min}} \) of KHN at measurement points on the surfaces of specimens irradiated with the light curing units are also shown in Table 2. For all specimens, the minimum values were 53–92% of the maximum values. Figure 8 shows the inhomogeneity ratios of KHN across the surfaces of the specimens. The values were 0.41 for QTH-J, 0.27 for QTH-L, 0.47 for QTH-W, 0.08 for LED, and 0.40 for PAC.

**Fig. 7** Comparison of KHN distributions on the top surface of specimens irradiated with five light curing units: (a) QTH-J; (b) QTH-L; (c) QTH-W; (d) LED; (e) PAC.

**Fig. 8** Comparison of the inhomogeneity ratios of Knoop hardness number of specimens irradiated at 0.1 mm distance from the tip. Bracket-connected groups mean that they do not differ statistically \( (p>0.05) \).
Inhomogeneous intensity distribution of radiated light may be attributed to an inherent flaw of light curing units using light bulbs and light guides (Fig. 1). Many factors interfere with the homogeneity of light radiated from the guide tip to the material, including the optical system, degradation of the optical filter, damage to the light guide, and contamination of the light guide tip. In particular, the optical system—comprising the light bulb, reflector, condenser lens, and light guide consisting of numerous fine optical fibers—plays an important role in generating inhomogeneous radiation light.

With the QTH lamps, the light bulb emitted inhomogeneous light due to these two factors: (1) the bulb, being the center of luminescence, had a long, non-flat tungsten filament in a coil shape; and (2) rough alignment between the light bulb and reflector. As for the PAC bulb and LED device, their centers of luminescence were two closely placed electrodes and a small semiconductor respectively. Similarly, these configurations could not produce completely homogeneous light. Moreover, a suboptimal optical arrangement of the condenser lens, optical filter, and light guide would impair the homogeneity of radiated light. Not surprisingly therefore, our results showed drastic variations in light intensity at different points across the face of the guide tip for all the light curing units tested (Fig. 4).

The inhomogeneity ratios of the QTHs and PAC reached 0.69–0.81, indicating a marked inhomogeneity in light intensity distribution on the irradiation plane over the material (Fig. 5). Main et al.9 and Moseley et al.10 assessed the radiation light of UV and visible QTH dental light curing units, and reported on non-uniform distribution of the radiated light. Their reported minimum intensity values at 20–39% of the maximum values across the light guide were similar to our inhomogeneity ratio values of the QTHs.

The greatest inhomogeneity in radiated light was observed for PAC, for which the minimum light intensity was only 19% of the maximum intensity (Table 2). For the PAC used in this study, several factors affected the distribution of the radiated light, such as the very large size of the light bulb and a light guide consisting of very loose acrylic fibers randomly bundled together (Fig. 1). The latter factor thus caused a more inhomogeneous distribution of radiated light intensity than the other light units.

In contrast, the LED could emit relatively homogeneous light because of two factors: (1) small, flat, filament-less light luminescence in the LED device; and (2) a simple, efficient optical system with an appropriate condenser lens in the unit. Therefore, it was clearly shown here that different optical systems among the different light curing units could cause different light intensity distribution patterns.

One way to compensate for the inhomogeneity of radiated light may be to increase the distance between the light guide tip and material. When a light beam is radiated from the optical fiber bundled into the guide tip, it disperses to a certain degree as it leaves the fiber and overlaps with beams from the other fibers, as shown in Fig. 9. The resultant overlapping effect of many beams thus leads to homogeneity—which should increase with increasing distance from the guide tip to the material. However, for QTH-J, QTH-L, and LED, no significant differences in the distribution of radiated light intensity were observed at all distances up to 5.0 mm from the guide tip to the light sensor (Fig. 6). Although QTH-W and PAC had lower inhomogeneity ratios at the maximum distance of 5.0 mm, significant inhomogeneous light intensity distribution remained. The dispersion degree of light radiated from the light tip depends on the numerical aperture (NA) of the optical fiber, which characterizes the range of angles over which the system can emit light. The NA of a step-index optical fiber is defined as follows:

\[
NA = \sin(\theta_{\text{max}}) \equiv n_1 \sqrt{2\Delta}
\]

\[
\theta_{\text{max}} = \sin^{-1}(NA)
\]

where \(\theta_{\text{max}}\) is the half-angle of the maximum cone of radiated light that can exit the fiber (Fig. 9), \(n_1\) is the refractive index of the core, and \(\Delta\) is the difference in refractive index between the core and cladding of the optical fiber.

The NA of general optical fibers ranges from 0.3 to 0.5, thereby rendering \(\theta_{\text{max}}\) to be 17–23°. For an optical fiber with \(\phi 1.0 \text{ mm} \) and NA at 0.5, the cal-
calculated diameter of the cone of light irradiating the material surface at a distance of 5.0 mm was 1.4 mm. Therefore, beams from adjacent optical fibers in the guide tip would not overlap each other perfectly on the material even when the tip was 5.0 mm from the surface. However, a distance greater than 5.0 mm would cause a marked decrease in light intensity. Therefore, inhomogeneity of radiated light could not be compensated effectively by increasing the distance between the guide tip and material to 5.0 mm.

In terms of KHN, the inhomogeneity ratios across the surfaces of the specimens exposed to the light curing units were smaller than those for light intensity. Nonetheless, significant inhomogeneity occurred in surface hardness distribution for all the irradiated specimens (Figs. 7 and 8). Despite its high-power light source, even the PAC could not eliminate the inhomogeneity in surface hardness (Table 2). This indicated that markedly inhomogeneous light emitted by light curing unit could significantly affect the polymerization of a material.

Chen et al. reported on disagreement between the non-uniform surface hardness distribution of a material and uniform radiated light calculated using the photon migration model. However, they did not consider the effect of inhomogeneity of light radiating from the light curing unit. As for Pilo et al., they reported that a mere 10% decrease in light intensity at the surface of a composite resin caused a significant decrease in the polymerization of the resin. Although it is clinically difficult to detect inhomogeneity in the surface hardness of a restoration, results in this study indicated that inhomogeneity in radiated light resulted in inhomogeneous polymerization in some areas of the restoration below the guide tip (Figs. 4 and 7). Such inhomogeneous effect might then cause locally inferior physical and mechanical properties, low color stability, and increased water sorption of the restoration. Any contamination and degradation of the light bulb, optical filter, and light guide fiber would also increase the inhomogeneity of radiated light and polymerization of the restoration.

Miyaji reported that a carefully designed industrial light unit resulted in a light intensity inhomogeneity that was less than 10%, which was significantly lower than the values obtained for the dental light curing units examined in this study. Although our results may not apply to all commercial light curing units, most dental light curing units lack an efficient optical system that can compensate for an inhomogeneous light intensity distribution. In view of this current status of dental light curing units, it is thus necessary to further investigate and pursue other means to compensate for the inhomogeneity of radiated light so as to obtain a more homogeneous light quality.

CONCLUSIONS

Our results revealed drastic variations in radiated light intensity at different points across the face of the guide tip for all the light curing units tested. In particular, the QTH and PAC units, as compared to LED, showed marked inhomogeneity in light intensity distribution on the irradiation plane over the material. It was also found that inhomogeneity of radiated light could not be effectively compensated by increasing the distance between the guide tip and material. Consequently, markedly inhomogeneous light radiated by the dental light curing unit significantly affected the polymerization of the material.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support provided by Mr. Ken Miura and Mr. Takuro Mikami, Kagoshima University Dental School. This work was partially supported by a Grant-in-aid for Scientific Research from the Japan Society for the Promotion of Science.

REFERENCES

Inhomogeneity of radiated light


