Accuracy of LED and Halogen Radiometers Using Different Light Sources

HOWARD W. ROBERTS, DMD*
KRAIG S. VANDEWALLE, DDS, MS†
DAVID W. BERZINS, PHD‡
DAVID G. CHARLTON, DDS, MSD§

ABSTRACT

Purpose: To determine the accuracy of commercially available, handheld light-emitting diode (LED) and halogen-based radiometers using LED and quartz-tungsten-halogen (QTH) curing lights with light guides of various diameters.

Methods: The irradiance of an LED curing light (L.E.Demetron 1, SDS/Kerr, Orange, CA, USA) and a QTH curing light (Optilux 501, SDS/Kerr) were measured using multiple units of an LED (Demetron L.E.D. Radiometer, SDS/Kerr) and a halogen radiometer (Demetron 100, SDS/Kerr) and compared with each other and to a laboratory-grade power meter (control). Measurements were made using five light guides with distal light guide diameters of 4, 7, 8, 10, and 12.5 mm. For each light guide, five readings were made with each of three radiometers of each radiometer type. Data were analyzed with two-way analysis of variance/Tukey; $\alpha = 0.05$.

Results: In general, both handheld radiometer types exhibited significantly different irradiance readings compared with the control meter. Additionally, readings between radiometer types were found to differ slightly, but were correlated. In general, the LED radiometer provided slightly lower irradiance readings than the halogen radiometer, irrespective of light source. With both types of handheld radiometers, the use of the larger-diameter light guides tended to overestimate the irradiance values as seen in the control, while smaller-diameter light guides tended to underestimate.

CLINICAL SIGNIFICANCE

The evaluated LED or halogen handheld radiometers may be used interchangeably to determine the irradiance of both LED and QTH visible-light-curing units. Measured differences between the two radiometer types were small and probably not clinically significant. However, the diameter of light guides may affect the accuracy of the radiometers, with larger-diameter light guides overestimating and smaller-diameter guides underestimating the irradiance value measured by the control instrument.

(*J Esthet Restor Dent* 18:214–224, 2006)

*Fellow, Graduate Dental Biomaterials, Marquette University, Milwaukee, WI, USA
†Director, Dental Materials Evaluations, USAF Dental Evaluation and Consultation Service, Great Lakes, IL, USA
‡Director, Graduate Dental Biomaterials, Marquette University, Milwaukee, WI, USA
§Senior research scientist, Naval Institute of Dental and Biomedical Research, Great Lakes, IL, USA

DOI 10.1111/j.1708-8240.2006.00023.x

Visible-light-curing (VLC) units are indispensable to the practice of dentistry. These devices are used to initiate the cure of bonding systems, a number of bases and liners, provisional and definitive restorative materials, as well as various luting agents. Adequate polymerization of these materials depends on the visible light source's power density (irradiance), wavelength, and exposure duration. Unless these three factors are within certain parameters characteristic to each, respective materials may fail to polymerize adequately and exhibit poor physical properties, making restorations susceptible to early failure.[1]

Clinicians need an accurate, convenient method for detecting degradation of VLC unit performance so that corrective actions can be taken if required. Commercially available handheld dental radiometers are a relatively inexpensive and simple means of monitoring VLC unit performance, and the relative accuracy of dental radiometers when compared to laboratory standards has been proven in several reports.[2–5] Second-generation light-emitting diode (LED) VLC units are now available to dentists and, although these LED units are designed to have a more reliable and consistent performance, one recent study has suggested the possible need for routine evaluation of their performance.[6] Quartz-tungsten-halogen (QTH, halogen) VLC units exhibit diminished performance with time,[7,8] resulting from degradation of the bulb,[7] reflector[7] and internal filters,[8] autoclaving of the light guide,[9] adhesion of remnants of previously exposed restorative materials,[10] and exposure of the light guide to disinfection chemicals.[11] Also, breakage or disruption of the light guide's optical fibers has also been implicated as a factor.[8] The need for regular evaluation of a VLC unit's performance has been recommended, because in many situations the clinician may not be aware of substandard curing light performance.[8] Various methods of analyzing curing light performance and depth of cure have been advocated, including simple scrape tests,[12–14] surface hardness testing,[15–18] and infrared spectroscopy.[12,17] None of these tests is ideal, however. The scrape test, while easily performed, has been suggested to be an unreliable indicator of the quality of cure because of its overestimation of curing depth.[12] Both surface hardness and infrared (IR) spectroscopic testing require laboratory testing equipment and are impractical for the clinician to use.

Perhaps the most convenient method for determining if a curing light is performing properly is by using its built-in radiometer (if present) or a separate, commercially available handheld radiometer. Several reports have determined that a dental radiometer can provide an accurate means of correlating irradiance and VLC unit performance.[2–4,18–21] However, the accuracy of dental radiometers has been reported to be sensitive to the diameter of the distal tip of the light guide.[5] Research has indicated that distal light guide diameters of less than the standard 7.5 mm underestimate irradiance, while larger light guides overestimate light unit performance.[5]

Shortall and colleagues[3] converted QTH VLC unit irradiance readings obtained with different handheld radiometers to relative power density values based on the percentage of output normalized to the size of the radiometers' aperture windows. The relative power density values were then compared with the resin composite depth of cure measurements obtained with a resistance penetrometer.[3] Although the researchers reported that the normalized radiometer readings correlated with depth of cure, absolute irradiance values were not provided.[3]

Peutzfeldt[18] tested five different QTH VLC units with a radiometer that used a combination of 10 LED indicator lights to indicate irradiance levels. Depending on the number/color of LED indicators that were illuminated, clinicians could assess the performance of their VLC units. The radiometer was found to detect a difference in irradiance produced between different VLC units, and that the assessed VLC output correlated with resin degree of cure as determined by IR analysis.[18] The author concluded that the radiometer could be a reliable means of monitoring VLC unit performance.[19] These results contrasted with those of Hansen and Asmussen,[21] who found that none of three radiometers tested with 20 different VLC units in their study was reliable.

Lee and colleagues[20] evaluated the spectral sensitivity of an earlier model of the halogen-based radiometer used in this study, comparing the radiometer's irradiance readings with the spectral distributions of a scanning monochrometer. Using five different QTH VLC units, the authors reported that no evidence existed that the radiometer determined the irradiance based on the entire spectrum (400–520 nm) used in the study. However, the radiometer was found to be more sensitive in the 450 to 500 nm spectral range required for the initiation of camphorquinone. This finding indicated a strong correlation between the radiometer's spectral sensitivity and applied irradiance. The authors concluded that the curing radiometer could be an effective tool for assessing the curing efficiency of QTH VLC units.[20]

Rueggeberg[4] evaluated the performance of two different handheld radiometers using a standardized light source. Using an innovative technique, the author was able to obtain radiometer readings to a resolution of 1 mW/cm^2.[4] Both radiometers effectively eliminated wavelengths outside of the 400 to 515 nm range, and both radiometers provided precise results. However, the two radiometers were not absolutely accurate and one radiometer gave significantly higher power density values. The overall conclusion of this report was that handheld radiometers could be useful instruments in the periodic clinical assessment of VLC unit performance.[4]

Visible-light-activated resin systems have traditionally used a diketone photoactivator such as camphorquinone, which upon exposure to light of a certain wavelength, creates free radicals that initiate the polymerization process.[22–24] The effective wavelength for activating camphorquinone has been reported to be between 410 and 500 nm, with a peak wavelength of 470 nm.[23–25] To address more demanding esthetic needs, some manufacturers have included other activator molecules, such as 2,2-dimethoxy[1,2]diphenylethanone (DMBZ),[25] diphenyl (2,4,6-trimethylbenzoyl) phosphinoxid (Lucirin TPO),[25] and 1-phenyl-1,2-propanedione (PPD)[24] that do not impart a yellow tint to resins, as does camphorquinone. The peak activation wavelengths of Lucirin TPO, DMBZ, and PPD are reported to be 410 or less.[25]

LED VLC units use special semiconductors for the electroluminescence of light instead of the hot filament found in QTH light units.[26] By using LEDs, these units have longer life spans, more consistent output, and lower power consumption than QTH curing lights.[27] No ultraviolet or IR light is also emitted, which reduces internally produced heat and reduces the need for a noisy cooling fan. Because most of the energy is determined by the semiconductor, the majority of the emitted light is concentrated in a narrow spectral band around 470 nm; this is ideally suited for polymerizing resins that use a camphorquinone-based photoinitiator system.[28] Despite claims of consistent light output from LED units, a recent report has suggested that LED light units should be evaluated on a regular basis.[6]

In response to the advent of second-generation LED VLC units, commercially available handheld LED radiometers have recently been marketed. According to the manufacturer, both LED and halogen-based radiometers are based on a silicon detector and use a bandpass filter to limit the radiometer measurement to wavelengths of approximately 400 to 500 nm. However, LED radiometers are calibrated to a narrow-band LED light source, whereas the halogen-based radiometer is calibrated to a wider-range halogen light source. Theoretically then, LED and halogen radiometers should provide different readings, depending on the light source. Clinicians who currently own older radiometers for use with QTH VLC units may question the appropriateness of using them with LED light units. It is possible that radiometers intended for measuring the irradiance of QTH VLC units may not yield accurate readings if used with LED VLC units. Also, it is not known if the distal tip diameters of curing light guides affect LED radiometers in the same fashion as they do halogen radiometers.[5]

The halogen and LED radiometers used in this evaluation are similar in construction but differ in two areas: the results display and the calibration method. The halogen radiometer has an analog scale of from 0 to 1,000 mW/cm^2, whereas the LED radiometer contains an analog scale from 0 to 2,000 mW/cm^2. Accordingly, one possible difficulty in using the halogen radiometer to measure LED VLC unit irradiance is that halogen radiometer may not contain a broad enough range to accurately measure some of the more powerful LED VLC units. Also, the LED radiometer has a voltage divider that causes half as much meter deflection as the halogen radiometer for a given generated millivoltage when exposed to a specific power density. The ability to detect accurate readings on the LED radiometer may be less than that of the halogen radiometer because irradiance values must be interpolated to a higher extent by the eye. Another concern relates to calibration method. The halogen-based radiometer is calibrated using a QTH light source while the LED-based radiometer is calibrated using a special, narrow-band LED light source. The manufacturer of the radiometers maintains that the two types of radiometers respond differently to different light sources and will provide inaccurate readings. For example, if an LED light is measured using the halogen-based radiometer, the value provided may be lower than expected. On the other hand, if a QTH VLC unit is tested with the LED-based radiometer, the value will be higher than expected (SDS/Kerr Technical Consultant, personal communication).

The purpose of this study was to determine the accuracy of two commercially available handheld LED and halogen radiometers when used to measure the irradiance of LED and QTH VLC units. The first hypothesis tested was that there would be a difference between the irradiance levels recorded with the two radiometer types depending on the type of light source. Specifically, the halogen radiometer will underestimate the irradiance of an LED VLC unit and the LED radiometer will overestimate the irradiance of a halogen VLC unit, relative to each other. The second hypothesis tested was that it was expected that with either type of handheld radiometer, the use of a larger light guide would tend to overestimate the irradiance values compared with a laboratory-grade laser power meter, while smaller-diameter light guides would underestimate.

MATERIALS AND METHODS

Two models of commercial handheld radiometers were used in this study: one marketed for use with halogen VLC units (Demetron 100, SDS/Kerr, Orange, CA, USA) and one designed for use with LED VLC units (Demetron L.E.D. Radiometer, SDS/Kerr). Three radiometers of each type were used (serial numbers 143255, 143272, 143287, and 79300420, 79300486, 79300826, respectively). Irradiance values of a halogen light source (Optilux 501, SDS/Kerr) and an LED light source (L.E.Demetron 1, SDS/Kerr) measured by the radiometers were compared with control values determined using a laboratory-grade power meter (PowerMax 5200 with PM10 Probe, Molectron, Portland, OR, USA) that had recently undergone routine manufacturer maintenance/calibration.

For each VLC light source, irradiance was measured on both types of radiometers and the power meter using five different light guides having different distal end diameters: 4, 7, 8, 10, and 12.5 mm (part numbers 21185, no longer available, 20941, 20898, and 20812, respectively). Light guide proximal diameters were 7.5, 11.5, 8, 10, and 12.5 mm, respectively. Light guides having the 4 and 7 mm distal end diameters are considered "turbo tips," as there is a narrowing of the guide diameter from proximal to distal. Because the radiometers report irradiance values using an analog scale, measurements were recorded as estimated values according to the nearest scale markings. Five readings were made for each of the five sizes of light guides, for each of the three units of each type radiometer. For each grouping tested, the mean values for each type of radiometer were then calculated for the final mean value ($N = 3$ specimens per experimental grouping for each test condition).

Although the manufacturer specifically recommends against using light guides with exit diameters less than 7 mm, a 4-mm guide was used for comparison with previous studies. When using the commercial radiometers to measure light unit irradiance, the light guide exit aperture was placed in contact with the radiometer aperture window and maintained in a fixed position with a holding device. Irradiance measurements using the laboratory-grade power meter were made with the distal end of the light guide at a fixed position 1 mm from the detector surface, as recommended by the manufacturer in order to prevent damage to the detector. The power density values determined with the power meter were derived from measured power (mW) divided by the area of the distal fiber-optic surface area (cm^2) of the light guide using an electronic digital caliper (Max-9, Fowler Ltd., Louisville, KY, USA). The halogen unit was activated for three, 60-second periods, each separated by 1 second to eliminate the possibility of intensity variations resulting from a cool bulb.[22] In addition, the unit was allowed to cool for 5 minutes after every 20 minutes of use to prevent the possibility of damage from prolonged continuous use. To ensure that the commercial power used to operate the halogen unit did not vary during its use, all electrical power was supplied using a regulated power source (Model 1001P, California Instruments, San Diego, CA, USA). The L.E.Demetron 1 battery component was fully charged prior to its activation.

The emission spectra of the curing lights were recorded with a spectrophotometer (PR-650 SpectraScan SpectraColorimeter, Photo Research, Inc., Chatsworth, CA, USA) at a distance of 1 m from a standardized white reflecting surface. The spectral absorbance of camphorquinone (ScienceLab, Kingwood, TX, USA) was determined in methanol using an ultraviolet-visible spectrophotometer (8452A, Hewlett Packard, Palo Alto, CA, USA). Bandpass filter function was evaluated for each radiometer type. The filter was removed from all radiometers and placed over the end of the light guide of the halogen VLC unit. The light was activated and allowed to pass through the radiometer bandpass filter. The corresponding emission spectrum was recorded using the spectrophotometer as before. The mean area under each of the resultant profiles was estimated per radiometer type by summation of all the data points.

Data were analyzed using a two-way analysis of variance (ANOVA/Tukey's test: $\alpha = 0.05$) to evaluate the effects of radiometer/power meter and light guide diameter on irradiance. Furthermore, a one-way ANOVA and Tukey's test ($\alpha = 0.05$) was used to evaluate the effect of radiometer/power meter per light guide diameter. An unpaired t test was used to compare the mean summation of data points of the bandpass filter profiles. Statistical analysis was performed using SPSS (version 13.0, SPSS Inc., Chicago, IL, USA) statistical software.

RESULTS

The data obtained are depicted in Figures 1 and 2. Two-way ANOVA found that a difference existed based on light guide diameter and radiometer type (both $p < 0.001$). However, a significant interaction was present in the between-subject effects. Statistical analysis using one-way ANOVA found that for each type of VLC unit, a difference existed ($p < 0.05$) based on radiometer type and power meter.

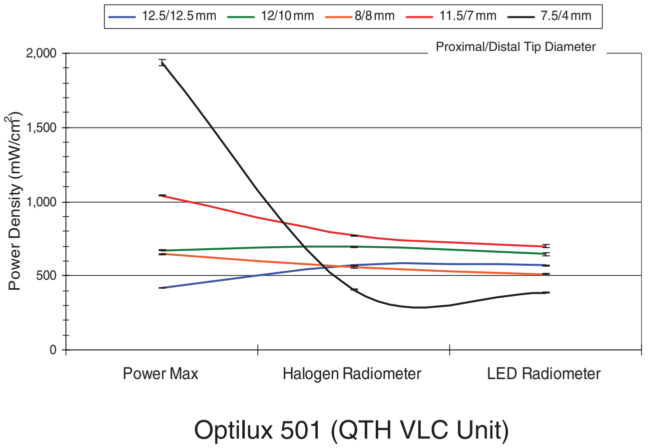

Figure. 1. Power density determined by two radiometer types and power meter (control) as a function of distal tip diameters when using the quartz-tungsten-halogen visible-light-curing (QTH VLC) unit. N = 3 specimens per group. Vertical bar = ±1 SD.

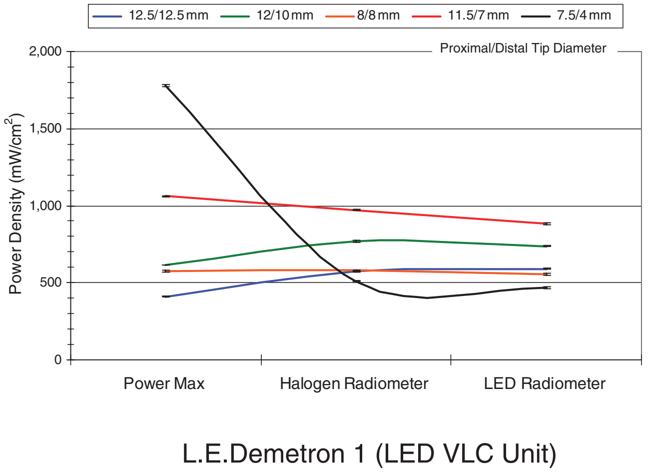

Figure 2. Power density determined by two radiometer types and power meter (control) as a function of distal tip diameters when using the light-emitting diode visible-light-curing (LED VLC) unit. N = 3 specimens per group. Vertical bar = ±1 SD.

Emission spectra of the two VLC curing units are displayed in Figure 3. The emitted spectra produced from the halogen VLC that were passed through the radiometer bandpass filters were found to be very similar, as shown in Figure 4. The summation of data points of the LED radiometer bandpass filter profile was found to be significantly greater than the summed data points of the halogen radiometer bandpass filter ($p = 0.006$).

Although the mean irradiance readings overall differed significantly from those of the laboratory-grade power meter ($p < 0.001$), the readings of the two types of radiometers were found to correlate well (Pearson's, $R^2 = 0.97$) for both types of light sources. The correlation analysis can be seen in Figures 5 and 6.

DISCUSSION

The first hypothesis was generally false. Although differences were found between the irradiance levels recorded with the two radiometer types depending on the type of light source, the results were the opposite of what was expected. For all measurement groups, values obtained using the halogen-based radiometer were significantly greater then those using the LED radiometer, except for the 12.5-mm

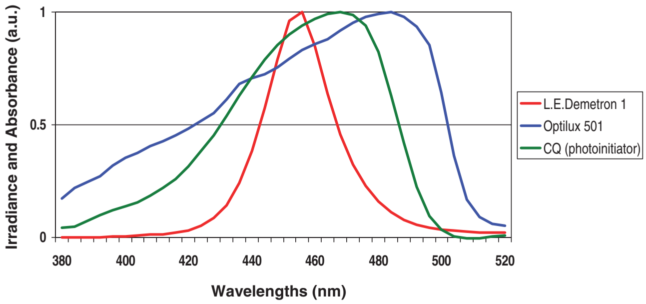

Figure 3. Emission spectra of the halogen and light-emitting diode visible-light-curing units and absorbance spectrum of camphorquinone (CQ).

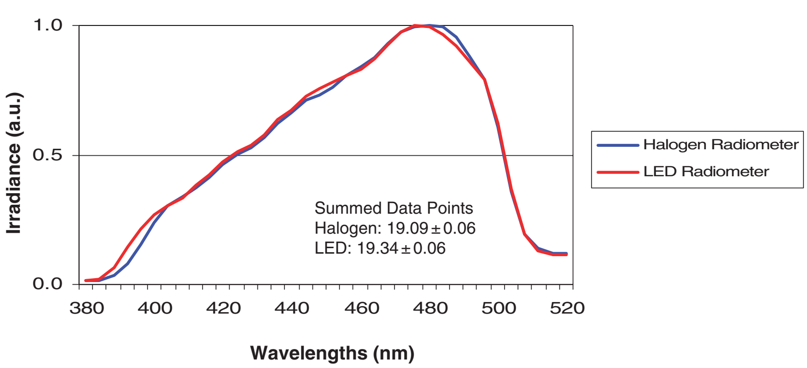

Figure 4. Bandpass filter profiles of halogen and light-emitting diode (LED) radiometers produced from emitted light from the halogen visible-light-curing unit.

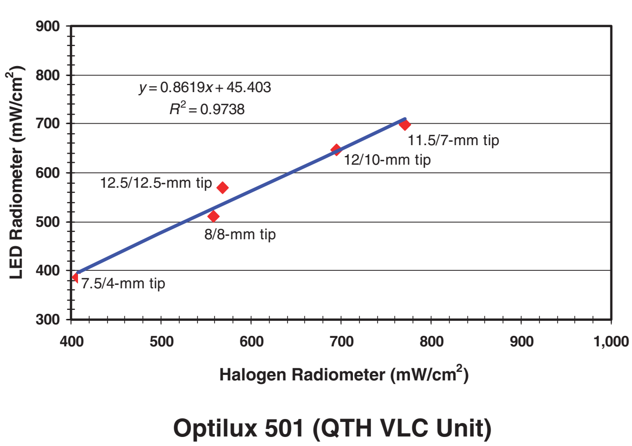

Figure 5. Correlation between the light-emitting diode (LED) and halogen radiometers using the quartz-tungsten-halogen visible-light-curing (QTH VLC) unit.

light guide where the two values were not different with the halogen source; and the LED radiometer was significantly higher for the LED source (see Figures 1 and 2). The bandpass filters of both radiometers were observed to display similar attenuation profiles. However, the LED bandpass filter was found to pass slightly more emitted light than did the QTH filter (see Figure 4). From this, one would expect a higher response from the LED radiometer, but this was not supported from the experimental data. Perhaps the newer LED radiometers use photodiodes with a different spectral range and responsiveness.

The irradiance readings of the two different handheld radiometer types were found to correlate well, irrespective of light source (see Figures 5 and 6). The slope values of the regression lines were almost identical in both cases—0.86 and 0.85, respectively. The regression shows that, in general, the QTH radiometer was more responsive (ie, gave higher readings) than the LED radiometer, supporting the experimental results. However, the variation between the radiometers was observed to be of a minor nature. It is the authors' opinion that measured differences between the radiometer results, regardless of light source, would not make a clinically significant difference.

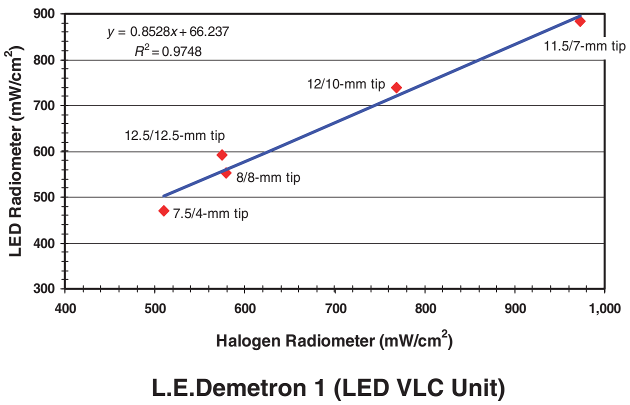

Figure 6. Correlation between the light-emitting diode (LED) and halogen radiometers using the LED visible-light-curing (VLC) unit.

The second hypothesis was true; for each type of radiometer a difference was found among irradiance levels with respect to distal light guide diameter. With one exception (ie, LED VLC unit with the 8-mm light guide), the irradiance values of both light sources obtained with both types of commercial radiometers significantly differed ($p < 0.05$) from the readings of the laboratory-grade power meter. The diameter of the light guides affected accuracy of the radiometers with larger-diameter light guides overestimating and smaller-diameter guides underestimating the irradiance value measured by the control instrument (see Figures 1 and 2).

Few studies have compared the accuracy of commercial handheld radiometers with that of a laser power meter used as a reference standard. In a study comparing irradiance values of a QTH VLC unit measured using three different handheld halogen radiometers, Leonard and colleagues[5] found that the commercial radiometers yielded significantly different values compared with those of the laser power meter. The present study found similar results. Likewise, the effect of light guide diameter was also similar for the two studies. Both concluded that results obtained with the handheld radiometers were dependent upon the diameter of the distal end of the light guide. For example, in the study by Leonard and others,[5] a light guide with a 4-mm distal diameter and the same curing light produced irradiance values ranging from 713 mW/cm^2, using a handheld halogen radiometer, to 2,574 mW/cm^2, with a power meter. While the power meter measures all power from the light guide regardless of diameter, the commercial radiometers have fixed apertures and measure light restricted to the aperture.[5] Using the power meter, the power density is determined by dividing the measured power by the manually determined area of fiber-optic bundles on the distal end of the light guide. The commercial radiometers calculate power density based on the area of their fixed apertures, independent of the source of the light guide diameter, and therefore do not differentiate between light guides of different diameters. In general, when using commercial radiometers and the same light source, larger-diameter light guides provide higher power density values (mW/cm^2) and smaller-diameter light guides provide lower power density values (mW/cm^2) compared with power density values determined using a power meter.

Despite the differences found between the commercial radiometers and the laser power meter standard, the data of this study confirm the findings of earlier works that handheld radiometers can serve an important purpose in performing regular maintenance evaluation of VLC units.[2–4,19,20] Handheld radiometers should not be expected to provide precise radiometric values for VLC units; however, they can indicate the deterioration of VLC unit performance when readings are taken at periodic intervals and compared. However, clinicians should be aware that light guide distal end diameter can influence the readings of handheld radiometers and should use the same light guide when monitoring VLC performance.

CONCLUSIONS

For both types of handheld commercial radiometers, the use of a larger-diameter light guide tended to overestimate irradiance readings when compared with the control, while use of a smaller-diameter guide tended to underestimate irradiance.

Irrespective of light source, the LED radiometer generally provided slightly lower irradiance readings than those of a halogen radiometer.

DISCLOSURE

The views expressed in this manuscript are expressively those of the authors and do not represent the opinions of the US Air Force, the US Navy, the Department of Defense, or the US Government. None of the authors has a financial interest in any of the products or materials used in this evaluation.

REFERENCES

1. Rueggeberg FA, Caughman WF, Curtis JW Jr. Effect of light intensity and exposure duration on cure of resin composite. Oper Dent 1994;19:26–32.
2. Fowler CS, Swartz ML, Moore BK. Efficacy testing of visible-light-curing units. Oper Dent 1994;19:47–52.
3. Shortall AC, Harrington E, Wilson HJ. Light curing unit effectiveness assessed by dental radiometers. J Dent 1995;23:227–32.
4. Rueggeberg FA. Precision of hand-held dental radiometers. Quintessence Int 1993;24:391–6.
5. Leonard DL, Charlton DG, Hilton TJ. Effect of curing-tip diameter on the accuracy of dental radiometers. Oper Dent 1999;24:31–7.
6. Uhl A, Mills RW, Rzanny AE, Jandt KD. Time dependence of composite shrinkage using halogen and LED light curing. Dent Mater 2005;21:278–86.
7. Friedman J. Variability of lamp characteristics in dental curing lights. J Esthet Dent 1989;1:189–90.
8. Barghi N, Berry T, Hatton C. Evaluating intensity output of curing lights in private dental offices. J Am Dent Assoc 1994;125:992–6.
9. Rueggeberg FA, Caughman WF, Comer RW. The effect of autoclaving on energy transmission through light-curing tips. J Am Dent Assoc 1996;127:1183–7.
10. Strydom C. Dental curing lights—maintenance of visible light curing units. SADJ 2002;57:227–33.
11. Dugan WT, Hartleb JH. Influence of a glutaraldehyde disinfecting solution on curing light effectiveness. Gen Dent 1989;37:40–3.
12. DeWald JP, Ferracane JL. A comparison of four modes of evaluating depth of cure of light-activated composites. J Dent Res 1987;66:727–30.
13. Cook W. Factors affecting the depth of cure of ultraviolet-polymerized composites. J Dent Res 1980;59:800–8.
14. Fan PL, Schumacher RM, Azzolin K, et al. Curing-light intensity and depth of cure of resin-based composites tested according to international standards. J Am Dent Assoc 2002;133:429–34.
15. Asmussen E. Restorative resins: hardness and strength vs. quantity of remaining double bonds. Scand J Dent Res 1982;90:484–9.
16. Ferracane JL. Correlation between hardness and degree of conversion during the setting reaction of unfilled dental restorative resins. Dent Mater 1985;1:11–4.
17. Rueggeberg FA, Craig RG. Correlation of parameters used to estimate monomer conversion in a light-cured composite. J Dent Res 1988;67:932–7.
18. Peutzfeldt A. Correlation between recordings obtained with a light-intensity tester and degree of conversion of a light-curing unit. Scand J Dent Res 1994;102:73–5.
19. Pires JA, Cvitko E, Deheny GE, Swift EJ Jr. Effects of curing tip distance on light intensity and composite resin microhardness. Quintessence Int 1993;24:517–21.
20. Lee SY, Chiu CH, Boghosian A, Greener EH. Radiometric and spectroradiometric comparison of power outputs of five visible light-curing units. J Dent 1993;21:373–7.
21. Hansen EK, Asmussen E. Reliability of three dental radiometers. Scand J Dent Res 1993;101:115–9.
22. Cook WD. Spectral distributions of dental photopolymetization sources. J Dent Res 1982;61:1436–8.
23. McCabe JF, Carrick TE. Output from visible-light activation units and depth of cure of light-activated composites. J Dent Res 1989;68:1534–9.
24. Park YJ, Chae KH, Rawls HR. Development of a new photoinitiation system for dental light-cure composite resins. Dent Mater 1999;15:120–7.
25. Uhl A, Michaelis C, Mills RW, Jandt KD. The influence of storage and indenter load on the Knoop hardness of dental composites polymerized with LED and halogen technologies. Dent Mater 2004;20:21–8.
26. Stahl F, Ashworth SW, Jandt KD, Mills RW. Light-emitting diode (LED) polymerisation of dental composites: flexural properties and polymerisation potential. Biomaterials 2000;21:1379–85.
27. Jandt RD, Mills RW, Blackwell GH, Ashworth SH. Depth of cure and compressive strength of dental composites cured with blue light emitting diodes (LEDs). Dent Mater 2000;16:41–7.
28. Kurachi C, Tuboy AM, Magalhaes DV, Bagnato VS. Hardness evaluation of a dental composite. Dent Mater 2001;17:309–15

Reprint requests: Howard W. Roberts, DMD, 310 C B Street, Building 1H, Great Lakes IL 60088; Tel.: (847)688–7676; Fax: (847)688-7667; e-mail: hwroberts@nidbr.med.navy.mil