Irradiance Uniformity and Distribution from Dental Light Curing Units

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ABSTRACT

Problem: The irradiance from dental light-curing units (LCUs) is commonly reported as a single number, but this number does not properly describe the light output.

Purpose: This study examined the irradiance uniformity and distribution from a variety of LCUs as well as the effect of different light guides.

Materials and Methods: Five LCUs representing quartz-tungsten-halogen, plasma arc, and light emitting diode units were evaluated. One LCU was evaluated using two different light guides (Standard or Turbo style). The total power emitted from each LCU was measured and the irradiance calculated using conventional methods (I_{CM}). In addition, a beam profiler was used to determine the optically active emitting area, the mean irradiance (I_{BP}), the irradiance distribution, and the Top Hat Factor (THF). Five replications were performed for each test and compared using analysis of variance with Fisher's PLSD tests at a pre-set alpha of 0.05.

Results: The spatial distribution of the irradiance from LCUs was neither universally symmetrical nor was it uniformly distributed across the tip end. Significant differences in both the emitted power and THF were found among the LCUs. The THF values ranged from a high of 0.74 ± 0.01 to a low of 0.32 ± 0.01. Changing from a standard to a turbo light guide increased the irradiance, but significantly reduced beam homogeneity, reduced the total emitted power, and reduced the optical tip area by 60%.

Conclusions: Using different light guides on the same LCU significantly affected the power output, irradiance values, and beam homogeneity. For all LCUs, irradiance values calculated using conventional methods (I_{CM}) did not represent the irradiance distribution across the tip end of the LCU.

CLINICAL SIGNIFICANCE

Irradiance values calculated using conventional methods assume power uniformity within the beam and do not validly characterize the distribution of the irradiance delivered from dental light curing units.

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INTRODUCTION

Photocuring resin-based restorative materials are essential components of contemporary dental practice. Light produced from a light-curing unit (LCU) is aimed at the resin surface to induce a uniform, optimal polymerization reaction. Adequate light exposure should result in a biocompatible restoration with the manufacturers' intended physical properties and clinical longevity. If insufficient light reaches the resin, inadequate polymerization of the resin occurs,[1] which adversely affects both the physical and chemical properties of the restoration.[2–9] A poorly polymerized restoration may result in premature clinical failure because of marginal defects, secondary caries, or restoration fracture. In addition, the biocompatibility of the restoration is adversely affected when the resin is undercured.[10–13]

Recently, the light output from LCUs was measured at 1-mm intervals across the face of the light guide and a "beam inhomogeneity" factor calculated.[14] However, it takes time to make such multiple measurements and the output from some LCUs is not stable, with some delivering more and others less power toward the end of the light-curing cycle.[1,15] This instability in light output would distort the final tip-end irradiance map. Unlike making a visual estimation of the intensity of a projected light beam,[16] or stepping a detector across a light beam,[14] commercial beam analyzers take a snapshot of a light source and can accurately evaluate the distribution of power within a light beam. Software then calculates a weighted average of the power values within a defined beam area. This value is described as the "Top Hat Factor" (THF) and provides an indication of the uniformity of power distribution across the light beam.[17,18] When the total measured power is applied to a known area of light distribution, the power received by each pixel in the detector's diode array can be converted into irradiance units and the software generates maps of the irradiance distribution. If all the pixel readings indicate identical power levels, all the irradiance values across the surface will be equivalent and a value of unity is applied to the image (THF is 1.0). The literal 3D representation of this relationship for a circular beam therefore takes the shape of a figurative "Top Hat": flat on the peripheral "brim" where no light falls, and cylindrical-shaped where the beam is emitting. THF values lower than unity indicate relatively less uniformity in the distribution of the irradiance across the surface. One study has reported THFs ranging from 0.57 to 0.76 from five different LCUs. No images were shown of the beam profiles from plasma arc (PAC) units or LCUs that did not use a light guide, but images of the beam profiles from two lights that used fiber optic light guides suggested that beam profiles from dental LCUs were universally symmetrical.[18]

Many previous studies have assessed the depth of cure, hardness, or degree of conversion of composite resins cured with different LCUs.[1,3–7,12,13,15,16,19–24] As all these reports used a single irradiance value to describe the output from an LCU, it might be assumed that the exit irradiance is uniformly distributed across the tip end. However, this assumption should not be universally made because it is now known that the exit irradiance from some LCUs is nonuniform.[14,18,25,26] In one study, the effect of this nonuniformity on resin polymerization was demonstrated by taking hardness measurements in 1-mm increments from the center of the specimen and extending 4 mm in both east-west and north-south axes. The four hardness values made at similar distances from the center of the specimen were averaged and reported as a single value.[25] Whereas this may produce valid results when the light beam has radial symmetry, averaging these four values may mask the effects of spatial beam inhomogeneity on resin polymerization at the target.

Because it is now known that the irradiance is not distributed uniformly, further examination using laboratory grade, calibrated instrumentation, and a better method to describe the irradiance from an LCU is required. Such an effort should provide a more thorough understanding for variation in curing effectiveness among different LCUs used in research studies and in general dental practices.

The aim of the present study was to further quantify and qualify the irradiance distributions from a variety of commercial LCUs. Characterization was provided both in terms of the THF, as well as mapping the local irradiance across the tip end using isometric color-coded images, and determining the irradiance distributions within the tip ends. The research hypotheses tested were that: (1) the irradiance uniformity (as described by the THF) is significantly different among various types of LCUs, (2) the irradiance distribution across the exit tip of dental LCUs is not universally radially symmetrical, (3) the use of different light guides on the same LCU significantly alters irradiance values as well as beam uniformity, and (4) when irradiance is calculated using conventional methods (I_{CM}) from the ratio of the total radiant power to the area of the tip end, the resulting single value does not adequately represent the irradiance distribution from the LCU.

MATERIALS AND METHODS

Table 1 lists the five photocuring units examined. The units were chosen to represent a wide variety of commercially available, contemporary dental LCUs: a quartz-tungsten-halogen unit (QTH), a PAC unit, and a variety of light

TABLE 1. LIGHT-CURING UNITS TESTED AND RELEVANT CHARACTERIZATION (*N* = REPLICATIONS, MEAN ± SD).

Light curing units and manufacturers	Light curing unit type	Stated diameter of light guide entrance/exit	Total emitted power (mW)* *N* = 10	Calculated tip-end irradiance (I_{CM}) (mW/cm²) *N* = 10	Top hat factor (THF)* *N* = 5
Sapphire, Den-Mat Holdings, Santa Maria, CA	PAC	Reverse Turbo 5.5/9 mm	1,158 ± 12	2,208 ± 23	0.57 ± 0.01
Bluephase 16i Ivoclar Vivadent Inc. Amherst, NY	LED	Turbo, 13/8 mm	689.2 ± 4	1,714 ± 5	0.50 ± 0.01
FLASHLite Magna Discus Dental, Culver City, CA	LED	No light guide, plastic lens at tip end	1,179 ± 8	1,129 ± 8	0.32 ± 0.01
Optilux 501 Kerr Corp., Orange, CA	QTH	Standard 11/11 mm Regular power mode	588.3 ± 7	786.0 ± 9	0.64 ± 0.01
Bluephase 16i Ivoclar Vivadent Inc. Amherst, NY	LED	Standard, 13/13 mm	756 ± 7	725 ± 7	0.60 ± 0.01
SmartLite IQ Dentsply Inc. York, PA	LED	Turbo, 13/8.5 mm	286 ± 2	570 ± 3	0.74 ± 0.01

*Within a parameter, all values were significantly different among light-curing units, $p < 0.05$.

emitting diode (LED)-based units. The PAC unit used a 5.5/9-mm reverse turbo light guide. Two LED-based LCUs used turbo-tipped light guides, and one LED unit (FLASHLite Magna, Discus Dental, Culver City, CA, USA) used only a clear plastic covering over the three LED dyes. In addition, one of the LED-based LCUs (Bluephase 16i, Ivoclar Vivadent Inc., Amherst, NY, USA) was tested with two different glass-fibered light guides: a 13/8-mm turbo and a 13/13-mm standard tip.

Power Measurement and Conventional Irradiance Measurements

The total power output from each LCU was measured independently using two different calibrated thermopiles and two meters (two different PM-10 detectors and FieldMax meters, Coherent Inc., Santa Clara, CA, USA). The emitting end of each LCU was held in close approximation to, but not touching, the detector surface. In all cases, the PM-10 detector surface diameter exceeded the beam diameter from the LCU. Five readings were obtained in a random order for each LCU using each detector. Power values obtained for each detector were compared for each LCU using a 2-tailed, unpaired, Student's *t*-test at a pre-set alpha of 0.05. There was no significant difference in measured power between the two thermopile detector systems. Thus, to more accurately reflect the mean power output from each LCU, the five values obtained for each system were pooled into one data set of 10 replications. An irradiance value was calculated for each unit using the conventional manner by dividing the mean power values by the tip end area (I_{CM}).[6,19,27,28] To achieve this calculation, the LCU's tip end diameter from where light would emit was measured five times with digital calipers (Digimatic 500-196-20, Mitutoyo, Mississauga, Ontario, Canada) in a random sequence of curing lights. For the units using light guides, the diameter of the fiber optic bundle was measured using 2.5× magnification. As the FLASHLite Magna unit did not use a light guide, the boundaries of the light source were estimated and then measured five times. The tip end area was calculated from the calliper-measured mean tip diameter for each LCU and this fixed area used to calculate the irradiance for each LCU.

Irradiance Values Determined Using Beam Profiler

The irradiance across the light emitting tip area from each LCU was determined using an instrument designed to accurately characterize light beams (LBA-USB-L070 Beam Profiler, Ophir-Spiricon, Logan, UT, USA). Figure 1 shows the lensed CCD camera, target, and LCU attached to an optical bench. The distance between the camera and the plane of the frosted surface of the diffusive glass target (DG2X2-1500, Thor Laboratories, Newton, NJ, USA) was the same for all the LCUs. The light-emitting end of each LCU was placed in contact with the frosted surface of the target and the resulting image was monitored on the computer screen. Prior to beam imaging, the pixel dimensions were calibrated in the plane of the glass target, enabling precise linear measurement of the images. Data were displayed graphically in real-time using software (LBA-USB-SCOR vs. 4.84, Ophir-Spiricon) on a personal computer. Prior to beam imaging, the system was corrected for ambient light and pixel response (UltraCal, Ophir-Spiricon). The LCU was then activated, and the lens iris was adjusted to use the full dynamic range of the detector without saturation. For each LCU, the mean power value previously measured using the thermopiles was entered into the beam analyzer software. The diameter of the active light beam from each LCU was determined by the beam profile software and used to calculate the irradiance (I_{BP}) related to the active light emitting area where the irradiance values were above 50 mW/cm^2. The LBA software scaled the power levels to 2 and 3 dimensional color-coded irradiance levels

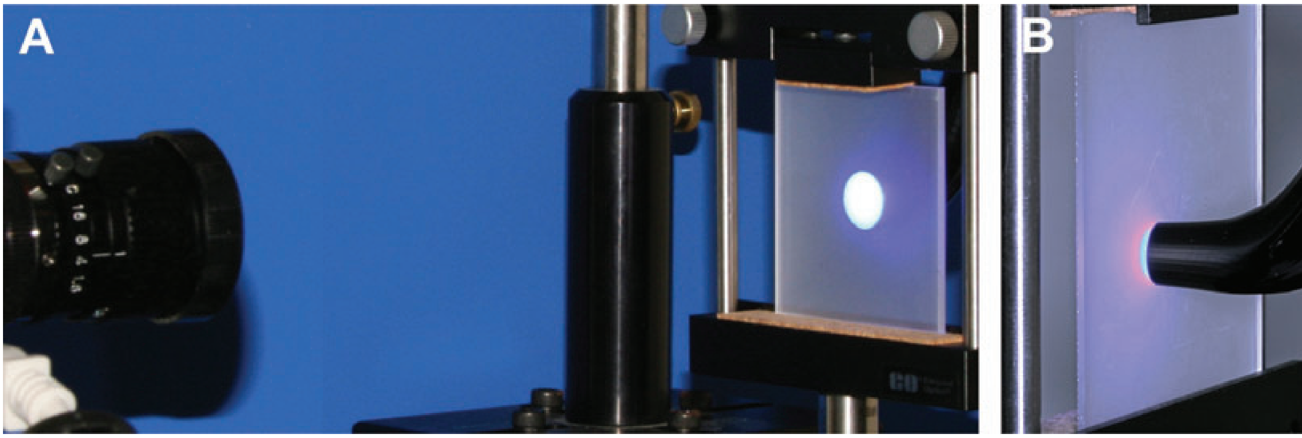

Figure 1. A, *Lensed beam analyzer CCD camera, diffusive glass target, and light-curing unit (LCU) mounted on an optical bench showing image of the output from the LCU on the screen.* B, *The light guide against the surface of the diffusive target.*

according to the pixel value measured with respect to the dynamic range of the instrument. The beam analyzer software also calculated the THF across the target beam image for each LCU. The experiment was repeated five times, testing the curing lights in a random order.

Distribution of Irradiance at the Tip of the LCUs

Because of differences in spectral output from the LCUs and the nonuniform spectral sensitivity of the beam analyzer camera, it was not possible to place the same irradiance scale on each image. Instead, each image was individually calibrated according to the power recorded for the LCU by setting the highest light level measured to take on the highest array count. As the LBA software offers limited options to customize the output, the 307,200 data points from the 640 × 480 CCD array were exported into a spreadsheet/graphics package (SigmaPlot v11.1, Systat Software, Inc., San Jose, CA, USA) and histograms were generated showing the irradiance levels with respect to the proportion of emitting tip area occupied by those values. The percent of the beam area that occupied specific irradiance ranges between 50 and 4,000 mW/cm^2 was also calculated based on the five recordings made of each LCU.

Effect of Light Guide

To determine the effect of light guide type on power output and irradiance distribution, the irradiance profiles obtained when using the same LCU body (Bluephase 16i), but with either a 13/8-mm turbo tip or a standard 13/13-mm light guide, were compared.

Analysis

Statistical analysis utilized analysis of variance to examine the effect of LCU type on total emitted power and THF values. The Fisher's PLSD post-hoc comparison test was used to examine pair-wise differences in power or THF values among the LCUs. All statistical testing was performed at a pre-set alpha of 0.05.

RESULTS

Power and Irradiance Values Obtained Using the Conventional Method (I_{CM})

Table 1 presents summary statistics of power outputs, calculated irradiances (I_{CM}) (power/area), and THFs. Statistical analyses indicated significant differences in both emitted power and irradiance among all the LCUs: each with $p < 0.05$. Because the mean caliper-measured diameter was taken to be a fixed value, the coefficient of variation of the irradiance was the same as that for the power. The emitted power measured on the thermopiles ranged from a high of 1,179 ± 8 mW for the FLASHLite Magna, to a low of 286 ± 2 mW for the SmartLite IQ. The calculated irradiance values (I_{CM}) ranged from 2,208 mW/cm^2 for the Sapphire PAC unit, to a low of 570 mW/cm^2 for the SmartLite IQ unit. When interchanging light guide types on the same LED unit body, compared with the standard light guide, the turbo tip significantly reduced the total emitted power by 9% from 756 ± 7 mW to 689 ± 4 mW ($p < 0.05$), decreased the tip area by 60% from 1.042 to 0.403 cm^2, but increased the calculated irradiance by more than 2.3 times: from 725 mW/cm^2 to 1,714 mW/cm^2.

Beam Profile Irradiance Values (I_{BP})
Table 2 displays the mean ± SD irradiance (I_{BP}) values calculated using the beam profiler software. Irradiance results calculated using the conventional method (I_{CM}) of measuring the tip end diameter with a caliper and from the active light emitting area as reported using the beam profile software (I_{BP}) were within 4% except for the FLASHLite Magna, which showed an approximate 22% reduction from 1,129 to 884 mW/cm^2, and the SmartLite IQ, which increased 30%: 570 to 741 mW/cm^2.

Beam Irradiance Uniformity Showing an Ideal Top Hat Factor
Figure 2 shows an example of a light source that very closely represents a "perfectly uniform beam." The source used for this analysis was the exit port of a 6-in integrating sphere (Labsphere, North Sutton, NH, USA) that had an internal 35-watt calibration lamp. As can be seen, the pattern of light distribution with respect to the zero-level, flat background plane seems to take on the form of a cylinder with a flat top: a "Top Hat." The measured THF value of this uniform light source was near unity: 0.96. As expected for this high THF value, the irradiance distribution was extremely narrow, with an SD of only 15 mW/cm^2 and a coefficient of variation of 9.4%.

Beam Irradiance Uniformity
Statistical analysis indicated significant differences ($p < 0.05$) in THF values among the curing light units tested. The highest THF value

TABLE 2. MEAN CALIPER-MEASURED TIP DIAMETER, MEAN CALCULATED IRRADIANCE (ICM), AND MEAN BEAM PROFILE CALCULATED IRRADIANCE (IBP) ±SD OF THE IRRADIANCE DISTRIBUTION ACROSS THE TIP. BEAM PROFILE DIAMETERS ARE PROVIDED AFTER APPLYING A 50 MW/CM^2 MINIMUM THRESHOLD VALUE TO DISCRIMINATE THE BEAM FROM BACKGROUND LIGHT.

Light curing units	Caliper-measured diameter of tip-end (mm) $N = 5$	Mean ± SD I_{CM} (mW/cm^2) $N = 10$	Optical diameter of tip-end (mm) Mean ± SD $N = 5$	Mean I_{BP} (mW/cm^2) $N = 5$	SD of the I_{BP} across the light tip (mW/cm^2)	Coefficient of variation I_{BP} (%)
Sapphire	8.17 ± 0.03	2,208 ± 23	7.92 ± 0.02	2,205	898	40
Bluephase 16i 13/8 mm Turbo	7.16 ± 0.03	1,714 ± 5	7.16 ± 0.02	1,673	716	43
FLASHLite Magna	11.53 ± 0.02	1,129 ± 8	11.50 ± 0.03	884	946	107
Optilux 501	9.76 ± 0.10	786 ± 9	9.54 ± 0.02	780	230	30
Bluephase 16i 13/13 mm Standard	11.52 ± 0.06	725 ± 7	11.19 ± 0.03	745	284	38
SmartLite IQ	7.99 ± 0.05	570 ± 3	6.93 ± 0.02	741	237	33

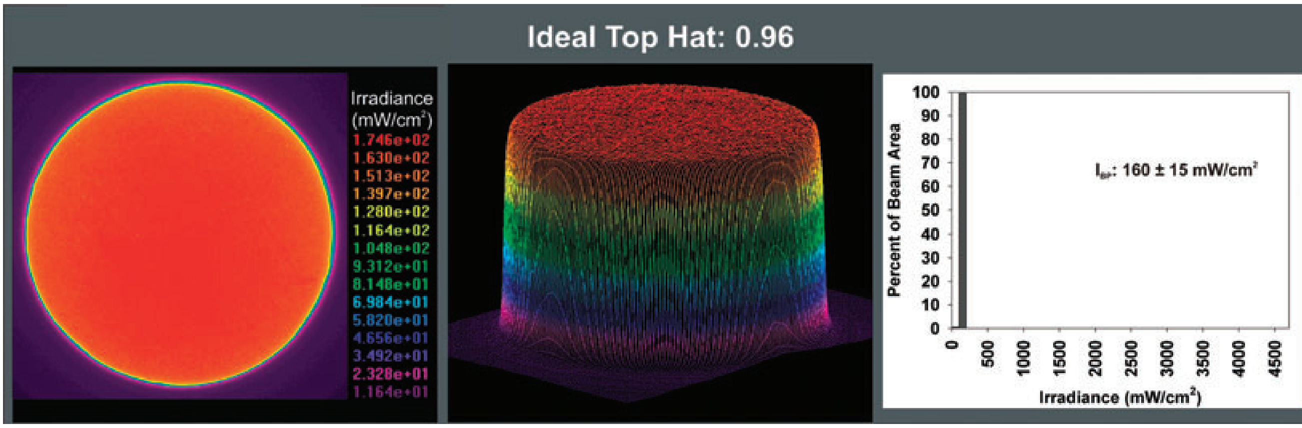

Figure 2. 2D and 3D views of the beam profile from the exit port of an integrating sphere (uniform light source) with a homogeneous irradiance distribution across the light beam and an almost perfect Top Hat (0.96). The histogram shows the percent of the beam area delivering the measured irradiance. Note that the maximum Y-value is 100% whereas the Y-values are four times smaller (max. 25%) in the histograms shown in Figures 3–7. The I_{BP} was calculated from the measured total power and the active port diameter measured using the beam profiler. The coefficient of variation was 9.4%.

(0.74 ± 0.01 indicating the most uniform beam irradiance) was found with the lowest powered LED-based unit (SmartLite IQ). The lowest THF (0.32 ± 0.01) was found for the FLASHLite Magna, which had only a plastic cover over the bare LED dyes. Interchanging different light guides also demonstrated significant differences in THF. The 13/8-mm turbo light guide used with the same LCU body provided a significantly lower THF value (0.50 ± 0.01) than the standard 13/13-mm glass-fibered guide (THF: 0.60 ± 0.01).

Irradiance Distribution across the Beam Surface

Table 2 gives the mean I_{BP} ± SD and coefficients of variation of the irradiance distributions across the light tips based on the beam analyzer data. The coefficient of variation ranged from 29.5% for the Optilux 501 (THF: 0.64) to 107% for the Magna (THF: 0.32). Table 3 shows irradiance value (I_{BP}) calculated using the beam analyzer data together with the percent of the beam area occupied by ranges of irradiance values between 50 and >4,000 mW/cm². Two and three-dimensional representations of the irradiance across the tip ends from the LCUs are shown in Figures 3 through 7. As all camera images were taken at the same focal distance, the images reflect the differences in tip end diameters, but the irradiance scale is unique for each image. The data used for the 2D and 3D representations are presented in the form of a histogram showing the percent of beam area as a function of irradiance delivered. The conventionally measured overall irradiance value (I_{CM}) was also placed on each histogram for a comparison.

Beam Profiles

Figure 3 shows an example of the most uniform LCU beam (SmartLite IQ), which had the highest THF (0.74 ± 0.1). Table 3 shows that this LCU delivered little irradiance (5.2% of tip area) above 1,000 mW/cm² and 80% of the tip end area delivered an irradiance between 500 and 1,000 mW/cm². Figure 4 shows an example of the Optilux 501 with the 11/11-mm standard light guide and a THF of 0.64 ± 0.1. This unit delivered an irradiance above 1,000 mW/cm² across 16.2% of the tip and no irradiance above 1,238 mW/cm². Figure 5 shows an example of the Bluephase 16i with the 13/13-mm standard light guide (THF: 0.60 ± 0.01) and the same unit

TABLE 3. PERCENT OF BEAM AREA DELIVERING VARIOUS IRRADIANCE LEVELS (MEAN ± SD).

Light curing unit	Percent of beam area delivering irradiance values					
	<500 mW/cm^2	>500 mW/cm^2	>1,000 mW/cm^2	>2,000 mW/cm^2	>3,000 mW/cm^2	>4,000 mW/cm^2
Sapphire	8.8 ± 0.1	91.2 ± 0.1	87.5 ± 0.1	68.4 ± 1.0	17.0 ± 0.7	0.4 ± 0.1
Bluephase 16i 8 mm Turbo	4.4 ± 1.2	95.6 ± 1.2	78.7 ± 0.8	34.0 ± 0.5	4.1 ± 0.0	0
Magna	43.3 ± 0.7	56.7 ± 0.7	29.5 ± 0.2	10.9 ± 0.4	4.2 ± 0.1	2.1 ± 0.1
Optilux 501	13.4 ± 0.2	86.6 ± 0.2	16.4 ± 0.8	0	0	0
Bluephase 16i 13 mm standard	24.6 ± 0.2	75.4 ± 0.2	23.0 ± 1.4	0	0	0
SmartLite IQ	14.8 ± 0.2	85.2 ± 0.2	5.2 ± 3.0	0	0	0

body used with the 13/8-mm turbo light guide (THF: 0.50 ± 0.01). Together with Tables 1 through 3, Figure 5 demonstrates how the power outputs, irradiance values, and their distributions across the tip end were affected merely by interchanging light guides within the same curing unit. The spatial beam profiles were completely different between the two light guides; the turbo light guide produced a conical beam distribution delivering irradiance levels up to 3,769 mW/cm^2 over a small area (<4% of the total tip end area) at the very center of the light guide tip. In contrast, the standard light guide on the same LCU delivered a more homogeneous irradiance over a larger proportion of the tip end, with values >1,000 mW/cm^2 occupying 23% of the tip end area and reaching a maximum value of only 1,390 mW/cm^2 at the center of the tip. Figure 6 shows an example of the Sapphire PAC unit that used a 5.5/9-mm reverse turbo light guide (THF: 0.57 ± 0.01). Note that the light beam has many high irradiance peaks reaching up to 4,444 mW/cm^2, and 68% of the tip end area delivers light in the 2,000 to 4,000 mW/cm^2 range. Figure 7 shows an example of the FLASHLite Magna LED, which uses no fiber optic light guide. The light beam from this unit has a low THF (0.32 ± 0.01), is not radially symmetrical, and has three irradiance peaks associated with the location of the three LED dyes and four satellite reflective peaks. Although these high irradiance peaks reach 5,834 mW/cm^2, they are very localized and are delivered over <1% of the beam area. The irradiance is less than 500 mW/cm^2 over 43% of the beam area. Figure 8 shows an image of the three LED dyes within the head of the FLASHLite Magna LCU taken through an orange filter (Cure-Shield, Premier Dental, Plymouth Meeting, PA, USA). The location of these three dyes corresponds to the 3D image of the tip end showing the three high level values directly placed over the LED dyes and the lateral reflections from these dyes.

DISCUSSION

The experimental data validated the first two research hypotheses, stating that the degree of irradiance uniformity (as measured by THF) would be significantly different among various types of LCUs, and that irradiance distribution across the exit tip of dental LCUs would not be universally radially symmetrical. There was a significant ($p < 0.05$) variation in the tip-end irradiance homogeneity, as described using the THF among QTH, PAC, and LED units. These differences are also evident by information in Tables 2 and 3 and Figures 3 through 7. Table 2 shows the corresponding differences in the SD and the coefficients of variation of the irradiance across the exit tip ends when the

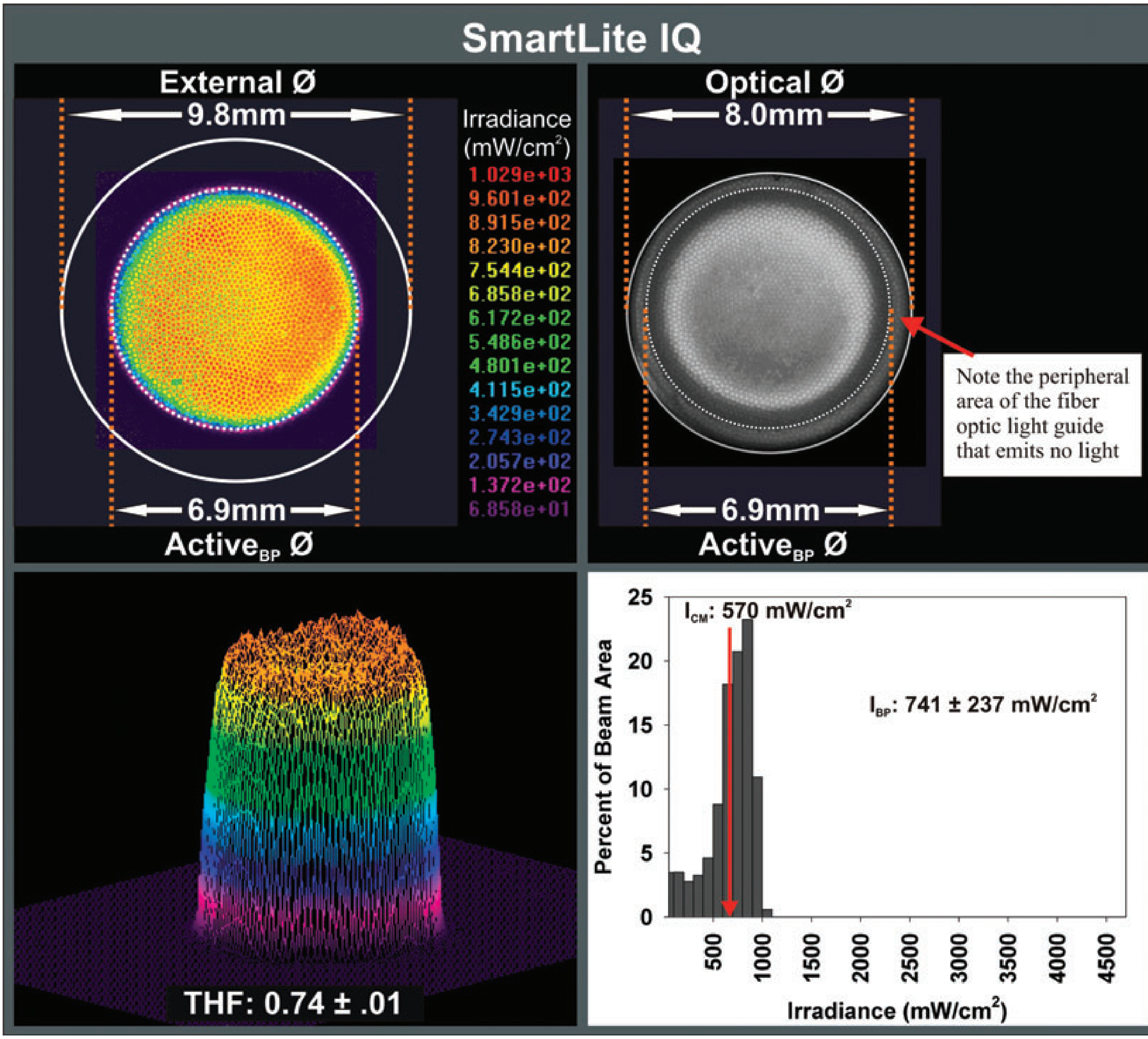

Figure 3. 2D and 3D views of the beam profile and irradiance distribution from the SmartLite IQ. This light-curing unit had the most uniform irradiance distribution across the tip end with a Top Hat Factor (THF) = 0.74. The 2D view shows both the external diameter (Φ) of the light guide and the optically active diameter, where the irradiance is greater than 50 mW/cm². The histogram shows the percent of the light beam area delivering different irradiance levels. The I_{CM} and the I_{BP} are shown on the histogram. Small variations in the 3D view are because of the finite size of the individual optical fibers in the light guide. The image of the end of the SmartLite IQ light guide shows that the optically active diameter of the light guide (6.9 mm) is less than the physical fiber optic bundle diameter (8.0 mm).

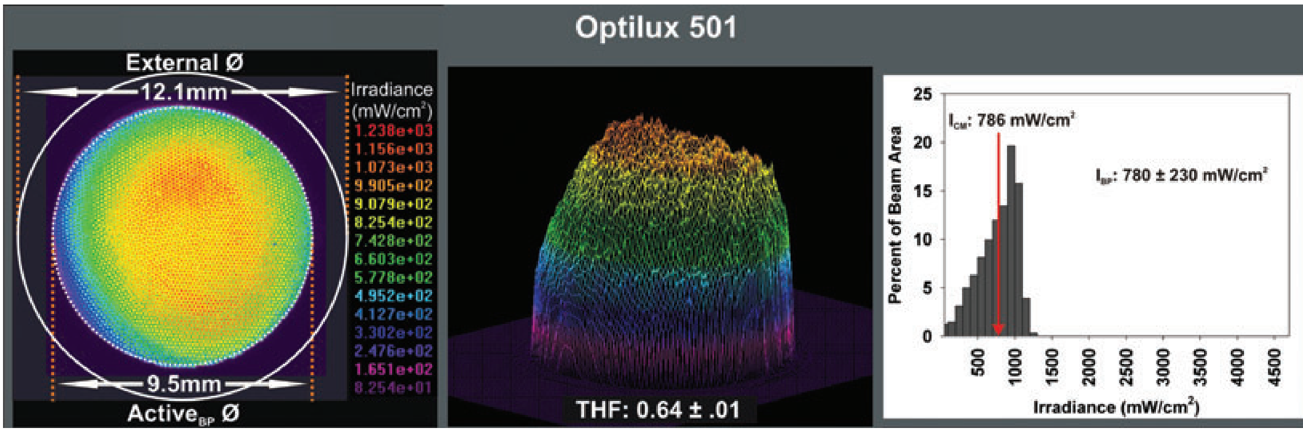

Figure 4. 2D and 3D views of the beam profile and irradiance distribution from the Optilux 501 using an 11/11-mm standard light guide. Note the difference between the external diameter (Φ) of the light guide and the optically active diameter where the irradiance is greater than 50 mW/cm². This unit had a Top Hat Factor (THF) = 0.64. The I_{CM} and the I_{BP} are shown on the histogram that shows the percent of light beam area delivering different irradiance levels.

irradiance was calculated from all the beam profile data. This disparity ranged among LCUs from the ones presenting relatively similar irradiance values across the tip of the light guide (SmartLite IQ, THF: 0.74, and Optilux 501, THF: 0.64) to one demonstrating a wide field of relatively low values with isolated locations of high irradiance (FLASHLite Magna, THF: 0.32). The coefficient of variation ranged from 29.5% for the Optilux 501 to 107% for the Magna. Two previous articles[18,25] have used light beam analysis instrumentation to characterize beam uniformity from various QTH and LED-based LCUs. Both publications showed that the light output was not uniform across the face of the light guides, but the selected 2D and 3D representations of the irradiance showed a radially symmetrical irradiance distribution at the tip ends of the LCUs.[18,25] The present study confirmed the lack of spatial irradiance uniformity among LCUs, but, in addition, found that the FLASHLite Magna did not deliver a radially symmetrical irradiance distribution at the tip end of the LCU.

The third research hypothesis, which assumed that using a different light guide on the same LCU would alter irradiance values as well as beam uniformity, was upheld. When the Bluephase 16i was fitted with two different light guides, the power output, irradiance, THF values, and beam profiles were all significantly different. Figure 5 shows that both light guides on the Bluephase 16i displayed radial symmetry across their tip ends, but the turbo light guide delivered a conical shaped irradiance profile with an intense peak irradiance >3,000 mW/cm² over just 4.1% of the total area of the tip. This irradiance concentration resulted in a relatively low THF factor of 0.50 ± 0.01. The 13/13-mm standard light guide produced a more homogeneous irradiance distribution across the tip end, with 52% of the tip delivering irradiance values between 500 and 1,000 mW/cm². This increased uniformity produced a significantly higher THF value (0.60 ± 0.01) and smaller variation in the irradiance distribution than that seen from the turbo tip (coefficient of variation: 38.1% for the standard tip and 42.8% for the standard tip). When viewed in the 3D depiction of the beam profile (Figure 5A and B), these findings are also illustrated by the very

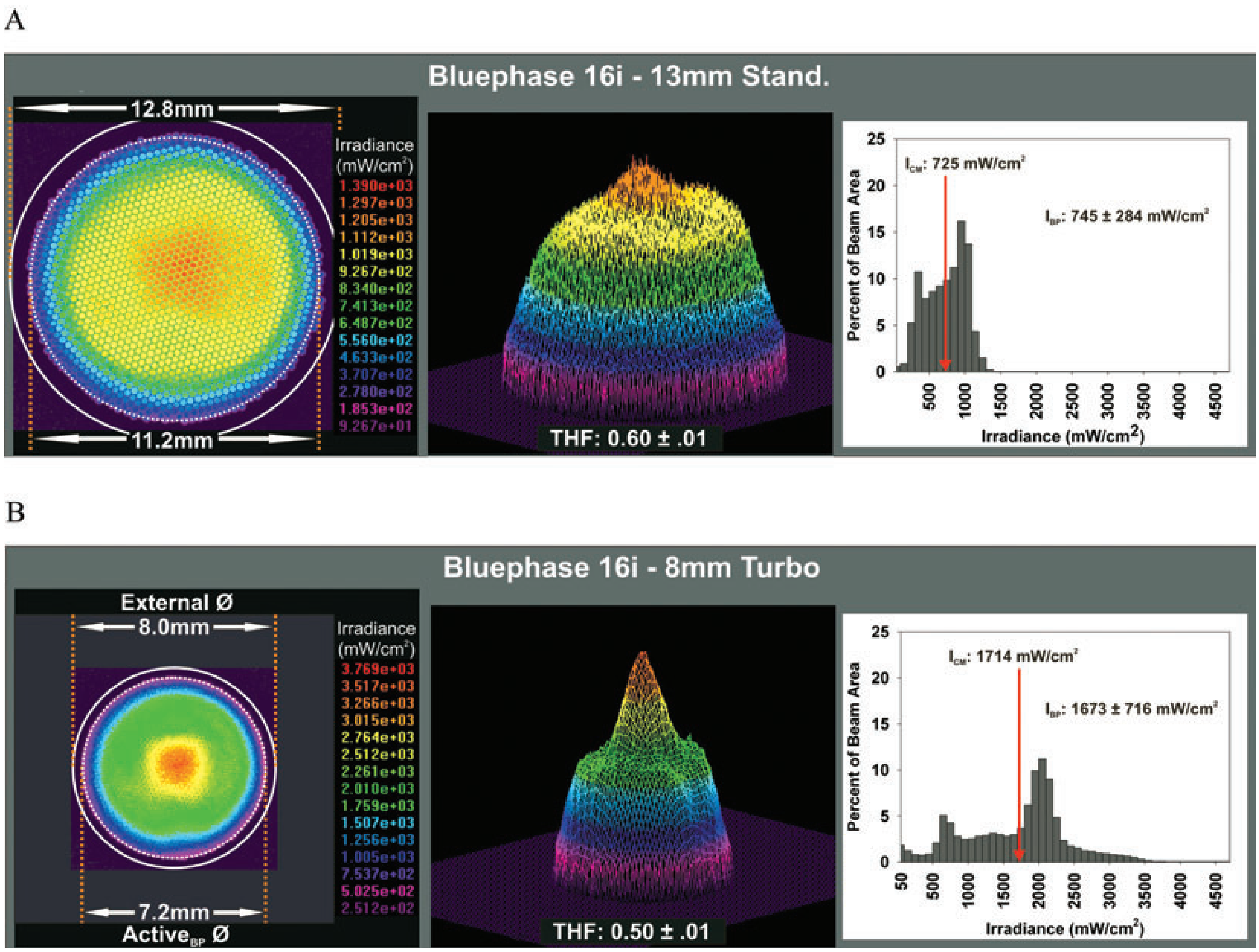

Figure 5. 2D and 3D views of the beam profile and irradiance distribution from the Bluephase 16i using a 13/13-mm standard (A) or a 13/8-mm Turbo light guide (B). Note the intense conical peak irradiance at the center of the turbo light guide (B). Note the difference between the external diameter (Φ) of the light guide and the optically active diameter where the irradiance is greater than 50 mW/cm². The I_{CM} and the I_{BP} are shown on the histogram that shows the percent of light beam of the top of the hat because of the finite size and boundaries of the individual optical fibers in the light guide. THF = Top Hat Factor.

sharp-edged, cylindrical output of irradiance profile with only a slightly rounded top surface. Table 1 shows that significantly more power was emitted using the standard light guide (756 ± 7 mW) than when using the turbo light guide (689 ± 4 mW), but the irradiance was higher using the turbo tip light guide at the tip end compared with when the standard 13-mm light guide was used on the same LCU. Other studies have also reported that turbo light guides delivered a higher irradiance at the tip end compared with standard light guides.[29–31] This difference in the effect of turbo and standard light guides on irradiance can be explained by the different diameters of the light guides, as even small changes in the diameter greatly affect the emitting area and thus the irradiance. The standard

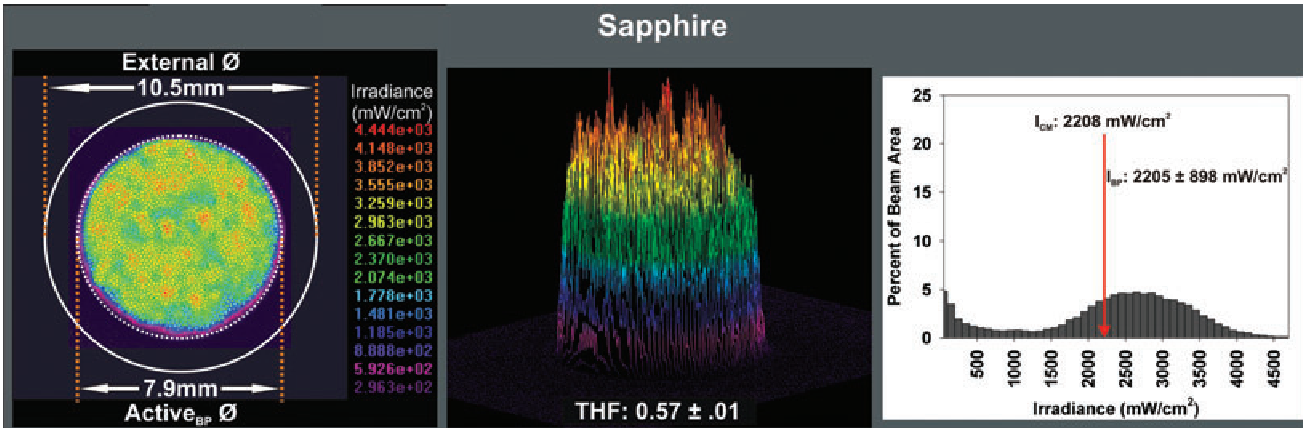

Figure 6. 2D and 3D views of the beam profile and irradiance distribution of the irradiance from the Sapphire PAC unit using a 5.5/9-mm reverse turbo light guide. Note the difference between the external diameter (Φ) of the light guide and the optically active diameter where the irradiance is greater than 50 mW/cm². This unit had a Top Hat Factor (THF) = 0.57. The histogram shows the percent of the beam area delivering the measured irradiance. The isolated irregular high irradiance peaks and troughs are due to the design of the light guide. The I_{CM} and the I_{BP} are shown on the histogram that shows the percent of light beam area delivering different irradiance levels.

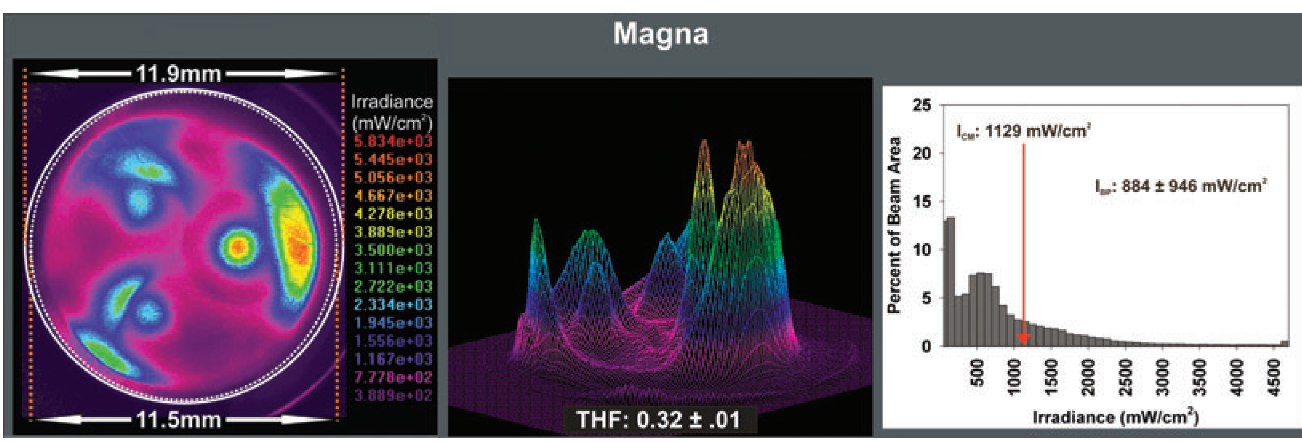

Figure 7. 2D and 3D views of the beam profile and irradiance distribution of the irradiance from the FLASHLite Magna, which does not use a light guide. The 2D view shows the external diameter (Φ) of the light guide and the active diameter where the irradiance is greater than 50 mW/cm². This unit had a Top Hat Factor (THF) = 0.32 with seven high irradiance peaks delivered over a small percent of the beam area. The histogram shows the percent of the beam area delivering the measured irradiance. The I_{CM} and the I_{BP} are shown on the histogram that shows the percent of light beam area delivering different irradiance levels. Note that the beam is not radially symmetrical and has three irradiance peaks associated with the location of the three LEDs and four satellite reflective peaks. Note also that one LED chip is more powerful than the other two.

light guide in the present study had a caliper-measured tip diameter of 11.52 mm. This produced an area of 1.04 cm² compared with a calliper-measured tip diameter of 7.16 mm and a corresponding area of only 0.40 cm² for the turbo light guide. Even though the standard light guide delivered significantly greater power, the turbo light guide was 3 mm smaller in diameter. By reducing the distal tip end area to

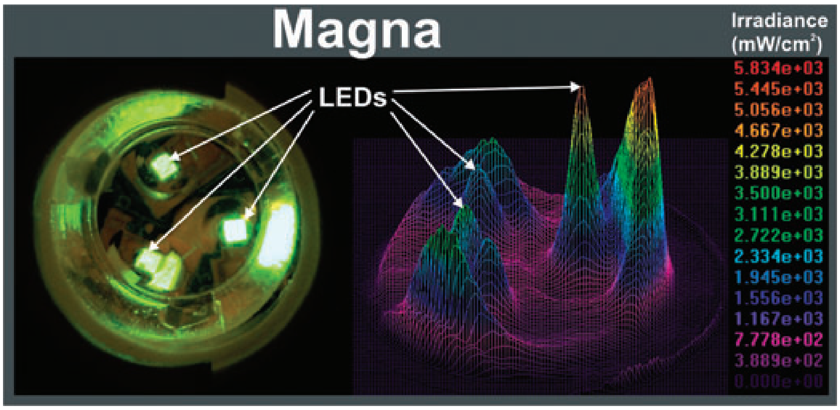

Figure 8. FLASHLite Magna unit showing the location of the three different light-emitting diode (LED) dyes (indicated by arrows) and the light beam profile showing three irradiance maxima directly over the LEDs. The four additional maxima are related to lateral reflections.

40% from 1.042 cm^2 to 0.403 cm^2, even though the overall power output was lower, the turbo light guide generated a total tip irradiance that was more than 2.3 times greater (from 725 to 1,714 mW/cm^2) than did the standard light guide ($p < 0.05$).

The fourth hypothesis was found to be true. Tables 2 and 3 and Figures 3 through 7 show that, when irradiance was calculated as a single value (I_{CM}) by dividing the total power by the area of the tip, this irradiance value did not adequately represent how the irradiance was distributed across the tip end of the LCU. Despite the result that all the light units delivered an $I_{CM} \geq 570$ mW/cm^2, Table 3 shows that only four of the units (Sapphire, Optilux 501, SmartLite IQ, and Bluephase 16i with the turbo light guide only) delivered greater than 500 mW/cm^2 over more than 80% of the tip area. The histograms in Figures 3 through 7, the SDs and coefficients of variation reported in Table 2, and the percent distribution reported in Table 3 provide a more complete depiction of the irradiance distribution generated by the LCUs. In contrast, the conventionally calculated irradiance (I_{CM}) only provides an overall average irradiance across the tip end of the light guide and cannot reflect the large range of irradiance values within the beam. Table 3 shows that, in some instances, a high proportion of the tip area delivered much less than the mean irradiance value. For example, the mean ± SD irradiance (I_{BP}) of the FLASHLite Magna was 884 ± 946 mW/cm^2, and 43.3% of the area delivered less than 500 mW/cm^2. This discrepancy resulted in a large coefficient of variation of 107% for this LCU. For the Sapphire, the I_{BP} was 2,205 ± 898 mW/cm^2, but only 8.8% of the area delivered less than 500 mW/cm^2, whereas 17% of the area produced more than 3,000 mW/cm^2.

THF

The results suggest that the THF should not be used as the sole descriptor of beam homogeneity; instead, the actual pattern and proportioning of irradiance distributions across the beam must be taken into account as well as the overall mean irradiance value. Among the LED-based units, the SmartLite IQ delivered the highest THF value (0.74 ± 0.1), which was attributed to a well-matched LED source, reflectors, focusing lens, and light guide. The most strikingly wide irradiance distribution was observed using the FLASHLite Magna. As shown in Figures 7 and 8, the irradiance distribution from this LCU is unique compared with all the other units studied in that it consisted of seven irradiance peaks originating from the combination of direct emission from the three LED dyes and the lateral emissions caused by the reflector arrangement. Figure 8 shows that this LCU does not use a light guide and has three LED chips covered by a disposable plastic cover. At the tip of this LCU, the output from the three chips remained independent and was not the same from all three LEDs. This difference in chip output may be related to differences in driving current to the individual chips, or because of the LED binning process (variation in the LED chip characteristics within the tolerances specified by the curing light manufacturer).

Differences in I_{CM} and I_{BP} Values

An important finding of the study was the observation that a physical measurement of the optical bundle diameter does not accurately describe the optically active diameter of the tip end when the light is on. The I_{CM} was derived from measuring the diameter of the light guides using calipers (Table 1), whereas the I_{BP} was more accurately derived from measuring the optically active beam diameter delivering an irradiance >50 mW/cm^2. The variances between the mean I_{CM} and I_{BP} values shown in Table 2 are because of differences in the way the diameter of the light sources were measured. The irradiance values were similar for three lights, but they were quite different for the FLASHLite Magna and SmartLite IQ LCUs. This difference can be explained by the difficulty in determining the active light-emitting diameter for the FLASHLite Magna when using calipers because the unit has no light guide. Another example of this finding is the SmartLite IQ. Figure 3 shows that this unit had an emitting diameter of 6.93 mm when measured using the beam analyzer compared with 7.94 mm when measured with calipers. This difference occurred because the internal lensed light source inside this unit was smaller than the diameter of the entrance to the fiber optic light guide and almost no light enters or exits from the peripheral portions of the light guide. Figures 3 through 7 also show that the outer diameter of the light guide that covers the tooth is greater than the optically active diameter. Thus, the operator must realize that not all of the tooth under the light guide is receiving sufficient light.

Where THF and Histograms Differ

Exemplifying this concept are the data associated with using two different light guides on the same LED unit body. When the standard guide was used, an I_{BP} value of 745 mW/cm^2 was achieved within a range of 1,300 mW/cm^2 (Tables 2 and 3 and Figure 5). The THF for this unit was 0.60 ± 0.01. Using the turbo guide resulted in a higher I_{BP} value of 1,673 mW/cm^2, but the irradiance was delivered over a range of 3,400 mW/cm^2 at a lower THF value of 0.50 ± 0.01.
Figure 6 illustrates the beam profile from the Sapphire LCU. This unit had a THF value between those of the previous LCUs mentioned (THF: 0.57 ± 0.01); however, it delivered a much greater mean I_{BP} value of 2,205 mW/cm^2, all within an irradiance range of 4,450 mW/cm^2. Thus, although the THF values provide a relative index of differences in beam homogeneity, they cannot predict the range of irradiance values. This information can be obtained from the SD and coefficients of variation of the mean beam profile irradiance (I_{BP}).

Research and Clinical Implications

If the output from dental LCUs were that of a "perfect beam," as illustrated in Figure 2, calculating the irradiance from total power as a function of the area would accurately describe the light distribution across the beam and none of the issues raised in this paper would have research or clinical implications. However, the large variation in beam homogeneity and irradiance distributions that were found across the tip ends of the five LCUs and the observation that light does not always exit from the entire tip diameter present important considerations. When characterizing the output from LCUs, it can now be seen that the previous assumptions of either a homogeneous distribution of radiation across the beam or a radial symmetry of that distribution are not common. This lack of uniformity needs to be evaluated using techniques described in the present research to provide researchers with a better idea of the consistency of light output. For example, current research protocols of rigidly holding the light guide while irradiating specimens for hardness testing, depth of cure analysis, or bond strength testing[16,27] should be reconsidered, as such methodologies could lead to erroneous and inconsistent results. In addition, clinicians need to be aware of these differences in irradiance distribution because the extent and rate of curing of photo-activated restorative material targets is directly affected. Patterns in the extent of composite surface cure, as reflected by hardness values, have been found to reflect the irradiance distribution delivered by the beam.[14,25] These localized differences in resin curing may lead to variation in surface hardness, which might then affect rates of wear as well as flexural strengths and moduli, which could ultimately affect restoration integrity.

Although not every dental LCU was evaluated in this study, it is thought that the range of units selected represents a good sampling of the variety of units currently on the market. Future studies should continue to examine differences in beam homogeneity and should focus on examining the variation in distribution of emitted LED wavelengths from polywave LED units. In addition, the effects of disparity in general irradiance values on depth of cure testing and general mechanical properties need to be evaluated as well as the effect of intentionally moving the light tip during exposure in order to minimize the effects of localized irradiance differences.

CONCLUSIONS

Within the limitations imposed by the experimental design used in the current study, the following conclusions may be made:

1. The uniformity of the irradiance at the exit tip end of dental LCUs greatly varies among commercial products and types of light-generating methods
2. The irradiance at the emitting tip end of a wide variety of dental LCUs is not universally radially symmetrical and can be quite inhomogeneous
3. The use of different light guides on the same LED unit body can result in greatly different irradiance and homogeneity values
4. The common method of measuring a single irradiance value to characterize a specific LCU does not truly reflect the large range in the irradiance across the exit tip of dental LCUs
5. When describing the irradiance from dental LCUs, the overall irradiance, the distribution of that irradiance across the light beam, and the THF should be included

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