Original Article

Evaluation of Light Curing Units Used for Polymerization of Orthodontic Bonding Agents

Nanako Oyama, DDS[a]; Akira Komori, DDS, PhD[b]; Rizako Nakahara, DDS, PhD[c]

Abstract: This study evaluated the light intensity of various light curing units, the effect of distance of the light guide, and the validity of a tapered light guide. Light curing units tested included (1) four blue light–emitting diode curing units, Lux-O-Max, LEDemetron1, Ortholux LED, and The Cure; (2) two tungsten-quartz halogen curing units, Optilux 501 and Co-bee; and (3) one plasma arc curing unit, Apollo95E. The Optilux 501 was also evaluated for combinations of normal mode and boost mode and Standard tip and Turbo tip light guide. The spectral output of each unit was measured from 300 to 600 nm with a spectroradiometer. The light intensities at distances of zero, five, 10, 15, and 20 mm were determined with the radiometer. The peak value of Ortholux LED and The Cure surpassed that of Apollo95E. The light intensity significantly decreased with distance. Although The Cure showed a higher light intensity than the LEDemetron1 at zero-mm distance, the light intensity of the LEDemetron1 was higher than that of The Cure at five to 20 mm, resulting in no significant difference. The boost mode increased light intensity at any distance. Although the Turbo tip enhanced light intensity at zero-mm distance, reduction of light intensity by Turbo tip was demonstrated at five- to 20-mm distance. (*Angle Orthod* 2004;74:810–815.)

Key Words: Light curing units, Blue light–emitting diode, Tungsten-quartz halogen, Plasma arc

INTRODUCTION

The use of light-cured bonding systems has become popular since photoactivated materials were developed.[1–3] Such bonding systems have been widely accepted among orthodontists because of their ease of use and the extended time available to obtain proper bracket position before polymerization is initiated. Most visible light–cured resins use camphorquinone, which is sensitive to light in the blue region of the visible light spectrum, with peak absorption at approximately 470 nm. Free radicals are produced and initiate the polymerization.[4,5]

Tungsten-quartz halogen curing units (TQH) have been conventionally used as the source of visible light. TQH is an incandescent lamp that produces a broad spectral emission. Much of this is infrared energy that generates heat, and therefore the lamp becomes extremely hot. Because of this heat generation, the power loss reaches 70%, and less than 1% of the electrical energy is used for light emission. In addition, the light intensity decreases to 10% when a filter is used to reduce infrared energy and obtain the optical wavelength range required for curing composite resin.[6,7] Halogen bulbs have a limited effective lifetime of around 100 hours and reduce power output by degrees because of the high temperature produced and deterioration of the components.[8] These units deliver 400–900 mW/cm^2, and a 40-second light curing time per site is recommended to gain an adequate polymerization.[9,10] The total light curing time thus approaches 15 minutes, which is too long for both the orthodontists and the patients. To resolve these disadvantages, modifications have been performed that increase the light intensity by the use of improved light guides, such as a tapered light guide.[11–13]

In the late 1990s, the plasma arc curing unit (PAC) was introduced as an alternative for rapid light curing. It uses a high-frequency electrical field to generate its plasma energy. It does this by transforming xenon gas into a mixture of ions, electrons, and molecules thereby releasing a significant amount of energy as plasma.[14] PAC produces high-intensity lights delivering more than 1800 mW/cm^2, which is nearly fourfold greater compared with the conventional TQH, and the light can be filtered to a narrow bandwidth concentration of 450–500 nm for peak absorption of campherquinone.[14] Other studies stated that two to three seconds were insufficient to achieve adequate cure, and that six to nine seconds produced an adequate physical property

[a] Instructor, Orthodontic Unit, Nippon Dental University Hospital, Tokyo, Japan.

[b] Assistant Professor, Department of Orthodontics, Nippon Dental University, Tokyo, Japan.

[c] Professor and Chair, Department of Orthodontics, Nippon Dental University, Tokyo, Japan.

Corresponding author: Akira Komori, Department of Orthodontics, Nippon Dental University, 2-3-16 Fujimi, Chiyoda-ku, Tokyo 102-8158, Japan (e-mail: komo@msi.biglobe.ne.jp)

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TABLE 1. Light Curing Units Used

Light Units	Source	Output Mode	Light Guide	Manufacturer
Lux-O-Max	LED	—	8 mm	Akeda Dental A/S, Lystrup, Denmark
LEDemetron1	LED	—	11 mm	Sybron Dental Specialties/Kerr, West Collins, Orange, Calif
Ortholux LED	LED	—	8 mm	3M Unitek, Monrovia, Calif
The Cure	LED	High power	—	Spring Health Products, Norristown, Pa
Optilux501	Halogen lamp	Normal	11-mm standard tip	Sybron Dental Specialties
		Normal	8-mm turbo tip	
		Boost	11-mm standard tip	
		Boost	8-mm turbo tip	
Co-bee	Halogen lamp	—	11 mm	GC Corporation, Tokyo, Japan
Apollo95E	Xenon arc lamp	—	8 mm	Dental/Medical Diagnostics, Woodland Hills, Calif

of resins and resin-reinforced glass ionomer cements equal to those produced with 40-second exposures of conventional TQH.[15–18] However, PAC units have several disadvantages, eg, they are expensive and of a relatively large size and complex construction.[19]

Light curing units with gallium nitride blue light–emitting diodes (LED) have also been developed.[20] The spectral output of LED falls within the absorptive region of camphorquinone, so the LED requires no filters to produce blue light. The spectrum flux of LED is concentrated over a much narrower bandwidth than that of TQH or PAC.[21–23] LEDs have many advantages compared with TQH such as a lifetime of more than 10,000 hours, invariable output energy over this term without degradation, and suitability for portable use because of low energy consumption and resistance against shock or vibration. They produce between a 410 and 500 nm. Although the LED shows 70% of the irradiance produced by the TQH, the depth of cure produced by the LED was greater than that by the TQH.[21] Furthermore, advances in the power output of LEDs have allowed LEDs to achieve a higher irradiance than TQH. These high-intensity LEDs may decrease total light curing time.

The light intensity is affected by various clinical exposure uses. It is recommended to place the light guide as close as possible to the surface of the light-cured adhesive, which is rarely performed in clinical orthodontic practice. The distance between the light guide and orthodontic bracket base corresponds to the diameter of the light guide when the light guide is placed against the tooth surface at an angle of 45°. This distance of approximately 10 mm may adversely affect the light intensity received by the light-cured adhesives inside the bracket base.[24]

The purpose of this study was to evaluate the light intensity of conventional TQH, PAC, and LED and to determine the effect of distance while moving the light guide away. The validity of a tapered light guide was also assessed.

MATERIALS AND METHODS

Seven light curing units were used in this study: Lux-O-Max, LEDemetron1, Ortholux LED, The Cure, Optilux501, Co-bee, and Apollo95E (Table 1). All units were new and unused. The cordless-type light curing units, Lux-O-Max, LEDemetron1, Ortholux LED, and Co-bee, were supplied with fully charged batteries. Optilux501 was also evaluated using combinations of the normal mode and boost mode and two types of light guide tip (11-mm Standard tip and eight-mm Turbo tip).

The spectral output of each light curing unit was measured from 350 to 550 nm with a spectroradiometer (USR-40V, USHIO, Tokyo, Japan). A Broadband Power/Energy Meter (30 W, MELLES GRIOT, Carlsbad, Calif) was used to calibrate the value measured by the spectroradiometer.

A curing radiometer (Model100, Demetron Research Corp, Danbury, Conn) was used to measure the light intensity of emissions between 400 and 525 nm. The diameter of all light guide tips was standardized to produce equivalent exposed areas. The measuring window of the radiometer was covered with black paper with a five-mm hole. When the light intensity exceeded the range of the curing radiometer (1000 mW/cm^2), measurement was performed through a filter (ND0.3, FUJIFILM, Tokyo, Japan) and adjusted. Each light curing unit was warmed up for 30 seconds before commencement of each test. The end of the light guide was placed in contact with the center of the measuring window of the curing radiometer at right angles, and each reading of the maximum power output was obtained within five seconds after light passed through the measuring window. Similarly, measurements were performed at five-, 10-, 15-, and 20-mm distance from the light guide. Each distance was standardized by using acrylic tubes, eight mm in diameter and five, 10, 15, and 20 mm long. To obtain the consistency of the results in power output, five measurements were repeated after an interval of one minute. One operator performed all measurements to eliminate any bias.

Means and standard deviations of the light intensity at each distance were calculated for each group. The data were subjected to a repeated-measures analysis of variance (ANOVA) to determine whether any significant difference existed between the light intensity at each measurement ($P < .05$). The Scheffé test was carried out to identify statistical

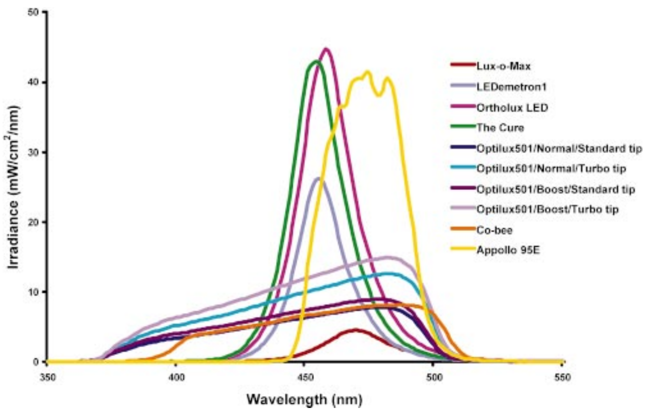

FIGURE 1. The spectral output of each light curing unit.

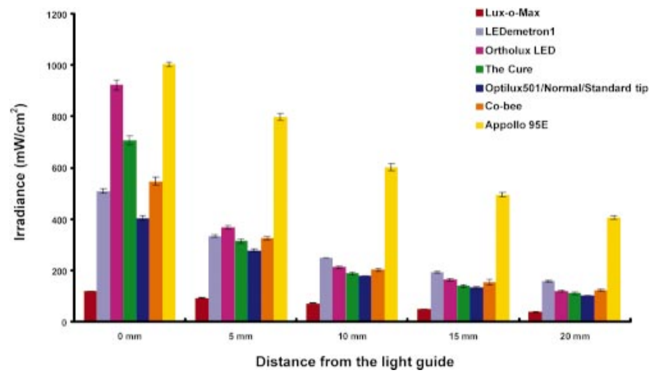

FIGURE 2. The light intensity measured with the curing radiometer at the defined distance.

differences in light intensity between any two groups at 5% level of significance when ANOVA indicated that a significant difference existed.

RESULTS

Figure 1 shows the spectral output of each light curing unit used in this study. The peak value ranged from 44.7 to 4.5 mW/cm². Ortholux LED showed the highest peak value at 458 nm. The peak value of Optilux501 with Turbo tip was 12.6 mW/cm² in normal mode and 14.9 mW/cm² in boost mode. The peak value of Optilux501 with Standard tip was 7.8 mW/cm² in normal mode and 8.9 mW/cm² in boost mode.

Means and standard deviations of the light intensity measured with the curing radiometer at the defined distances are shown in Table 2 and Figure 2. Apollo95E showed the highest value at any distance. Ortholux LED, The Cure, LEDemetron1, and Lux-O-Max decreased the light intensity by 60%, 56%, 34%, and 23% at five-mm distance and by 77%, 73%, 51%, and 40% at 10-mm distance, compared with the value at zero-mm distance. Although The Cure showed higher light intensity than LEDemetron1 at zero-mm distance, the light intensity of LEDemetron1 was higher than that of The Cure at five to 20 mm. As a result, there was no significant difference between The Cure and LEDemetron1. There were statistically significant differences in light intensity between all pairs of light curing units except between The Cure and LEDemetron1. The order of light intensity from highest to lowest is as follows: Apollo95E > Ortholux LED > The Cure, LEDemetron1 > Co-bee > Optilux501 > Lux-O-Max. The light intensity significantly decreased with distance, and the rate of fall of light intensity diminished with distance.

The light intensity of Optilux501 with each combination of different modes and light guides at the defined distance is shown in Figure 3. In the normal mode, Turbo tip enhanced light intensity by 26% compared with Standard tip at zero-mm distance. By moving the light guide away to a five-mm distance, Standard tip and Turbo tip decreased light intensity by 31% and 61%, respectively. As a result, Standard tip showed a 29% higher light intensity than Turbo tip at the five-mm distance. The reduction of light intensity by Turbo tip was demonstrated at five- to 20-mm distance in both normal mode and boost mode. With Standard tip at zero-mm distance, boost mode increased the

TABLE 2. Total Sample Means and Standard Deviations (SD) of Light Intensity (mW/cm²) Measured with the Curing Radiometer

	Distance From the Light Guide (mm)									
	Zero		Five		10		15		20	
Light Units	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Lux-O-Max	120	0	93	2.7	72	2.7	50	0	38	2.7
LEDemetron1	508	8.4	334	5.5	250	0	192	4.5	158	2.7
Ortholux LED	924	19.5	368	8.4	212	4.5	164	5.5	118	4.5
The Cure	708	17.9	314	8.9	188	4.5	139	6.5	110	6.1
Optilux501										
Normal/Standard tip	404	8.9	278	4.5	180	0	132	2.7	100	0
Normal/Turbo tip	508	21.7	196	5.5	120	7.1	94	2.2	74	5.5
Boost/Standard tip	482	8.4	313	4.5	200	0	152	4.5	112	4.5
Boost/Turbo tip	600	7.1	216	5.5	131	2.2	100	0	84	2.2
Co-bee	548	14.8	326	5.5	202	4.5	154	8.9	123	4.5
Apollo95E	1004	8.9	798	14.8	602	14.8	494	8.9	406	5.5

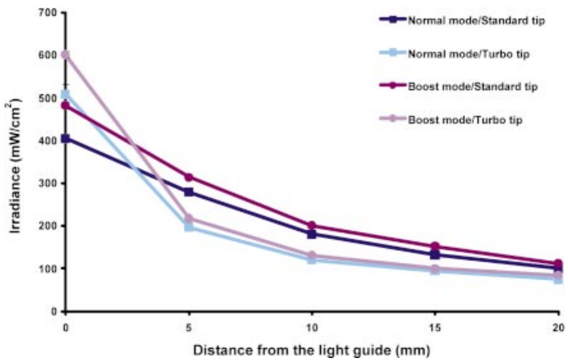

FIGURE 3. The light intensity of Optilux501 with each combination of different modes and light guides at the defined distance.

light intensity by 19% over normal mode. Although the rate of increment of light intensity diminished with distance, enhancement of light intensity with boost mode was seen at all distances with both Standard tip and Turbo tip. There were statistically significant differences between all combinations of mode and light guide. The order of light intensity with each combination of different modes and light guides from highest to lowest is as follows: boost mode/Standard tip > boost mode/Turbo tip > normal mode/Standard tip > normal mode/Turbo tip.

DISCUSSION

Light-cured dental materials are polymerized by the actions of photoinitiators. Camphorquinone is used as the major photoinitiator of composite resin and reacts most efficiently to wavelengths between 410 and 490 nm.[4,5,25] The light curing units used in this study all fall within this range. Ortholux LED, The Cure, and PAC showed approximately a five times higher peak irradiance than TQH. However, the spectral outputs of LED and PAC were concentrated over a much narrower wavelength band than that of TQH, and the absorption ranges of some photoinitiators such as 1-phenyl-1,2-propanedione and bisacylphosphine oxide fall outside this range and such materials might thus not react adequately.[26,27]

Although the irradiance of TQH was approximately two times higher than that of conventional LEDs such as Lux-O-Max, there were no significant differences in the measurements of the depth of cure, compressive strength, or flexural strength between TQH and conventional LED.[22,23] Mills et al[21] measured the depth of cure with an experimental LED with an irradiance of 290 mW/cm^2 and TQH adjusted to an irradiance of 300 mW/cm^2, and concluded that LED cured significantly deeper than TQH. Dunn and Taloumis[28] compared the shear bond strength of orthodontic brackets cured with LED and TQH and concluded that there were no significant differences in shear bond strength, although irradiance of TQH was nearly seven times greater than that of LED. These reports proved that conventional LED has a curing ability equal to that of TQH regardless of its lower irradiance value.

Opportunities to use battery-powered light curing units have recently increased. The output intensity of the battery-powered conventional TQH units shows a tendency to reduce light intensity on repeated activations without intervening recharging.[29] This situation often occurs when light exposure is performed after all the brackets are placed. In clinical practice, an irradiance of 400 mW/cm^2 is needed to obtain uniform and maximal cure, and periodic checking of light intensity has thus been recommended.[9] The battery-powered LED would emit a continuous and stable light without any degradation of power output because of its lower power consumption.

In addition to the performance of the light curing unit itself, light scattering is affected by shade, translucency, filler content, particle size, etc.[9,25,30,31] Lighter shade shows a greater depth of cure because light can pass easily. Myers et al[32] compared the light intensity transmitted by composite resin of A4 and A1 shade and concluded that the light intensity of A4 was half of that of A1. Shortall et al[33] compared the depth of cure of A2, A3.5, and C2 shade composite resins and stated that A2 demonstrated greater depth of cure than A3.5. On light exposure for bracket bonding, it may be considered that the enamel with darker color is related to decreased light transmission.

The light guide should be positioned such that the light impacts on the surface of light-cured adhesives as close to the perpendicular as possible. However, the light cannot reach directly to the surface of the bracket base. Practitioners place the light guide in a tipped position as close to the brackets as possible. The light exposure in this tipped position is affected by the exposure direction. The maximum light intensity occurs when the surface of light guide is perpendicular to the surface of light-cured adhesives. As the light guide is tipped, the circular spot changes to an ellipse, whose area is greater than that of the circular spot, and thus the light density is decreased. Williams and Johnson[34] stated that tipping at 40° from the perpendicular decreased light intensity by 18% and concluded that the light guide tipped by more than 30° might lead to the risk of inadequate curing. Transillumination has also been used to cure the composite resin under the metal brackets.[35,36] During light exposure with transillumination, the light passes through the tooth structure including enamel and dentin. One mm of tooth structure was sufficient to reduce the light intensity to approximately 30% of its initial value.[24] In orthodontic practice, transillumination would result in a serious reduction of light intensity because anterior teeth range from five to seven mm in faciolingual width.[37]

The light intensity is also affected by the distance between the end of light guide and the surface of adhesive.[38] The drop in light intensity with distance is exponential, and one mm of air reduces the light intensity by approximately 10%.[24] Sakaguchi et al[39] remarked that the light output diminished severely at distances more than two mm and was just by 25% of the maximum value at four-mm distance. Clinically realistic distances of five to 10 mm would dramatically decrease the light intensity. In this study, a distance of five mm with the Optilux501 in normal mode showed decreases of 31% for Standard tip and 61% for Turbo tip, and at 10 mm, decreases of 55% for Standard tip and 76% for Turbo tip.

Tapered light guides such as Turbo tip were developed to condense the light energy and might be expected to increase the light intensity. Turbo tip showed its maximum ability in contact with the surface of curing radiometer. Moving away from the surface, however, a greater drop in power density occurred, and the Standard tip delivered greater light intensity than Turbo tip at distances greater than five mm. In this study, Turbo tip increased the light intensity by 26% in comparison with the Standard parallel-sided light guide. However, Turbo tip decreased the light intensity by 29% when the light guide and the radiometer were separated by five mm. These findings were in agreement with previous studies that Turbo tip resulted in a significant reduction in light intensity with distance.[40–42] Bishara et al[11] evaluated the effect of the difference between a four-mm mini Turbo tip and a 11-mm Standard tip and concluded that there was no significant difference in bond strength. Although the use of Turbo tip increased light intensity, severe reduction was noted with distance.

Some light curing units have an enhanced output mode such as boost mode for increasing light intensity. Boost mode showed a higher light intensity by approximately 20% than conventional output mode at zero-mm distance. However, the enhancement of light intensity by boost mode was also diminished with increasing distance from the end of the light guide. At distances more than five mm, boost mode increased light intensity by approximately 10%. This increase was too low to compensate the decreased light intensity because Optilux501 in normal mode decreased 31% for Standard tip and 61% for Turbo tip at five-mm distance. Boost mode might not increase the useful light intensity when the light guide is positioned away from the bracket.

The reduction of light intensity depends on various clinical exposure terms such as the direction of light guide, shade of enamel, and distance between the end of light guide and the surface of adhesives. Distance is the most important factor in decreased light intensity. Although Turbo tip and boost mode are effective for restorative dentistry, the enhanced light exposure may not produce the expected light intensity because it is impossible to position the light guide at zero-mm distance from the adhesive under the bracket base. Increased curing time and light intensity can compensate the loss of light intensity caused by the clinical factors. PAC and high-intensity LEDs with parallel-sided light guides may be advantageous alternatives for light exposure in orthodontic clinical practice. Further study will be needed to evaluate the bond strength of adhesives cured by high-intensity LED with reduced curing time.

CONCLUSIONS

The spectral output and light intensity were measured with four LEDs, Lux-O-Max, LEDemetron1, Ortholux LED, and The Cure; two TQH, Optilux501 and Co-bee; and a PAC, Apollo95E. The effects of distance while moving the light guide away were determined. In the measurement of spectral output, Ortholux LED showed the highest peak value at 458 nm. The light intensity significantly decreased with distance. Although The Cure showed a higher light intensity than LEDemetron1 at zero-mm distance, the light intensity of LEDemetron1 was higher than that of The Cure at five to 20 mm. As a result, there was no significant difference between The Cure and LEDemetron1. The boost mode increased the light intensity at any distance. Although Turbo tip enhanced light intensity at zero-mm distance, reduction of light intensity by Turbo tip was demonstrated at five- to 20-mm distance.

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