The Effect of Distance from Light Source on Light Intensity from Curing Lights

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Purpose: To investigate how light intensity changes as the distance increases from the tip of the light guide.

Materials and Methods: Ten different curing light/light guide combinations were used. Light intensity was measured at 0, 3, 6, and 10 mm from the tip of the light guide with a radiometer. Measurements were repeated in five separate trials and the mean light intensity ± standard deviation was calculated. The fiber density was measured at the entrance and exit of all ten light guides and the light dispersion patterns were recorded.

Results: Light intensity decreased as distance increased for all lights tested; however, the rate and extent of this decrease was not similar for all lights ($p < 0.0001$). Turbo light guides exhibited a more rapid decrease in intensity as the distance increased than standard light guides. At 10 mm, all the turbo light guides had lost over 80% of their intensity recorded at 0 mm.

Conclusion: 1. The rate and extent of the decrease in intensity is not similar among curing lights ($p < 0.0001$). 2. It is not possible to predict light intensity at 10 mm from measurements made at 0 mm. 3. Curing light manufacturers should state intensity over clinically relevant distances (0 to 10 mm).

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Light-cured resin composites are widely used in dental restorations, as they are mercury-free and esthetically pleasing to the patient.[3,12] These tooth-colored composites are hardened by light from a light-curing unit (LCU). The power density from the LCU, also referred to as light intensity, is the number of photons per second (Watts [W]) emitted by the light source per unit area (W/cm^2).[2,5] It has been reported that a minimum power density of 300 to 400 mW/cm^2 is required to adequately cure a 1.5- to 2-mm increment of resin composite in the manufacturers' recommended curing time.[10,21] As light penetrates restorative materials, the intensity is greatly reduced by the resin and filler particles.[8,11,22,25,26] This creates a curing gradient where the composite is hardest at the surface closest to the light and progressively softer further away from the light.

The energy density (Joules/cm^2) received by the composite is calculated by multiplying the power density by the total exposure time.[2,5] Curing lights must provide sufficient energy to the composite to produce acceptable polymerization and hardness in the composite resin. It has been reported by Fan et al[10] that an energy density of 6 to 12 J/cm^2 was sufficient to cure most resin composites to a depth of 1.5 mm. However, some composites required more than 18 J/cm^2 to achieve an acceptable cure at 1.5 mm.[10]

The most common light source is a quartz-tungsten-halogen lamp (QTH).[5] Plasma arc (PAC) LCUs employ a different technology to produce a very high intensity light between two electrodes sur-

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rounded by electrically conductive gas (xenon) inside the LCU.[5] When a high voltage is applied, a broad-spectrum arc of light is generated that must be filtered to select only the wavelengths of light needed to polymerize dental resins. One manufacturer has claimed that in 3 to 5 s, their light provides polymerization equivalent to 30 to 40 s of light exposure using a conventional QTH curing light.[20] In recent years, light-emitting diodes (LEDs) have been used to create compact, cordless LCUs. LED technology is considered very promising for use in LCUs.[1,4,7] Dental resins irradiated using blue light LEDs have been reported to have a higher degree of polymerization, a more stable three-dimensional structure, and a significantly greater curing depth than those cured with conventional QTH lights.[15,17] However, these LCUs produce a narrow spectrum of light compared to either QTH or PAC lights. This may be why it has been reported that the hardness of some composites irradiated with LED curing lights was lower compared to when they were irradiated with QTH curing lights.[9]

In addition to the light source, the type of light guide used with a LCU may alter the power density from the LCU.[19,23,24] Light guides are usually composed of fiber optic bundles covered in a protective sheath. A standard light guide has fibers of uniform diameter throughout the length of the light guide. This creates equal fiber densities/mm^2 at both ends of the light guide. Conversely, turbo light guides that have been designed to increase power density at the end of the light guide[6] have fibers that taper from one end of the light guide to the other. Therefore, the fiber density is greater at the exit of the light guide, compared to the entrance. The increased fiber density at the exit concentrates the amount of light delivered by the LCU into a smaller area, thereby increasing the power density compared to a standard light guide on the same LCU. For one brand of turbo light guide, the increase in power density was observed up to 5 mm from the tip of the light guide, beyond which turbo light guides delivered a lower power density and dispersed the light more than a standard light guide.[19] In addition to standard and turbo light guides, there is another type of light guide that has a greater fiber density at the entrance than at the exit of the light guide, and for the purpose of this study will be called a “reverse turbo” light guide. This design reduces the power density at the exit, a feature that may only be desired on very high intensity lights.

Prati et al[18] have shown that the power density generated by LCUs decreases exponentially with distance through air, losing approximately 20% of total light intensity for every 1 mm of air space. Moseley et al[16] reported that as the distance from the light guide increased from 2 to 10 mm, light intensity dropped by 20%, 30% and 40% for three different curing lights. Price et al[19] reported that at 6 mm, the power density fell to 50% of its original value for the standard light guide and 23% of its original value when using the turbo light guide. These findings suggest that very little light intensity reaches the floor of deep preparations, which can exceed 7 mm.[13,14,26] This reduced light intensity could lead to inadequate curing of composite resins and subsequent failure of the restoration.

The purpose of this study was to investigate how light intensity changes as the distance increased from the tip of the light guide of currently available PAC, QTH, and LED light sources. The null hypothesis was that all curing light/light guide combinations would demonstrate a similar drop in light intensity as distance from the tip of the light guide increased.

MATERIALS AND METHODS

Ten different curing light/tip combinations were used (Table 1) to investigate how light intensity varies with distance through air. To represent a clinical situation where the distance from the light guide to the floor of the preparation may exceed 6 mm (Figs 1a to 1c), the light intensity was measured 0, 3, 6, and 10 mm from the tip of the light guide using a Cure Rite radiometer (serial number 5330, Dentsply Caulk, Millford, DE, USA).

Prior to each measurement of light intensity, the curing light was turned on for two curing cycles to warm the light source. Ten seconds into the third curing cycle (except for the Phase II and Sapphire lights which were tested after 3 to 5 s) the light guide was positioned over the Cure Rite sensor and the power density was recorded in mW/cm^2. Measurements were repeated in five separate trials, and the mean power density ± standard deviation was calculated.

The number of fibers per mm^2 was measured for the ten light guides used in this study. Magnified (1.6X) pictures of the entrances and exits of the light guides were taken with a photo macrographic camera (Zeiss-Tessovar, Oberkochen, Germany). The pictures of the ends of the light guides were printed and five random 4 mm^2 areas at each end

Table 1 Curing lights and light guides

Curing Light	Light Guide	Manufacturer
Sapphire (PAC)	9 mm	Den-Mat, Santa Maria, CA, USA
Phase II (High-Power QTH)	8 mm	Den-Mat
Astralis 10 (QTH) ECS Mode	13/8 mm Power Booster	Ivoclar Vivadent, St. Catherines, Ontario, Canada
VIP (QTH)	11 mm	Bisco, Schaumburg, IL, USA
Optilux 501 (QTH)	8 mm	SDS Kerr, Danbury, CT, USA
Optilux 501 (QTH)	8 mm Turbo+	SDS Kerr
Jetlite (QTH)	13/8 mm Turbo	J. Morita USA, Irvine, CA, USA
FreeLight (LED)	8 mm Turbo	3M ESPE, St Paul, MN, USA
Aqua Blue (LED)	8 mm High Power	TOESCO Toei Electric, Kanagawa, Japan
Versalux (LED)	8 mm	Centrix, Shelton, CT, USA

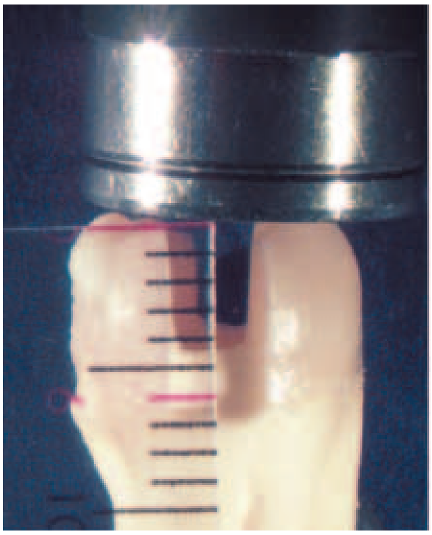

Fig 1a Tooth preparation extending just past the cementoenamel junction showing a preparation floor-to-light guide distance of 6.9 mm.

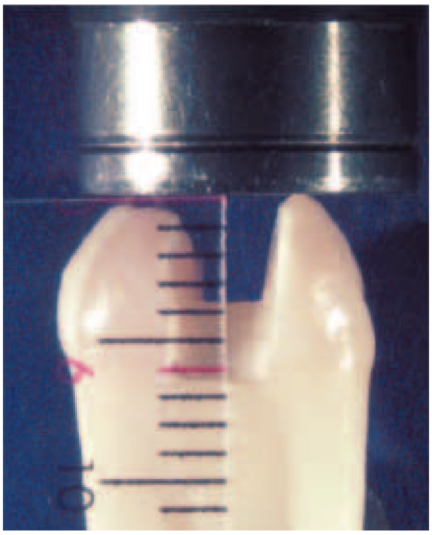

Fig 1b Tooth preparation extending just past the cementoenamel junction showing a preparation floor-to-light guide distance of 6.5 mm.

Fig 1c Tooth preparation extending just past the cementoenamel junction showing a preparation floor-to-light guide distance of 6.2 mm.

were selected. The fibers contained within the selected areas were counted and the mean number of fibers/mm^2 ± standard deviation was calculated.

Repeated Measures Analysis of Variance (ANOVA) was used to test for significant differences in the rate and extent of change in power density as the distance increased from the tip of the light guide. The power density produced by each curing light was ranked at each distance with Tukey's Studentized Range (HSD) Test.

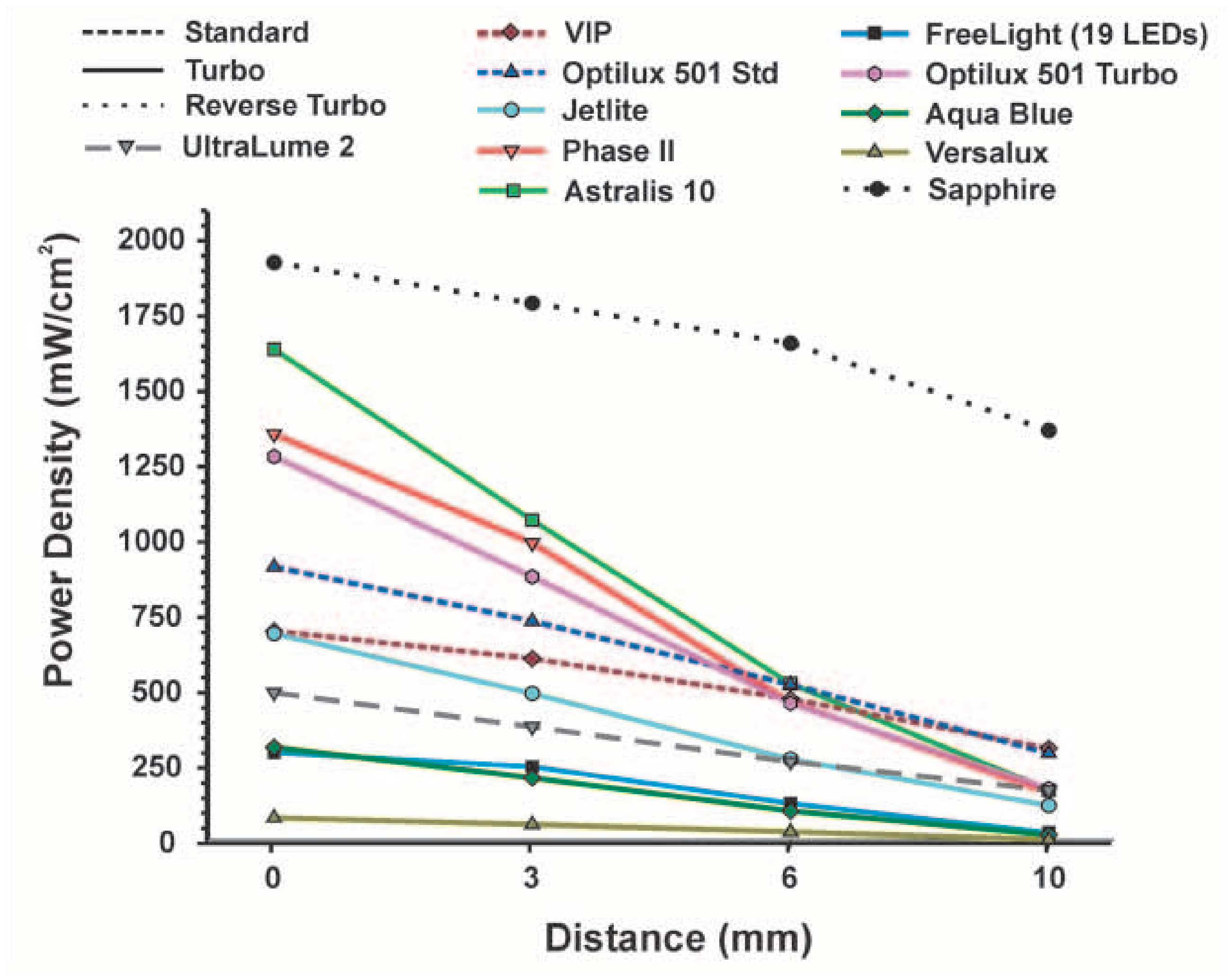

Fig 2 Power density vs distance from light guide.

RESULTS

The power density decreased for all lights when the distance between the light guide and the radiometer was increased ($p < 0.0001$), but the rate and extent of this decrease was not similar for all curing lights ($p < 0.0001$). Figure 2 shows a line plot of light intensity vs distance for each curing light/light guide combination. At 0 mm, there was a wide range in intensity among the different curing lights, ranging from 73 mW/cm^2 (Versalux) to 1931 mW/cm^2 (Sapphire). As the distance increased, the intensity decreased more rapidly from the tip of the turbo light guides (solid lines) than from the standard (dashed lines) or reverse turbo (dotted line) light guides. Figure 3 shows the percent reduction in power density, with respect to 0 mm. At 3 mm, no curing light lost more than 35% of its initial light intensity recorded at 0 mm. At 6 mm, which is typically encountered while curing deep preparations, most of the curing lights in this study lost over 50% of their initial intensity, the exceptions being Sapphire, VIP, and Optilux 501 (with standard light guide). When the distance was increased to 10 mm, all but the Sapphire, VIP, and Optilux 501 (standard light guide) had lost over 80% of their initial intensity. The intensity of the

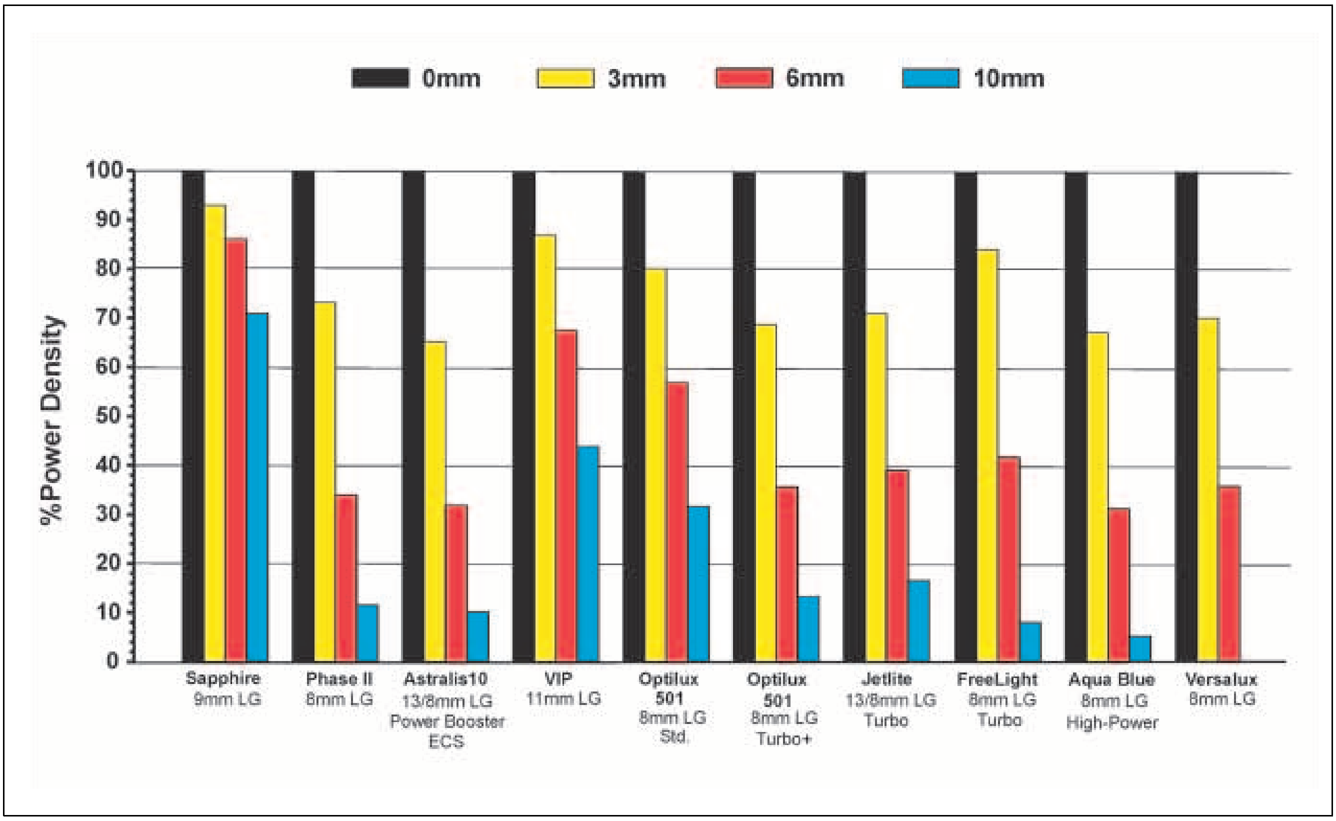

Fig 3 Reduction in power density (%) at 3, 6, and 10 mm from the light guide.

Table 2 Ranking of lights by power density at 0, 3, 6 and 10 mm

Curing light	Intensity (mW/cm^2) [Rank] 0 mm	3 mm	6 mm	10 mm
Sapphire	1930 [1]	1795 [1]	1661 [1]	1369 [1]
Astralis 10	1641 [2]	1069 [2]	522 [2.5]	166 [5]
Phase II	1357 [3]	993 [3]	460 [5]	157 [5]
Optilux 501 (t)	1280 [4]	880 [4]	456 [5]	170 [5]
Optilux 501 (s)	913 [5]	731 [5]	519 [2.5]	289 [2.5]
VIP	699 [6.5]	606 [6]	471 [5]	306 [2.5]
Jetlite	688 [6.5]	489 [7]	269 [7]	114 [7]
Aqua Blue	309 [8.5]	207 [9]	96 [9]	16 [8.5]
FreeLight	291 [8.5]	244 [8]	121 [8]	23 [8.5]
Versalux	73 [10]	51 [10]	26 [10]	0 [10]

Versalux light was so low at 10 mm that it could not be measured on the radiometer. Table 2 shows both the power density (mW/cm^2) and the rank of the curing lights at each distance. The Sapphire PAC light consistently produced the highest power density at all distances, while the Versalux consistently produced the lowest. Only the lights with standard light guides (Optilux 501 with the standard 8-mm light guide and the VIP light) improved significantly in rank as distance was increased ($p < 0.05$).

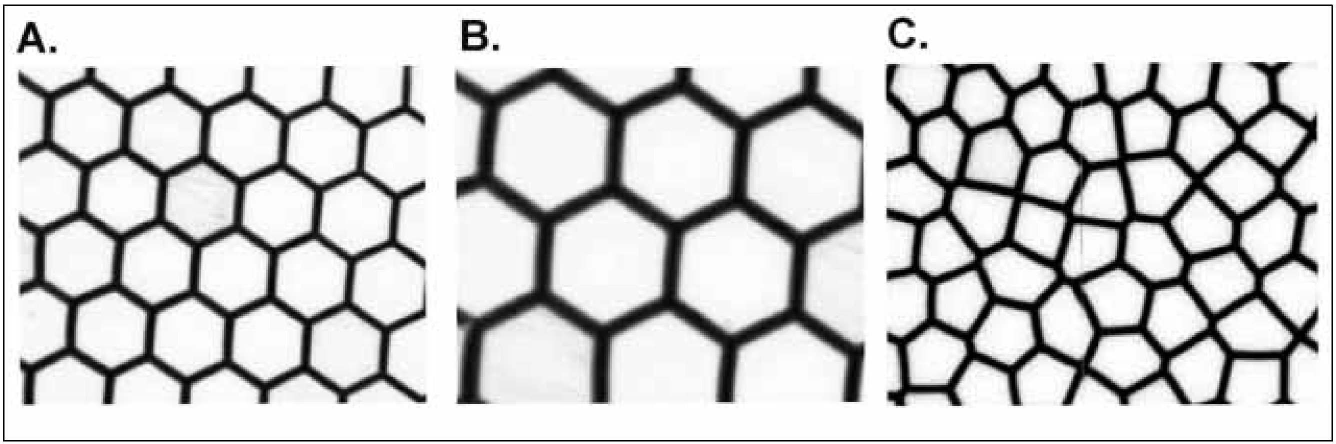

Fig 4 Fiber patterns showing smaller fibers at the exit (A) and larger fibers at the entrance (B) apertures for a turbo light guide, and an irregular fiber pattern (C) from another light guide. All micrographs taken at the same magnification (1.6X).

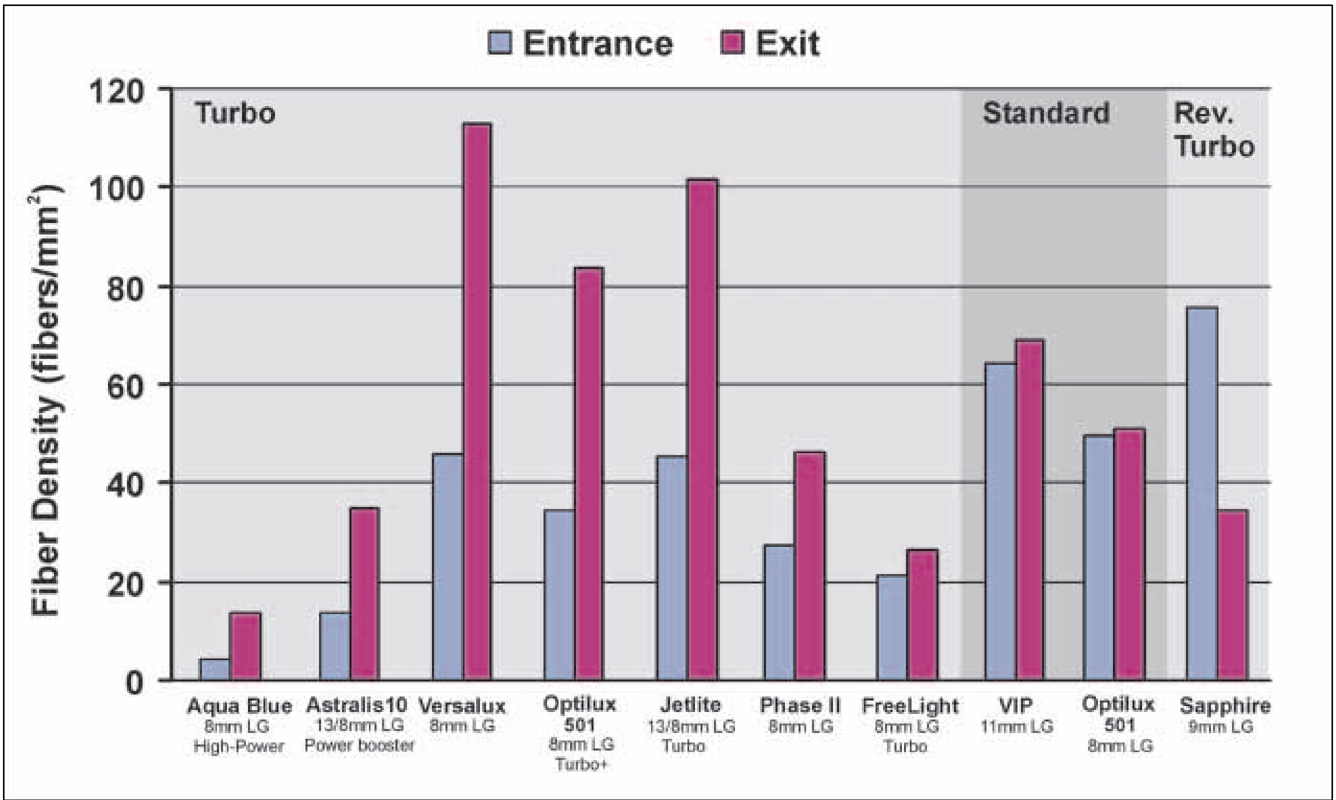

Fig 5 Entrance and exit fiber densities for various curing lights.

Figures 4A and 4B show the ends of the Optilux 13/8 turbo light guide. There is a uniform honeycomb-like fiber pattern at the exit and entrance apertures. The cross-sectional area of the entrance fibers is larger than that of the exit fibers, confirming that this is a “turbo light guide”. Figure 4C shows a light guide from a different manufacturer. Here the fiber pattern is irregular, which demonstrates that not all light guides are assembled in the same manner, and some contain regular fibers while others contain irregular fibers. Figure 5 shows the fiber density (fibers/mm^2) at the entrance and exit apertures of each light guide. The ratios of entrance to exit fiber density for the lights used in this study ranged from 0.30 to 2.18 and are shown in Table 3. The Sapphire PAC light guide, which is a “reverse turbo”, has a higher fiber density at the entrance than at the exit, effectively reducing the power density delivered by the light. The Optilux 501 standard 8-mm and the VIP light guides are classified as “standard” light guides and have very similar entrance and exit fiber densities. The remainder of the lights guides are all classified as “turbo” light guides, because the exit fiber density is higher than the entrance fiber density. The FreeLight 8-mm is classified as a “turbo” by 3M ESPE, but the difference in exit vs entrance fiber density values were small as compared to the difference found with the Versalux 8 mm or Optilux 13/8 turbo light guides.

Table 3 Fiber density ratios for various curing light guides

Curing light	Density ratio entrance:exit	Light guide classification
Aqua Blue	0.30	Turbo
Astralis 10	0.39	Turbo
Versalux	0.40	Turbo
Optilux 501	0.41	Turbo
Jetlite	0.45	Turbo
Phase II	0.60	Turbo
FreeLight	0.80	Turbo
VIP	0.93	Standard
Optilux 501	0.97	Standard
Sapphire	2.18	Reverse turbo

DISCUSSION

This study examined the effect of distance on light intensity and the light dispersion patterns from ten different curing light/light guide combinations. Included in these combinations were two standard light guides, seven turbo light guides, and one reverse turbo light guide. For the purpose of this study, a light guide was considered “turbo” if the ratio of entrance fiber density to exit fiber density was smaller than 0.9 (Table 3). If the ratio was larger than 1.1, the light guide was called a “reverse turbo”.

The results clearly show that although some curing light/light guide combinations increase the power density at short distances (ie, turbo light guides), the light disperses rapidly from the end of the light guide and may not be sufficient to polymerize resin at the bottom of deep preparations. These findings are supported by an initial study that compared two different light guides, one standard and one turbo, on the same LCU.[19] The authors concluded that manufacturers should report power density at both 0 and 6 mm, since significant differences exist between light guide designs.[19]

The curing lights in this study had very different initial light intensities at 0 mm (Table 2). Lights such as the Sapphire with very high power densities (1930 mW/cm^2 at 0 mm) would still be expected to produce a high power density 10 mm from the tip, as was observed in this study (1369 mW/cm^2 at 10 mm). Conversely, some lights such as the Versalux had a much lower initial light intensity (73 mW/cm^2 at 0 mm) which dissipated quickly within a short distance (0 mW/cm^2 at 10 mm).

It has been reported that the minimum QTH light intensity required to adequately cure most resin composites is between 300 and 400 mW/cm^2.[10,21] Table 2 shows that at 10 mm only the PAC light and the VIP curing light with standard light guide could deliver more than 300 mW/cm^2. Consequently these lights/light guide combinations may outperform other lights when curing resins in deeper preparations. Although this distance may seem large, this depth can occur in a clinical preparation as shown in Fig 1. If the light guide is 3 mm away from the surface of the tooth, then the bonding agent or composite resin may be 10 mm away from the light guide at the floor of a deep preparation.

The turbo light guides used in the present study delivered a higher power density than the standard light guide at distances of 0 mm and 3 mm from the tip (Table 2). Conversely, at distances of 6 mm and 10 mm, the standard light guides delivered greater power density than the turbo light guide (Table 2). The VIP light with a standard light guide and the Jetlite with a turbo light guide had statistically equivalent power densities at 0 mm ($p > 0.05$) (Table 2). Figure 3 shows that as the distance increased to 10 mm, there was a greater reduction in power density from the Jetlite compared to the VIP light (85% for Jetlite vs 56% for VIP).

A previous study using an Optilux 500 curing light showed that at 6 mm the power density fell to 50% of its original value for the standard light guide and 23% of its original value when using the turbo light guide.[19] The present study, which used the Optilux 501 and different turbo and standard light guides, found that at 6 mm the power density fell to 57% of its original value for the standard light guide and 36% of its original value with the turbo light guide. This reduction in intensity was less and may be explained due to the use of a different curing light and light guides. However, both studies showed that beyond 5 mm from the tip of the light guide, the standard light guide produced higher power densities than the turbo light guide when used on the same curing light.

This study shows that light intensity delivered by curing lights is dependent on the type of light guide used. Compared to standard light guides, turbo light guides demonstrate a wider dispersion pattern,[19] and therefore the intensity decreases more rapidly as the distance increases. Even among the turbo light guides, there are variable dispersion patterns, which may be due to differences in the fiber density ratios shown in Table 3 or due to differences in the arrangement of the fibers in the light guide as shown in Fig 4. Commercially available curing lights have different types of light guides. Therefore, investigators should use caution when evaluating curing lights, since the results may not be due solely to the different light sources, but may also be due to the effects of the different light guides.

CONCLUSIONS

1. The rate and extent of the decrease in light intensity was not similar for all the curing lights/light guides tested ($p < 0.0001$).
2. It is not possible to predict the light intensity from a curing light at a distance of 10 mm from intensity measurements made at 0 mm.
3. Manufacturers should state the power density over a clinically relevant distance (0 to 10 mm).
4. Turbo light guides generate greater power densities than standard light guides at short distances (0 mm, 3 mm), but the reverse is true at greater distances (6 mm and 10 mm).

Deep restorations may not be adequately cured if the duration of light exposure is based on data derived from measurements made with the tip of the light guide in close proximity to the radiometer or resin composite.

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