Power Distribution across the Face of Different Light Guides and Its Effect on Composite Surface Microhardness

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ABSTRACT

Purpose: The aim of this study was to examine the influence of light guide type on the distribution of irradiant emission from a light-emitting diode (LED) curing light and to measure the effect of light dispersion on surface microhardness across the top and bottom surfaces of two types of composite resins.

Materials and Methods: A laser beam analyzer (LBA-700, Spiricon) was used to evaluate light distribution (Top Hat factor [THF]) across the distal surface of a standard and turbo light guide from an LED curing light (Bluephase, Ivoclar Vivadent). Composites (Z100 [hybrid], A110 [microfill]; 3M ESPE) were placed in blackened rings (2×11 mm) and exposed at 0 mm for 5 seconds (Z100) or 15 seconds (A110) using the light guides at similar irradiance, energy density, and exit diameters ($N = 5$). Similar irradiance values were produced by using the turbo light guide on the "low power" setting of the curing light and the "high power" setting when using the standard light guide. THF values were analyzed with an unpaired *t*-test. Knoop hardness (KHN) was determined on the top and bottom surfaces (Leco) in 1-mm lateral increments from the specimen center and proceeding 4 mm in both east-west and north-south directions. The effects of the major factors (light guide type and lateral distance) on the hardness of each composite were analyzed using multiple analysis of variance (ANOVA), and a two-tailed, unpaired Dunnett's *t*-test determined when lateral hardness values significantly differed from that at the specimen center. The percentage difference between maximum and minimum (max-min) hardness values for each specimen, with respect to distance from specimen center, and the percentage decrease for the standard and turbo light guides, with respect to both composite resin types, were compared using ANOVA and the Tukey's post-hoc test.

Results: The standard guide had a significantly higher (i.e., more uniform light distribution) THF than did the turbo tip ($p < 0.001$). For the microfill, significant differences in hardness were found based on the distance from the specimen center ($p < 0.0001$), and with respect to the top or bottom surfaces ($p < 0.0001$). However, no difference was found between the two types of light guides ($p = 0.939$). For the hybrid, significant differences in hardness were found based on lateral distance ($p < 0.001$), surface ($p < 0.001$), and light guide type ($p = 0.045$).

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However, for both composites, significant interactions were present. Significant differences were found between hardness at the specimen center and at various lateral distances, depending on composite type, surface, and light guide type. The percent age max-min hardness decrease across the surface was significantly less for the standard light guide ($p < 0.0001$) and at the top surface ($p < 0.02$) with both composite resin types. Also, the least percentage max-min hardness decrease occurred on the top surface of the microfill material ($p < 0.001$).

Conclusion: The standard light guide produced a more homogeneous distribution of light across the tip end compared with the turbo light guide, based on the THF. Composite surface hardness patterns correlated with the applied irradiance distribution profiles, yielding greater hardness at higher irradiance locations for both top and bottom surfaces.

CLINICAL SIGNIFICANCE

Light guide selection may influence the uniformity of surface and subsurface hardness when light-curing composite resin restorations.

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INTRODUCTION

Dental light-curing units (LCUs) are typically equipped with fiber-optic light guides having various degrees of convergence between the proximal and distal tip ends (e.g., standard and turbo tips). Irradiance falling on the target may also be affected by the characteristics of the type of light guide used.[1] In the standard guide, the fiber bundles do not differ in diameter between the guide ends. However, with the turbo tip, each fiber has a larger diameter at the proximal than at the distal end, resulting in the same power exiting the tip end, but displaced over a smaller area, effectively increasing irradiance. As the distance from the light guide to the target increases, the irradiance decreases, but the rate of loss may be greater for turbo tips than for standard guides.[1] However, at clinically relevant distances, the benefit of this increase may be sacrificed because of greater dispersion.[2–6] Uniformity of power across the light guide end may affect the extent to which the target resin polymerizes. Emission from LCUs that is minimally divergent vertically and evenly distributed horizontally across the face of the light guide may maximize curing effectiveness and uniformity.

Commercial beam analyzers are used to evaluate the distribution of power within a laser beam.[7] Beams showing a more Gaussian distribution are used for precise cutting, whereas beams that have more uniformity are used for ablation.[7] The phrase “Top Hat factor” (THF) is used to provide a numerical value indicating the uniformity of power distributed across a projected beam area.[7] Light can be distributed across the tip end in a Gaussian distribution (THF = 0.5), with the highest value occurring in the middle and reduced levels toward the periphery. The distribution can also have a uniform, constant value, regardless of location (THF = 1). A THF of 1.0 implies power distribution literally taking the shape of a “top hat”: outside of the area of irradiation, no power exists, and inside that area, power distribution appears as a tall, flat, uniform cylinder, indicating that all power values across that surface are equivalent.[7] THFs ranging from 0.392 to 0.759 have been found for an assortment of curing light guides including fiber-optic, acrylic, and simple depression-style LED units (i.e., no light guide).[8]

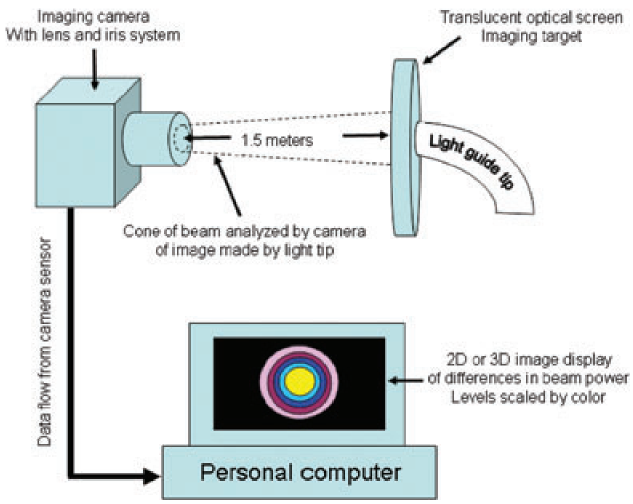

Figure 1. Diagram of the system for analyzing the curing light beam.

The clinical effects of variation in light distribution across the ends of various types of light guides used in dentistry are less known. One would assume that the more uniformly light is distributed across the tip end, the more uniform will be the polymerization of the restorative material, especially in cases involving large surface areas of exposure (large optical footprints).

The purpose of this study was to examine the distribution of light emitted from the same LED curing light when using two different light guides. Microhardness of the top (irradiated) and bottom (2-mm-deep) surfaces of two composite resin materials was measured and correlated with the distribution of the irradiant conditions established. It was hypothesized that the light guide showing the more homogeneous intensity distribution across the beam (i.e., highest THF) would provide the more homogenous surface hardness on both top and bottom composite resin surfaces.

MATERIALS AND METHODS

Light Distribution

A commercial laser beam analyzer (LBA-700, Spiricon, Logan, UT, USA) was used to evaluate light distribution at tip end (0-mm distance) using standard and turbo light guides from an LED curing light (Bluephase, Ivoclar Vivadent, Amherst, NY, USA). The curing light was held rigidly and was positioned so that the face of the guide was held parallel and in contact with the planar surface of a white optical screen (Da-Mat #40465, Da-Lite Screen Co., Warsaw, IN, USA). The light was projected through the screen and imaged with the camera lens of the beam analyzer mounted at a distance of 1.5 m from the screen (Figure 1). Five images were recorded for each light guide type. Power emitted from each light guide was measured using a calibrated meter (PowerMax 5200 with PM10 probe, Molectron, Portland, OR, USA) (Table 1). The total two-dimensional area projected on the imaging screen was assigned the corresponding measured power value to derive the irradiance of the projected light image. Software (LBA/PC Version 4.06, Spiricon) was used to determine the localized irradiance levels within the projected beam area displayed as a color-coded distribution. The distribution of irradiance across this area and the assigned THF value was provided by the software. Values of THF between the two light guide types were statistically compared using an unpaired *t*-test at an alpha of 0.05.

Optical images of the proximal and distal ends of both the standard and turbo light guides were obtained using a stereomicroscope (Wild Heerbrugg, Gais, Switzerland) and were digitally captured using a microscopic camera (Colorview II Imaging System, Brook-Anco Corporation, Rochester, NY, USA). The images were analyzed using a digital

TABLE 1. LIGHT GUIDE DIMENSIONS WITH MEASURED POWER, IRRADIANCE, AND TOP HAT FACTORS.

Light Guide	Entrance/Exit Diameter (mm)	Power (mW)	Irradiance (mW/cm^2)	Top Hat Factor (SD)
Standard	7.5/7.5	310	702	0.785 (0.003)
Turbo	12/7.4	308	716	0.610 (0.006)

TABLE 2. FIBER-OPTIC BUNDLE MEASUREMENTS FOR BOTH STANDARD AND TURBO LIGHT GUIDES.

Light Guide	Diameters (mm)	Number of Bundles	Size of Bundles (mm^2)
Standard	Proximal: 7.5	995	0.045
	Distal: 7.5	995	0.045
Turbo	Proximal: 12	1,475	0.077
	Distal: 7.4	1,475	0.029

imaging system (analySIS Pro, Olympus Soft Imaging Solutions Corp, Lakewood, CO, USA). The number and surface areas of individual and total fiber-optic bundles at each end of the guides were measured from the captured images (Table 2).

Hardness Testing

The composite resins selected represented a range of filler particle content: a hybrid (Z100, 3M ESPE, St. Paul, MN, USA) and a microfill (A110, 3M ESPE) material. Uncured composite paste was placed into a 2-mm-deep, 11-mm-diameter metal ring that had been painted black. The ring was placed on a clear polyester sheet (Mylar, DuPont, Wilmington, DE, USA) that rested on black, opaque paper. This arrangement provided a uniform, nonreflective background that minimized the optical effect of the ring surface on causing higher light intensity values at that interface. This arrangement minimized the possibility of elevated conversion values, thus the creation of artificially higher hardness in that area.[9] Another Mylar sheet was placed over the paste, and hand pressure was applied using the flat surface of a glass microscope slide to force the paste to fill the ring confines as well as to extrude excess material. The top glass slide was removed, and the distal end of the light guide was placed against the surface of the Mylar strip (i.e., 0 mm). Specimens were irradiated using similar irradiance values for 5 seconds (hybrid) or 15 seconds (microfill) using the two different light guides. Longer curing time was necessary for the microfill composite because of the scattering of light from the natural agglomeration of the small filler particles.[10] Similar irradiance values were produced by using the turbo light guide on the "low power" setting of the LCU and the "high power" setting when using the standard light guide (Table 1). Total emitted power was measured using a laboratory-grade, calibrated power meter (PowerMax 5200 with PM10 probe). Total irradiance was calculated by dividing the recorded power by the measured surface area of distal tip of the light guide (Table 1). The thickness of each polymerized specimen was measured using an electronic digital caliper (Max-9, Fowler Ltd., Louisville, KY, USA) to ensure a uniform value: 2.0 ± 0.1 mm. Five specimens were fabricated for each light guide and composite resin type (a total of 20 specimens). The specimens were then stored dry in a lightproof container.

Fifteen minutes after photocuring, surface microhardness values (Knoop hardness [KHN]) were obtained on the top and bottom specimen surfaces (#M400G2, Leco, St. Joseph, MI, USA).[9] Measurements were made in a

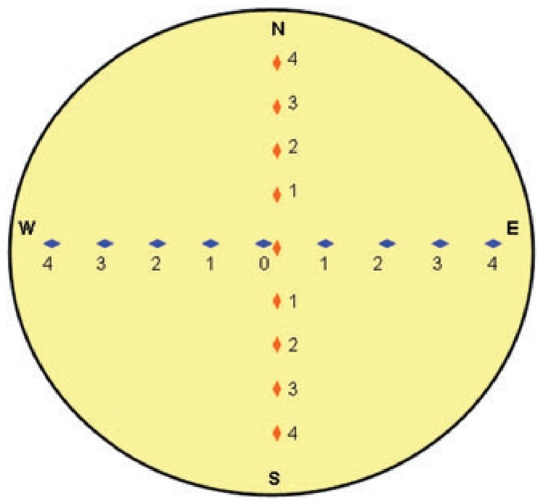

Figure 2. Diagram of the composite specimen with Knoop hardness measurements made in 1-mm increments in all four directions from the center.

sequential pattern, starting with the bottom surface of all specimens. Measurements were obtained in 1-mm increments from the specimen center and extending 4 mm in both x (east-west [E-W]) and y (north-south [N-S]) axes (Figure 2). To prevent erroneous readings, all hardness indents were kept at least three indentations apart. Hardness measurements were not taken past 4 mm from the specimen center to avoid any possible effect of the holding ring on composite resin polymerization, leaving 1.5-mm peripheral to the 4-mm measurement.[9] For a given specimen, the four hardness values at similar distances (N-S and E-W) from the specimen center were averaged and reported as a single value.

A three-way analysis of variance (ANOVA) was performed for each composite type to observe the effect of the independent variables on surface microhardness: light guide type (two levels); composite resin surface (two levels); and distance from the specimen center (four levels). Tukey's post-hoc test was used to compare pairwise differences between mean values ($\alpha = 0.05$). A series of one-way ANOVAs was performed to examine the effect of distance from the specimen center on hardness for a given surface, light guide type, and composite resin ($\alpha = 0.01$). A two-tailed, unpaired Dunnett's t-test was applied to the data to determine when lateral hardness values became statistically different from that at the specimen center ($\alpha = 0.01$). The percentage difference between maximum and minimum hardness values for each specimen with respect to distance from the specimen center was determined. The percentages were subjected to a two-way ANOVA per composite type to observe the effect of light guide type (two levels) and composite resin surface (two levels) ($\alpha = 0.05$). Also, the percentage difference for the standard and turbo light guides were analyzed separately with a one-way ANOVA and Tukey's post-hoc test to determine which composite resin surface displayed the least percentage decrease with both composite types ($\alpha = 0.05$). All statistical testing was performed using a statistical software package (SPSS version 10, SPSS, Chicago, IL, USA).

RESULTS

The THFs differed statistically between light guide types ($p < 0.001$), with the standard guide demonstrating a more uniform dispersion (THF = 0.785 ± 0.003) than that of the turbo tip (THF = 0.610 ± 0.006) (Table 1). Figure 3A displays the intensity profiles at the tip ends of the standard light guide in two-dimensional (2D) color contours as well as in three-dimensional (3D) isometric views, respectively. Figure 3B presents the digital image of the proximal and distal ends of the standard light guide. Figure 4A,B display the intensity

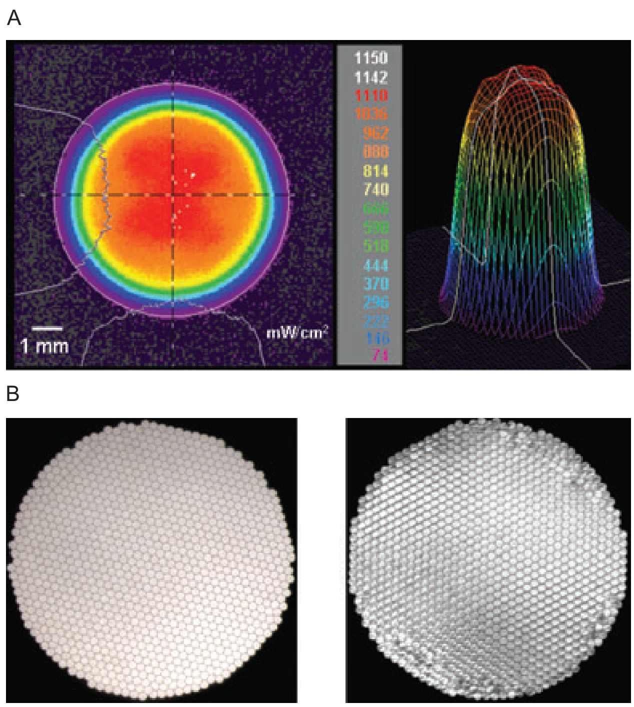

Figure 3. A, *Two- and three-dimensional beam profiles across the standard light guide tip (0 mm) (Top Hat factor = 0.785) and corresponding irradiance values (mW/cm^2). Total irradiance (white circle) = 702 mW/cm^2.* B, *Images of the proximal and distal ends of the standard light guide.*

profiles and digital images of the turbo light guide, respectively.

Hardness values of the top and bottom composite resin surfaces for the microfilled composite are presented in Figure 5. The three-way ANOVA found significant differences in hardness based on the distance from the center ($p < 0.0001$) and surface ($p < 0.0001$); however, no difference was found between the two types of light guides ($p = 0.939$). For the hybrid composite resin, Z100, significant differences in hardness were found based on distance ($p < 0.001$), surface ($p < 0.001$), and light guide type ($p = 0.045$) (Figure 6). However, for both composite resins, significant interactions were present. Hardness data were further analyzed with a series of one-way ANOVAs. A Bonferroni correction ($\alpha = 0.01$) was applied as a multiple-comparison correction because several statistical tests were performed simultaneously. Significant differences were found between the center and various distances from the center, depending on composite resin type, surface, and light guide type (Dunnett's t-test, $p < 0.01$). For the microfill material, surface hardness at 4 mm was significantly lower than at the specimen center for both the standard and turbo light guides at the top and bottom surfaces. Significantly lower hardness values were also found at 3 mm on the bottom surface with both light guide types, with respect to the specimen center. For the hybrid product, significantly lower hardness values were found at 4 mm from the center for both light guides and both surfaces. At a 3-mm distance, only the top surface using the standard guide produced hardness values that did not significantly differ from those at the specimen center. At 2 mm, only the bottom surface hardness values for each light guide type were significantly less than those at the specimen center (Figures 5 and 6).

The two-way ANOVA found that the percentage decrease from maximum to minimum hardness across the surface of the composite resin was significantly less when using the standard light guide ($p < 0.0001$), and also at the top surface ($p < 0.02$), with both composite resin types. No significant interactions were present ($p > 0.3$). The one-way ANOVA found that, with both the standard and turbo light guides, the least percentage

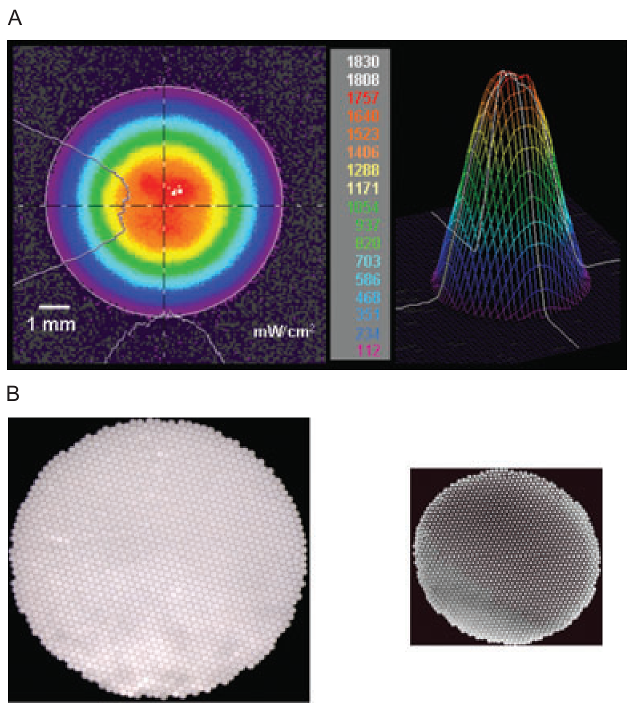

Figure 4. A, *Two- and three-dimensional beam profiles across the turbo light guide tip (0 mm) (Top Hat factor = 0.610) and corresponding irradiance values (mW/cm²). Total irradiance (white circle) = 716 mW/cm².* B, *Images of the proximal and distal ends of the turbo light guide.*

decrease occurred on the top surface of the microfill resin ($p < 0.001$) (Figure 7).

DISCUSSION

The hypothesis was upheld because the standard light guide had the most homogeneous intensity distribution (i.e., the highest THF) and also resulted in the least percentage decrease from maximum to minimum hardness across the specimen surface. The turbo light guide produced greater surface hardness near the specimen center and less hardness near the periphery compared with the standard light guide. The nonuniformity produced by the turbo light guide was more pronounced on the bottom surface (Figures 5 and 6). The greater hardness near the center of the composite resin specimen produced by the turbo light guide corresponds with the lower THF, indicating a more concentrated central irradiance. Hardness differences at the bottom surface become more apparent than at the top, irradiated surface because of light attenuation and an expected subsequent reduction in the degree of conversion.[11]

Laterally, beyond the edges of the light guide, the composite resin had a significant reduction in hardness relative to areas within the body of the composite resin exposed to the vertical beam. Practitioners should be aware that, although a light guide with a smaller diameter distal end, such as a turbo light guide, may increase irradiance, additional exposures may be necessary to adequately irradiate a larger surface area to compensate for the smaller tip of the light guide and the reduced light intensity near its edges.

If light striking the composite surface is not evenly distributed across the beam, uniform resin conversion may not occur within both the top and bottom surfaces. This nonuniformity may be more significant when polymerizing wider surface areas in larger restorations. Also, if the beam output is not homogeneous, the nonuniformity will only become larger with increasing tip distance, and the impact may be even greater.[8] Such an occurrence may be possible when using clinically relevant curing distances.[1]

The differences in power distribution of a beam profile can affect the quality of energy application.

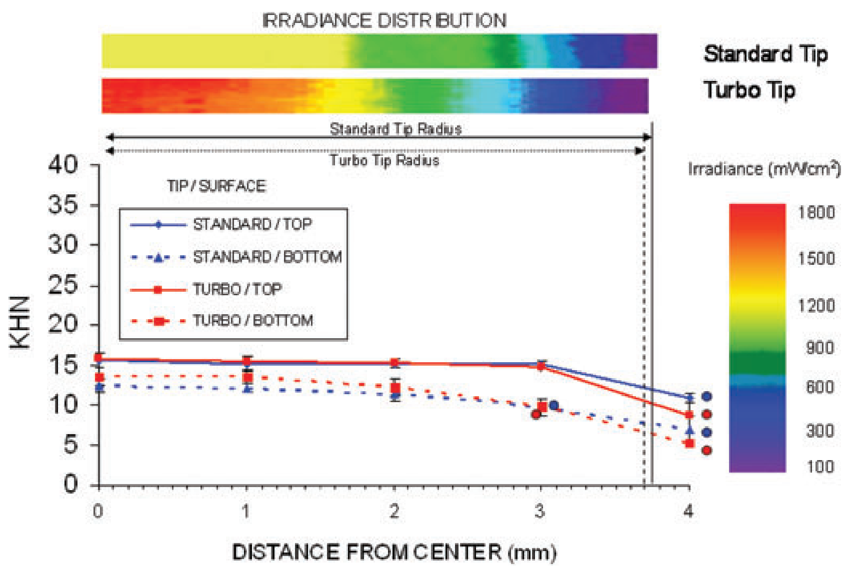

Figure 5. Microfill composite resin (A110) top and bottom surface hardness (Knoop hardness [KHN]) and corresponding power density distribution. KHN values at distances indicated by a colored circle are significantly different from that at the corresponding specimen center ($p < 0.05$). N = 5 specimens per group; vertical bar = 1 SD.

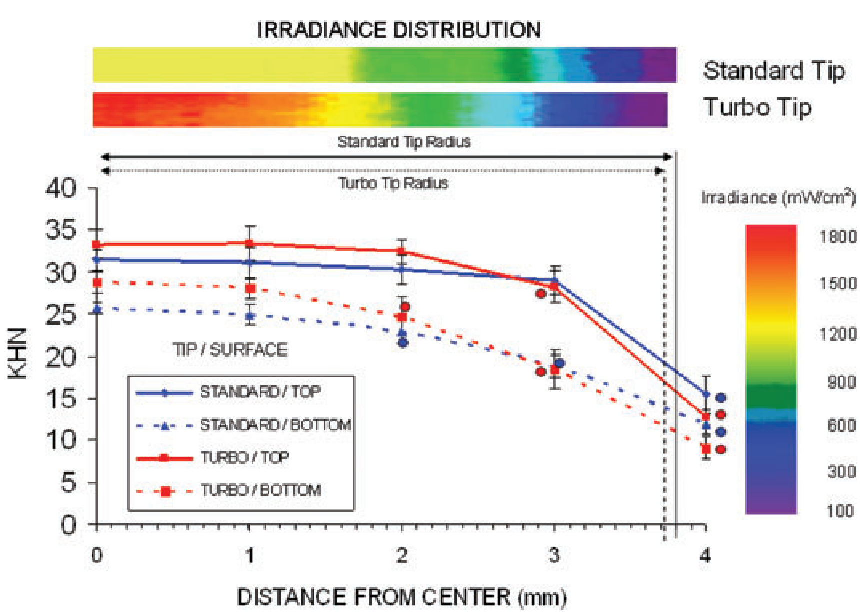

Figure 6. Hybrid composite resin (Z100) top and bottom surface hardness (Knoop hardness [KHN]) and corresponding power density distribution. KHN values at distances indicated by a colored circle are significantly different from that at the corresponding specimen center ($p < 0.05$). N = 5 specimens per group; vertical bar = 1 SD.

The results of this study suggest that the use of a light guide that creates a more homogeneous beam (i.e., higher THF) results in a more uniform distribution of composite resin surface hardness not only at the top, irradiated surface but also at 2 mm beneath this surface. Application of these findings may be clinically significant when polymerizing larger restorations, such as composite resin veneers.

It was interesting to note that the standard light guide contained fewer fiber-optic bundles than the turbo light guide; however, each type of light guide had a constant number of bundles throughout the guide. The standard guide had similar proximal and distal diameters with the same number and size of the individual bundles. However, the turbo light guide had a larger proximal area, with larger bundles that tapered to a smaller, similarly sized distal area as the standard light guide, but with bundles that were smaller in size (Figures 3B and 4B). With a larger proximal area, the turbo light guide was able to capture the available power and converge it into a smaller area, thereby increasing irradiance, but at the same time altering the distribution of the exiting light beam.

It should be emphasized that the purpose of this study was to isolate

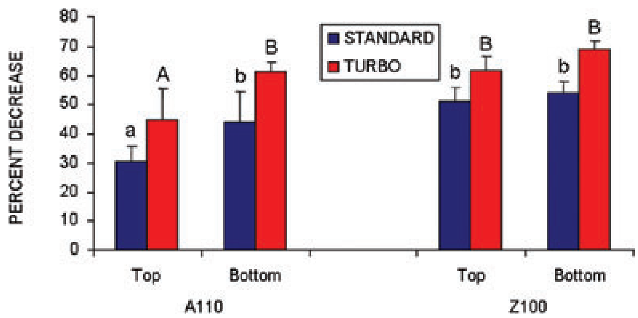

Figure 7. Percent decrease from maximum Knoop hardness of microfill (A110) and hybrid (Z100) composite resins on the top and bottom surfaces using the standard and turbo light guides. N = 5 *for each test condition. For a given composite and surface, use of the turbo tip provided a significantly greater decrease in hardness than did the use of the standard tip. Values denoted by similar lowercase (standard guide) or uppercase (turbo tip) letters are not significantly different.*

the effects of light distribution across the face of two different light guides and not to evaluate the overall performance of the light or the specific light guides at maximum power or exposure durations. To control for these variables, the turbo guide was used in the LED curing unit at reduced power to generate a similar irradiance to that created with a standard light guide with a similar distal diameter. In addition, the light guides were placed on the surface of the composite resin (i.e., 0 mm) before activation of the light. At greater exposure distances, the irradiance of the two light guides may not coincide because of the differences in light dispersion.[8] Also, the composite specimens were exposed for less than the optimal times in order to generate discernible differences with less-than-maximum polymerization. Hardness testing was used because of its simplicity with multiple measurements made at close intervals over long distances.[9] A good correlation exists between hardness and the relative degree of conversion for a specific composite resin.[11,12] Thus, relative comparison of hardness values at various lateral distances and at different surfaces of a given composite in this study also reflect similar trends in conversion value differences. A disadvantage of this study was that only one curing light and only one light guide of each type was tested. Significant variations in irradiance levels and light distribution could exist among individual curing lights or light guides within the same manufactured unit types. Also, the possible effects of nonconcentric, isolated areas or patterns of greater irradiance or "hot spots" on the face of the light guides was not examined or determined in this study. Another disadvantage of this study was that measurements were made more immediately—starting at only 15 minutes after photopolymerization. Different results and conclusions may occur after 24 hours or other testing intervals.

CONCLUSIONS

Based on the limitations of this study, the following conclusions may be made concerning the light guides evaluated:

1. The standard light guide produced a more homogeneous distribution of light across the tip end compared with the turbo light guide, based on the THF.
2. Composite surface hardness patterns correlated with the applied irradiance distribution profiles, yielding greater hardness at higher irradiance locations for both top and bottom surfaces.

DISCLOSURE

The views expressed in this article are those of the authors and do not reflect the official policy of the Department of Defense or other departments of the US government. The authors do not have any financial interest in the companies whose materials are discussed in this article.

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