Effect of high-irradiance light curing on exposure times and pulpal temperature of adequately polymerized composite

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This study investigated the effect of high-irradiance light-curing on exposure time and pulpal temperature of adequately-cured composite. Composite placed in a molar preparation was cured using high-irradiance light-curing units (Flashmax P3, Valo, S.P.E.C. 3 LED, Cybird XD) and tested for hardness occlusal-gingivally. The first group had exposure times set according to manufacturer settings (recommended), second group to yield 80% of maximum hardness at the 2 mm depth (experimental), and third group was set at 20 s (extended). Exposure time necessary to adequately polymerize the composite at 2 mm depth was 9 s for the Cybird XD and Valo and 12 s for S.P.E.C. 3 LED and Flashmax P3. None of the high-irradiance light-curing units adequately polymerized the composite at the manufacturer-recommended minimum-exposure times of 1–3 s. Exposure times necessary to adequately polymerize composite at 2 mm resulted in a maximum pulpal-temperature increase well below the temperature associated with possible pulpal necrosis.

Keywords: High-irradiance light-curing units, Depth-of-cure, Composite resins, Pulpal temperature

INTRODUCTION

The use of composite resins has become an integral part of the dental practice. A recent meta-analysis found more than 500 million direct dental restorations are placed each year worldwide, of which about 55% are composite resins or compomers¹. With this increase in use of composite resins, the light-curing unit has become an indispensable technology.

In an effort to improve patient care and reduce treatment times, manufacturers have exploited the theory of exposure reciprocity to justify fabricating light-curing units with increasing irradiance during the past 20 years. Moreover, the number of available high-irradiance light-curing units is on the rise with some units advertised as having an irradiance as high as 5,800 mW/cm².²,³ The concept of exposure reciprocity suggests different combinations of irradiation and exposure time will achieve the same degree of resin polymerization as long as the same radiant exposure is delivered.⁴,⁵ Therefore, increasing the irradiance of the light theoretically enables the manufacturer to reduce recommended exposure durations from 20 or 40 s to as little as 1 s.

Currently, there is limited research available to support exposure reciprocity for high-output light-curing units. When a composite resin is exposed to high level of irradiance, the reaction rates between production and destruction of intermediate molecular species may not be in balance and can affect polymer chain initiation, propagation, and termination efficiency.⁶ Laboratory studies have questioned the exposure reciprocity principle, finding that it was not well supported with irradiances over 1,500 mW/cm², resulting in less polymerization of composite resin.⁷ Insufficient polymerization has been associated with greater wear, and reduced depth of cure, hardness, and bond strength between the tooth and restoration.⁸

This investigation focused on four commercially available, high-irradiance curing units: Flashmax P3 (CMS Dental, Copenhagen, Denmark), Valo (Ultradent, South Jordan, UT, USA), S.P.E.C. 3 LED (Coltene, Cuyahoga Falls, OH, USA), and Cybird XD (Dentazon, Torrance, CA, USA). The Flashmax P3 reportedly has an irradiance of more than 5,800 mW/cm², with a 3 mm depth of cure for most materials in three seconds of exposure time. With the Valo light-curing unit, Ultradent advertises an irradiance output of 3,200 mW/cm² in “plasma” mode with an exposure time of three seconds for a 2 mm increment of material. Another available high-irradiance light-curing unit is the S.P.E.C. 3 LED which has an irradiance of 3,000–3,500 mW/cm². The S.P.E.C. 3 LED reportedly can cure to a depth of 2 mm with a one-second exposure time. Finally, the Cybird XD light-curing unit has a slightly lower irradiance at 2,700 mW/cm², but reportedly provides rapid polymerization of a 2 mm increment of composite resin material in three seconds.⁹
The potentially damaging effect of temperature increases on pulp tissue induced from high-irradiance light-curing units is of great concern. Increasing irradiance and exposure time is directly related to increases in temperature\(^{11,12}\). Consequently, curing devices with high irradiance should only be activated for a short time. Several of the curing-unit manuals recommend only a 2-s exposure to soft tissue to avoid burn trauma. However, it has been found that clinicians may arbitrarily double the manufacturer recommended exposure time to ensure adequate curing\(^{19}\). Arbitrarily increasing light-exposure times in an effort to prevent insufficient polymerization is not the solution, as this may result in thermal trauma to the pulp and surrounding tissues.

Efficiency and safety of light-curing units are of primary concern with the increase in usage of composite resins. As the availability of high-irradiance light-curing units increases, the potential for damaging effects also increases. It is hypothesized that manufacturer-recommended exposures for these high-irradiance light-curing units will prove inadequate to achieve optimal polymerization per increment of composite resin; hence longer exposures will be required. At the recommended times, exposure reciprocity may not be occurring regardless of the irradiance. If the recommended exposure periods are understated by the manufacturer, this could result in under-cured composite resins and suboptimal properties for the associated restorations, resulting in premature clinical failure. Arbitrarily increasing the exposure time of high-irradiance light-curing units to offset this result may generate thermal trauma to the pulp. The purpose of this study was to evaluate pulp-chamber temperatures by comparing the exposure durations provided by the manufacturer and those optimized by calculation based on achieving the recommended 80% of maximum hardness at a 2 mm depth. The null hypotheses were that there would be no differences in maximum pulpal temperature increase from baseline based on (1) type of light-curing unit or (2) exposure duration.

**MATERIALS AND METHODS**

The study methods were divided into two parts. In the first part, the investigators determined the exposure time necessary to provide an acceptable polymerization of composite restoration based on hardness ratios at 2 mm of depth with each of the light-curing units. In the second part, the investigators determined the effect of exposure time on the increase in pulpal temperatures.

**Test assembly**

The test assembly simulated an in vivo environment, with controlled intrapulpal physiologic temperature and intrapulpal fluid flow\(^{14}\). An extracted human mandibular molar without caries or restorations was used for investigational purposes. The Institutional Review Board at Wilford Hall Ambulatory Surgical Center, Joint Base San Antonio-Lackland approved this protocol (#FWH20160025N) and the use of extracted human molars.

A box measuring 3.1 mm (occluso-gingivally)×3.5 mm (bucco-lingually)×1.5 mm (mesio-distally or axially) was prepared at the mesio-occlusal aspect using a high-speed handpiece (430 SWL Starbright, StarDental, Lancaster, PA, USA), a NTI flat-end cylinder diamond (SC835-010, Axis Dental, Coppell, TX, USA), and an enamel hatchet (51/52 Hatchet, Hu-Friedy Mfg, Chicago, IL, USA). The test assembly is illustrated in Fig. 1. The box displayed a slight occlusal divergence to facilitate removal of composite resin samples. Spatial measurements were accomplished using an electronic digital caliper (GA182, Grobet Vigor, Carlstadt, NJ, USA). The cusp tips were flattened slightly to the level of the marginal ridge with a model trimer (12" Model Trimmer, Whip Mix, Louisville, KY, USA) to standardize the distance from the light source to the composite resin. Roots were reduced by one-third of their respective lengths to expose the canal spaces for tube insertion. The root canals were cleaned with a scaler (SM13/14 Curette, Hu-Friedy) and examined to ensure they were free of debris. The canals were enlarged and two metal tubes were inserted, one into each apex, and fixed into position with bonded flowable composite resin (Optibond FL bonding agent, Revolution flowable composite resin, Kerr, Orange, CA, USA). Tygon tubes (1/16" ID Tygon Tubing, Cole-Parmer, Vernon Hills, IL, USA), one for water inflow and one for water outflow, were connected to the metal tubes. An access channel was prepared at the distal surface of the tooth to permit access to the pulp chamber. A K-type thermocouple wire probe (Digit-Sense Type-K Wire Probes, 30 Gauge, Cole-Parmer) was directed through the channel and positioned on the wall of the pulp chamber directly adjacent of the Class 2 box preparation, near the 2 mm depth mark. The distal access opening and wires were stabilized and sealed using flowable composite resin (Revolution). A radiograph was made to confirm proper positioning of the thermocouple probe, after which its wire was connected to a datalogging thermometer (Extech SDL200 4-Channel Datalogging Thermometer, Cole-Parmer). The tooth was positioned next to an unprepared molar to simulate a representative clinical situation. In turn, the teeth were mounted in a custom-made epoxy slab (Epoxicure Resin, Buehler, Lake Bluff, IL, USA). The untreated molar was fixed with acrylic (GC Pattern Resin, GC, Tokyo, Japan). The treated tooth was mounted in polyvinyl siloxane impression material (Regisil PB, Dentsply, York, PA, USA) to permit limited movement and facilitate restoration removal.

The epoxy slab with mounted teeth was immersed into a thermostatically controlled water bath (StableTemp Digital Water Bath, Cole-Parmer) up to the cemento–enamel junction. Water temperature surrounding the partially immersed teeth was maintained between 34.9 and 35.0°C to simulate physiologic values. To mimic blood flow in the tooth, the tube for water outflow was connected to a negative pressure pump (NE-1000 Single Syringe Pump, Pump...
Table 1 Composition of Esthet-X HD composite resin

| Composite | Type          | Resin                                           | Filler                                      | Weight (%) | Volume (%) | Filler Size (μm) |
|-----------|---------------|------------------------------------------------|---------------------------------------------|------------|------------|------------------|
| Esthet-X  | Microhybrid   | Bisphenol-A glycidyl methacrylate (Bis-GMA),     | Barium aluminofluoroborosilicate glass;     | 77         | 60         | 0.02–2.5         |
| HD        | dimethacrylate| bisphenol-A ethoxy dimethacrylate (Bis-EMA),     | silica dioxide                              |            |            |                  |
|           |               | triethylene glycol dimethacrylate (TEGDMA)       |                                              |            |            |                  |

Systems, Farmingdale, NY, USA) while the tube for water inflow was directed through the thermostatically controlled water bath. Negative pressure from the pump induced water inflow from the water bath into the pulp space and out through the outflow tube. The intrapulpal fluid flow rate was established at simulated physiologic value of 0.0125 mL/min\(^{15}\). The flow rate was controlled by a regulator in the pump.

Part 1: Calculation of exposure time
The Class 2 preparation was restored using a microhybrid composite resin (Esthet-X HD, shade A2, Dentsply). Composition of the composite is listed in Table 1. A sectional matrix (Tofflemire, Water Pik, Ft. Collins, CO, USA) was utilized interproximally. The preparation was lightly coated with petroleum jelly (White Petrolatum USP, Fougera Pharmaceuticals, Melville, NY, USA) to facilitate removal of the restoration. Composite resin was placed in bulk and no bonding agents were applied. The composite resin was polymerized at 10, 15, and 20 s using a control light-curing unit (Bluephase 20i, Ivoclar Vivadent, Schaan, Liechtenstein) at 1,282±14 mW/cm\(^2\). The light-curing unit was stabilized using a custom positioning device made from vinyl polysiloxane impression material (Reprosil, Dentsply Caulk, Milford, DE, USA). This device stabilized and centered the light 1 mm from the surface of the tooth preparation. For each exposure time, five specimens were created. The composite resin specimens were removed from the preparation. Marginal flash and excess composite resin were removed using a FG superfine diamond (SF858-014, Axis Dental, Coppell, TX, USA) and polishing disks (Super Snap Disks, Shofu Dental, Kyoto, Japan). The intaglio and cameo surfaces of composite resin specimens were flattened slightly with 600, 1200, and 1500 grit silicon-carbide paper (Imperial Wetordry Sandpaper, St. Paul, MN, USA). The specimens were stored in distilled water for 24 h at 37°C in an incubator (Model 20 GC, Quincy Labs, Chicago, IL, USA).

Before hardness testing was accomplished,
specimens were dried and fixed to glass slides (Premiere Microscope Slides, C&A Scientific, Manassas, VA, USA) with cyanoacrylate (Permabond, Pottstown, PA, USA). Knoop hardness numbers (KHN) were determined on the intaglio surface for each specimen using a Knoop Hardness tester (LM300AT, Leco, St Joseph, MI, USA) with a 1.961 newton load for 10 s. Three hardness measurements were determined at 0.5 and 2.0 mm depths of the 3.1 mm-long specimen. The maximum hardness value was determined to be an average hardness of the measurements at the 0.5 mm depth with 20 s of exposure with the Bluephase 20i.

Composite resin specimens were then fabricated in the same manner as the control curing light (Bluephase 20i) using each of the four high-irradiance light-curing units (Flashmax P3, Valo, S.P.E.C. 3 LED, and Cybird XD) at maximum setting using the manufacturers’ recommended exposure time. Five specimens were created for each exposure time. Three hardness measurements were made at the depth of 0.5 and 2.0 mm. A specimen was considered to be cured at 2 mm if the hardness ratio (hardness/maximum hardness) was greater than 80%\(^{10}\). The experimental exposure time (i.e., time necessary to obtain a hardness ratio greater than 80% at 2 mm) was determined for each light-curing unit by using the manufacturer’s recommendation as a baseline, and extending the exposures in three-second increments.

The spectral radiant power as a function of wavelength for each light-curing unit was recorded by using an integrating sphere (sphere Ø=15 cm and entry port Ø=19 mm; Lapsphere, North Sutton, NH, USA) linked to a calibrated spectrophotometer (USB4000-UV-VIS, Ocean Optics, Dunedin, FL, USA). For each spectral radiant power function, the wavelength range of 320–600 nm was integrated to obtain the light-curing unit’s power. The power of each light-curing unit was measured three times and divided by the active area of its light tip to determine the irradiance (mW/cm\(^2\)) associated with each light-curing unit. The means and standard deviations of power and irradiance for each light-curing unit are shown in Table 2. Radiant exposure was calculated by multiplying the irradiance by the exposure time (J/cm\(^2\)). The means and standard deviations of radiant exposure are shown in Table 3.

### Table 2: Means and standard deviations of power and irradiance for each light-curing unit

| Light-curing unit | Power (mW) | Irradiance (mW/cm\(^2\)) |
|------------------|------------|------------------------|
| Bluephase 20i    | 567 (6)    | 1,282 (14)             |
| Flashmax P3      | 1,194 (11) | 2,702 (24)             |
| Valo             | 1,093 (14) | 2,473 (32)             |
| S.P.E.C. 3 LED   | 1,336 (69) | 3,024 (156)            |
| Cybird XD        | 1,404 (24) | 3,179 (53)             |

### Table 3: Means and standard deviations of radiant exposure and pulpal temperature increase (°C) for each light-curing unit at various exposure times. When comparing increase in pulpal temperature, groups with the same lower case letter per column and upper case letter per row are not significantly different (p>0.006)

| Light-curing unit | Recommended | Experimental | Extended |
|------------------|-------------|--------------|----------|
|                  | Radiant exposure (J/cm\(^2\)) | Increase in pulpal temp (°C) | Time (secs) | Radiant exposure (J/cm\(^2\)) | Increase in pulpal temp (°C) | Time (secs) | Radiant exposure (J/cm\(^2\)) | Increase in pulpal temp (°C) | Time (secs) |
| Bluephase 20i    | 10 12.8 (0.1) 0.89 (0.11) Ac | 20 25.6 (0.3) 1.81 (0.09) Ba | 20 25.6 (0.3) 1.81 (0.09) Ba |
| Flashmax P3      | 3 8.1 (0.1) 0.48 (0.08) Aab | 12 32.2 (0.3) 1.74 (0.17) Ba | 20 53.7 (0.5) 2.56 (0.06) Cb |
| Valo             | 3 7.4 (0.1) 0.80 (0.07) Abc | 9 22.6 (0.3) 2.32 (0.04) Bb | 20 50.3 (0.6) 4.00 (0.23) Cb |
| S.P.E.C. 3 LED   | 1 3.0 (0.2) 0.32 (0.23) Aa | 12 38.9 (2.0) 2.28 (0.29) Bb | 20 64.9 (3.1) 3.44 (0.42) Cbc |
| Cybird XD        | 3 9.5 (0.2) 0.98 (0.23) Ac | 9 28.1 (0.5) 1.66 (0.11) Ba | 20 62.4 (1.1) 2.88 (0.13) Cbc |
extended exposure time of 20 s (extended). In each instance, pulpal temperature was recorded throughout the light-curing procedure. Baseline and maximum temperatures were used to calculate the overall change. Existing restorative material was removed from the preparation, and the intrapulpal (i.e., intrachamber) temperature was allowed to return to baseline. The procedure then was repeated until three trials had been completed for each experimental condition. The mean maximum pulpal temperature increase was determined for each of the light-curing units at each exposure time (recommended, experimental, and extended). Data were analyzed using a two-way ANOVA and Tukey post hoc test to evaluate the effect of light-curing unit and exposure time on maximum pulpal temperature increase from baseline (alpha=0.05). A Pearson correlation was determined between the mean radiant exposure and pulpal temperature increase for the light-curing units. Statistical analysis was carried out using SPSS (Version 25, IBM, Armonk, NY, USA).

RESULTS

Part 1: Calculation of exposure time

The maximum hardness of the composite resin (52.2 KHN) was observed at the 0.5 mm depth with 20 s of light exposure using the Bluephase 20i light-curing unit (control) at 1,282±14 mW/cm². The composite resin specimens were determined to be adequately polymerized at the 2 mm depth if the hardness was 80% of the maximum hardness of 52.2 KHN. Hardness ratios of 60.6, 76.1 and 89.1% at the 2 mm depth using the Bluephase 20i light-curing unit were determined for 10, 15, and 20 s of exposure time respectively. The 20-s cure was the control and extended time for the Bluephase 20i (control light-curing unit).

Means and standard deviations of hardness ratios (%) are shown in Fig. 2. None of the high-irradiance light-curing units adequately polymerized the composite resin at the 2 mm depth at the manufacturer-recommended minimum exposure times of one or three seconds. However, based on hardness ratios, it was determined that the Flashmax P3 light-curing unit adequately polymerized the composite resin at 2 mm depth after 12 s (87.2%±4.9), Valo at 9 s (83.6%±3.8), S.P.E.C. 3 LED at 12 s (93.7%±4.9), and Cybird XD at 9 s (84.9%±4.1).

Part 2: Effect of exposure time on the increase in pulpal temperature

Means and standard deviations of pulpal temperature increase (°C) for each light-curing unit at various exposure times are shown in Table 3. With the recommended groups, Cybird XD (0.98±0.23°C) had the greatest temperature change, but it was not significantly different (p>0.41) from Valo (0.80±0.07°C) and Bluephase 20i (0.89±0.11°C). S.P.E.C. 3 LED (0.32±0.23°C) had the lowest temperature change, but it was not significantly different (p=0.52) from Flashmax P3 (0.48±0.08°C). For the experimental groups, Valo (2.32±0.04°C) and S.P.E.C. 3 LED (2.28±0.29°C) had significantly greater temperature changes (p<0.003) than Cybird XD (1.66±0.11°C), Flashmax P3 (1.74±0.17°C) and Bluephase 20i (1.81±0.09°C), each of which were not significantly different from each other (p>0.43). For the extended groups, Valo had the greatest temperature change (4.00±0.23°C), but it was not significantly different (p=0.06) from S.P.E.C. 3 LED (3.44±0.42°C). Bluephase 20i (1.81±0.09°C) had the lowest temperature change.

The results of the two-way ANOVA indicated the existence of statistically significant differences in mean maximal pulpal temperature increase from baseline based on light-curing unit (p<0.0001) and exposure time (p<0.0001). In addition, there was a statistically significant interaction (p<0.0001) between individual light-curing units and exposure time.

Increase in pulpal temperature was also analyzed via multiple one-way ANOVAs per light-curing unit and exposure time. A Bonferroni correction was applied because multiple comparison tests were completed.

![Hardness Ratio (%) at 2mm Depth](image_url)

Fig. 2  Mean hardness ratio (%) at 2 mm depth with various exposure times per light-curing unit. Heavy line at 80% indicates threshold for adequate polymerization. Error bars indicate ±1 standard deviation. Bluephase: Bluephase 20i, Flashmax: Flashmax P3, S.P.E.C. 3: S.P.E.C. 3 LED
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5,800 mW/cm² the Flashmax P3 emit an irradiance of approximately during clinical use. While the light-emitting diodes from or large diameter light guides that are recommended Flashmax P3 system uses a disposable tip with small and twelve times longer for the S.P.E.C. 3 LED. The recommendation for Flashmax P3, Valo, and Cybird XD were at least three times longer than the manufacturer curing units adequately polymerized the composite resin testing indicate that none of the high-irradiance light-related factors include photoinitiator type and concentration, and filler-particle size, load, and distribution. Light-related factors include irradiance, spectral distribution, exposure time, and light distribution and dispersion 19). A limitation to this irradiance, spectral distribution, exposure time, and light-related factors. Using the more clinically relevant tooth model in this study, twenty seconds of curing time was necessary using the control light-curing unit (Bluephase 20i, 1,282 mW/cm²) to adequately polymerize the composite resin at a depth of 2 mm. Ivoclar Vivadent, the manufacturer of Bluephase 20i, recommends a curing time of 10, 15, or 20 s at the high power setting depending on the type of composite resin 21).

The radiant exposure necessary to adequately polymerize a 2 mm increment of a composite resin has been reported to range from 6 to 24 J/cm² to as high as 36 J/cm² 22,23). In this study, using the manufacturers’ recommended exposure times, all of the high-irradiance light-curing units delivered radiant exposures in the lower limits of that range (3.0–9.5 J/cm²). However, as calculated, the amount of radiant exposure necessary to predictably obtain an 80% hardness ratio at a 2 mm depth were in the higher limits of the reported range (22.6–38 J/cm²). In addition, the depth of cure can be affected by the type and size of the testing mold, the composite resin, and light source 24,25). This investigation utilized a unique reusable tooth model and physiologic pulpal flow at oral temperatures to better mimic actual clinical conditions as reported in other published studies 26,27).

The term depth of cure refers to the thickness at which a composite resin can be placed to ensure adequate mechanical properties and biocompatibility. The depth of cure has been measured with several techniques, including bottom-top or bottom-maximum hardness ratios, degree of conversion, and scrape tests 28). Published studies demonstrate that the scrape test typically overestimates the depth of cure compared to other depth of cure techniques such as hardness ratios 29). Hardness testing is a popular indirect method because of its ease of use and good correlation with degree of conversion 29). Studies have defined the depth of cure based on hardness ratios at 80% —that is, the bottom surface is at least 80% as hard as the top surface 16,30). Others have suggested that the bottom or tested surface should be expressed as a ratio of 80% of maximum hardness, because top surface hardness can vary between groups depending on the type of light-curing unit 31). The maximum hardness may be found just below the top surface due to the presence of the oxygen-inhibited layer 31). In this study, maximum hardness was determined at 0.5 mm depth.

A critical concern during light curing is the effect of heat on the dental pulp. The dental pulp is highly vascularized tissue whose vitality may be compromised during restorative procedures. Preservation of pulpal health is one of the major objectives of restorative dentistry 32). Factors affecting the dental pulp during clinical procedures can be physical, chemical, biological, or thermal. In this study, the focus was narrowed to only thermal factors. The majority of studies concerning pulpal temperatures reference a study carried out over 50 years ago 33). In that trial, the teeth in five Rhesus monkeys were heated to a temperature of 275°C (± 50°C). The results showed that a 5.5°C intrapulpal temperature increase induced necrosis in 15% of the tested pulps; an 11°C increase induced 60%, and a 16°C increase induced 100% of the pulps tested having irreversible pulp damage 33). The results of that study set forth a threshold temperature for irreversible pulpal damage when an external temperature was applied to a tooth of 5.5°C.
The null hypotheses in this study were rejected. Statistical differences in maximum pulpal temperature change from baseline were found, based on light-curing unit, exposure time, and their interaction. At the manufacturers’ recommended exposure time of 1 or 3 s, all of the high-irradiance light-curing units had minimal pulpal temperature change with less than 1.0°C. However, none of the light-curing units adequately polymerized the composite resin at a depth of 2 mm.

With experimental exposure times (i.e., exposure time necessary to adequately polymerize the composite resin at a depth of 2 mm) of 9 or 12 s, the pulpal temperature change was minimal for Cybird XD and Flashmax P3, with an increase of only 1.66 and 1.74°C respectively. The control light-curing unit, Bluephase 20i, with an experimental exposure time of 20 s also resulted in a pulpal temperature increase of only 1.81°C. The pulpal temperature change was more substantial for Valo and S.P.E.C. 3 LED, with an increase of 2.32 and 2.28°C for experimental exposure times of 9 or 12 s respectively. Most importantly, these thermal increases are below the temperature increase of 5.5°C associated with possible pulpal necrosis. Even with an extended exposure time of 20 s, none of the high-irradiance light-curing units produced an increase in pulpal temperature greater than 5.5°C. Valo produced the greatest increase with 4.00°C, which was not statistically different from S.P.E.C. 3 LED with 3.44°C. The increase in pulpal temperature recorded using the Valo light-curing unit may be due, in part, from the design of the optical guide. The light-emitting diodes are located at the delivering end of the optical guide, whereas, the other light-curing units tested have a fiber-optic light guide over the diodes which may act as thermal buffer, reducing the heat emission.

Several studies have been published evaluating the effect of light-curing unit exposure on the temperature change in the pulp chamber of extracted teeth with and without preparations or restorative materials. Pulpal temperature increases varied considerably in these in vitro studies, from 1.5 to 23.2°C due to several different factors such as light-curing-unit type, irradiance, exposure duration, spectral emission, composite resin shade, tooth-to- and resin-to-light tip distance, and thickness of both composite resin material and remaining dentin. However, limited research has been published evaluating the effect of high-irradiance light-curing units on the increase in pulpal temperature. Even with extended light exposure times, none of the light-curing units in this study resulted in a pulpal temperature increase greater than 5.5°C. The relatively low increase in pulpal temperature may be due in part to the more conservative preparation in a molar.

Very limited information is available in the literature regarding in vivo pulpal temperature increase in human teeth exposed to light-curing units. Two recent in vivo studies by Zarpellon et al. and Runnacles et al. found that most commonly used curing-light exposure times did not cause a higher temperature increase than the threshold value of 5.5°C on human premolars using the same control light-curing unit in this study, Bluephase 20i. Only when an unrestored deep class 5 preparation was exposed to a significantly longer light-curing time (60 s) and significantly greater radiant exposure of (73.9 J/cm²) did the pulpal temperature increase reach 5.5°C. In this study, the greatest increase in pulpal temperature was produced by the Valo light-curing unit (4.00°C) with an extended curing time of 20 s and radiant exposure of 50.3 J/cm².

CONCLUSION
Caution is advised with the use of high-irradiance light-curing units with short exposure times to obtain adequate polymerization of composite resin. Within the limitations of this investigation, none of the high-irradiance light-curing units, Flashmax P3, Valo, S.P.E.C. 3 LED, or Cybird XD, adequately polymerized the composite resin used in this study to a 2 mm depth at the manufacturer-recommended exposure times in ideal laboratory conditions. The exposure times necessary to adequately polymerize the composite resin resulted in a maximum pulpal temperature increase of 2.32°C—well below the temperature increase of 5.5°C associated with possible pulpal necrosis. Even with an extended exposure time of 20 s, none of the light-curing units exceeded the threshold.

CONFLICTS OF INTEREST
The views expressed are those of the authors and do not reflect the official views of policies of the Uniformed Services University, Department of Defense, or its Components. The authors do not have any financial interest in the companies whose materials are discussed in this manuscript.

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