Effect of High-irradiance Light Curing on Depth-of-Cure and Pulpal Temperature

ABSTRACT

Aim: The purpose of this in vitro study was to investigate the effect of rapid light curing on depth-of-cure of composite resin and temperature changes in the pulp using curing lights with high irradiance. Materials and Methods: Composite resin was placed in the proximal box of a molar and cured using high-irradiance curing lights (Cybird, Dentazon; S.P.E.C. 3, Coltene; Valo, Ultradent; Flashmax P3, CMS) at their maximum irradiance settings. The composite specimens were tested for hardness at 0.5-mm increments occlusal-gingivally. The first group had exposure times set according to manufacturer settings (Recommended), the second group were set to yield 80% of maximum hardness value at the 2mm depth (Experimental), and the third group was set at 20 seconds (Extended). Results: The exposure time necessary to adequately polymerize the composite resin at 2mm depth was 9 seconds for the Cybird and Valo and 12 seconds for S.P.E.C. 3 and Flashmax P3. The temperature change for the Extended group was significantly greater than the Experimental group which was significantly greater than the Recommended group. Conclusions: None of the high-irradiance curing lights adequately polymerized the composite resin at the manufacturer-recommended minimum-exposure times of one or three seconds. The exposure times necessary to adequately polymerize composite to a depth of 2mm resulted in a maximum pulpal-temperature increase of only 2.3°C. Clinical Significance: Caution is advised with the use of high-irradiance curing lights with short exposure times to obtain adequate polymerization of composite resin. However, the increase in pulpal

temperature from high-irradiance light curing of proximal restorations may not be clinically significant in routine restorations.

Keywords: Laboratory research; high-irradiance light-curing units; depth-of-cure; composite resins; and 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 compomers.[1] 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 5800 mW/cm^2.[2,3] The concept of exposure reciprocity suggests different combinations of irradiance and exposure time will achieve the same degree of resin polymerization as long as the same radiant exposure is delivered.[4] This reciprocity is based upon the "total energy" concept, or radiant exposure, which states the process of light-induced polymerization is energy dependent and is a product of irradiance and time.[5] Therefore, increasing the irradiance of the light theoretically enables the manufacturer to reduce recommended exposure durations from 20 or 40 seconds to as little as 1 second.

Currently, there is limited research available to support exposure reciprocity for high-output light-curing units delivering more than 3000 mW/cm^2, despite commercially available light-curing units with similar or higher irradiance.[4] 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 1500 mW/cm^2, resulting in less polymerization of composite resin.[4] Insufficient polymerization has been associated with greater wear, and reduced depth of cure, hardness, and bond strength between the tooth and restoration.[3]

This investigation focused on four commercially available, high-irradiance curing units: Flashmax P3 (CMS Dental A/S, Copenhagen, Denmark), Valo (Ultradent, South Jordan, UT, USA), S.P.E.C. 3 LED (Coltene, Cuyahoga Falls, OH, USA), and Cybrid (Dentazon, Torrance, CA, USA). The Flashmax P3 reportedly has an irradiance of more than 5,800 mW/cm^2, with a 3mm depth of cure for most materials in three seconds of exposure time.[7] With the Valo light-curing unit, Ultradent advertises an irradiance output of 3,200 mW/cm^2 in “plasma” mode with an exposure time of three seconds for a 2-mm increment of material.[8] 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/cm^2. The S.P.E.C 3 reportedly can cure to a depth of 2mm with a one-second exposure time.[9] Finally, the Cybird XD light-curing unit has a slightly lower irradiance at 2,700 mW/cm^2, but reportedly provides rapid polymerization of a 2-mm increment of composite resin material in three seconds.[10]

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-second 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.[13] 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 2mm 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 2mm 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. A box measuring 3.1 mm (occluso-gingivally) X 3.5 mm (bucco-lingually) X 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), and an enamel hatchet (51/52 Hatchet, Hu-Friedy Mfg. Co., LLC, Chicago, IL, USA). 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 trimmer (12" Model Trimmer, Whip Mix Corp, 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 scalers 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 (Digi-Sense Type-K Wire Probes, 30 Gauge; Cole Parmer, USA) was directed through the channel and positioned on the wall of the pulp chamber directly adjacent of the Class 2 box preparation, near the 2mm 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, Vernon Hill, IL, USA). 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 Corp, 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. See Figure 1.

The epoxy slab with mounted teeth was immersed into a thermostatically controlled water bath (StableTemp Digital Water Bath, Cole-Parmer, USA) 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 Systems Inc, 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, York, PA, USA). See Table 1. A sectional matrix (Tofflemire, Water Pik Inc., 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 secs using a light-curing unit (Bluephase 20i, Ivoclar Vivadent, Amherst, NY, USA) as the control at 1282 ± 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 each light 1mm 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 Super Snap Disks (Shofu Dental Corp, San Marcos, CA, USA). 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 hours 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). Knoop hardness numbers (KHN) were determined on the intaglio surface for each specimen using a Knoop Hardness tester (Leco, LM300AT, St Joseph, MI, USA) with a 200 gram load for 10 seconds. Three hardness measurements were determined for each depth (i.e., 0.5, 1.0. 1.5, 2.0 and 2.5 mm) descending apically from the coronal portion of the 3.1mm-long specimen. The maximum hardness value was determined to be an average hardness of the measurements at the 0.5mm depth with 20 seconds of exposure with the Bluephase 20i.

Composite resin specimens were then fabricated in the same manner as the control group (Bluephase 20i) using each of the four high-irradiance light-curing units (Cybird, S.P.E.C. 3, Valo, and Flashmax P3) at maximum setting using the manufacturers' recommended exposure time. Five specimens were created for each exposure time. Three hardness measurements were made at each of the previously noted depths. A specimen was considered to be cured at 2mm if the hardness ratio (hardness/maximum hardness) was greater than 80%.[16] The Experimental exposure time (i.e., time necessary to obtain a hardness ratio greater than 80% at 2mm) 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. Radiant exposure was calculated by multiplying the irradiance by the exposure time (J/cm^2).

Part 2: Effect of Exposure Time on the Increase in Pulpal Temperature

Upon determination of the Experimental exposure time for each light-curing unit, the next phase of the investigation was initiated. The microhybrid composite resin (Esthet-X HD) was placed into the tooth preparation as previously described. Individual samples were polymerized at each manufacturer's recommended exposure time (Recommended), the experimental exposure time based on hardness ratios (Experimental), and an extended exposure time of 20 seconds (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, ,, Armonk, NY, USA).

RESULTS

Part 1: Calculation of Exposure Time

The maximum hardness of the composite resin (52.2 KHN) was observed at the 0.5mm depth with 20 seconds of light exposure using the Bluephase 20i light-curing unit (control) at 1282±14 mW/cm^2. The composite resin specimens were determined to be adequately polymerized at the 2mm 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 2mm depth using the Bluephase 20i light-curing unit were determined for 10, 15, and 20 seconds of exposure time respectively.

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

Part 2: Effect of Exposure Time on the Increase in Pulpal Temperature

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 (alpha=0.006). Temperature changes associated with Extended exposure times were significantly greater than those determined for Experimental exposure times ($p<0.0001$), and both Extended and Experimental produced temperature changes which were significantly greater than those associated with Recommended exposure times ($p<0.0001$). A significant positive correlation was found between radiant exposure and increase in pulpal temperature ($r=0.91$; $p<0.001$).

With the Recommended groups, Cybird (1.0±0.2°C) had the greatest temperature change, but it was not significantly different ($p>0.41$) from Valo (0.8±0.1°C) and Bluephase 20i (0.9±0.1°C). S.P.E.C. 3 (0.3±0.2°C) had the lowest temperature change, but it was not significantly different ($p=0.52$) from Flashmax P3 (0.5±0.1°C). For the Experimental groups, Valo (2.3±0.04°C) and S.P.E.C 3 (2.3±0.3°C) had significantly greater temperature changes ($p<0.003$) than Cybird (1.7±0.1°C), Flashmax P3 (1.7±0.2°C) and Bluephase 20i (1.8±0.1°C), each of which were not significantly different from each other ($p>0.43$). For the Extended groups, Valo had the greatest temperature change (4.0±0.2°C), but it was not significantly different (p=0.06) from S.P.E.C. 3 (3.4±0.4°C). Bluephase 20i (1.8±0.1°C) had the lowest temperature change. See Table 2 and Figure 3.

DISCUSSION

A variety of dental manufacturers are marketing new light-curing units with high irradiance levels - some approaching 6000 mW/cm^2.[7] The objective of the high irradiance is to shorten clinical curing times, and thereby address professional desires for improved clinical efficiency and productivity. Despite these efforts, laboratory evidence suggests that lower irradiance in conjunction with longer exposure times may yield improved composite resin properties.[13,17,18]

As hypothesized, the results from the initial hardness testing indicate that none of the high-irradiance light-curing units adequately polymerized the composite resin to a 2mm depth at the manufacturer-recommended exposure times of one or three seconds. The calculated Experimental exposure times necessary to adequately polymerize the composite resin restorations at 2mm were 9 seconds for the Cybird and Valo, 12 seconds for the S.P.E.C 3 and Flashmax P3, and 20 seconds for the control curing light, Bluephase 20i. These exposure times were at least three times longer than the manufacturer recommendation for Cybird, Valo, and Flashmax P3 and twelve times longer for the S.P.E.C. 3. The Flashmax P3 system uses a disposable tip with small or large diameter light guides that are recommended during clinical use. While the light-emitting diodes from the Flashmax P3 emit an irradiance of approximately 5800 mW/cm^2 with no tip, the larger tip significantly reduced the net irradiance to only 2702 ± 24 mW/cm^2. In this investigation, the large tip was chosen because it was easier to standardize the energy delivered to the composite resin material. Similarly, a recent study by Kutuk, et al found that using the smaller tip significantly reduced the measured irradiance of the Flashmax P3 from 7681.7±160.5 to 3052±71 mW/cm^2.[3]

The depth of cure of composite resin may be affected by composite- and light-related factors. Composite-related factors include shade, translucency, 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 study, however, is that only one representative type of composite resin was utilized. Esthet-X HD in shade A2 was selected for this study due to its relatively common microhybrid formulation.[20] Dentsply, the manufacturer of Esthet-X HD, recommends 10 to 20 seconds of exposure time depending on the irradiance of the curing light.[20] However, different results would be expected with different composite resins based on their composite-related factors. Using the more clinically relevant tooth model in this study, twenty seconds of curing time was necessary using the control curing light (Bluephase 20i, 1282 mW/cm^2) to adequately polymerize the composite resin at a depth of 2mm.

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/cm^2 to as high as 36 J/cm^2.[21,22] 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/cm^2). However, as calculated, the amount of radiant exposure necessary to predictably obtain an 80% hardness ratio at a 2mm depth were in the higher limits of the reported range (22.6-38 J/cm^2). In addition, the depth of cure can be affected by the type and size of the testing mold, the composite resin, and light source.[23-25] 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.[30,31] 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.[32] In this study, maximum hardness was determined at 0.5mm 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.[33] 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. 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.[34] The results of that study set forth a threshold temperature for irreversible pulpal damage when an external heat 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 seconds, 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 2mm.

With Experimental exposure times (i.e., exposure time necessary to adequately polymerize the composite resin at a depth of 2mm.) of 9 or 12 seconds, the pulpal temperature change was minimal for Cybird and Flashmax P3, with an only 1.8°C increase. The control light-curing unit, Bluephase 20i, with an Experimental exposure time of 20 seconds also resulted in a pulpal temperature increase of only 1.8°C. The pulpal temperature change was more substantial for Valo and S.P.E.C 3, with a 2.3°C increase for Experimental exposure times of 9 or 12 seconds 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 seconds, 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 4.0°C, which was not statistically different from S.P.E.C. 3 with 3.4°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 increase in the pulp chamber of extracted teeth with and without preparations or restorative materials.[35-38] 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.[39] 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.[11,12] Only when an unrestored deep class 5 preparation was exposed to a significantly longer light-curing time (60 seconds) and significantly greater radiant exposure of (73.9 J/cm^2) 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 (4.0°C) with an Extended curing time of 20 seconds and radiant exposure of 50.3 J/cm^2.

CONCLUSION

Caution is advised with the use of high-irradiance curing lights 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, or Cybrid, adequately polymerized the composite resin used in this study to a 2mm 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 2.3°C – well below the temperature increase of 5.5°C associated with possible pulpal necrosis. Even with an extended exposure time of 20 seconds, none of the light-curing units exceeded the threshold.

Disclaimer: The views expressed in this article are those of the authors and do not reflect the official policy of the United States Air Force, the Department of Defense, Uniformed Services University, or the United States Government. The authors do not have any financial interest in the companies whose materials are discussed in this article. The views of Dentsply, Dentazon, Coltene, Ultradent, Ivoclar, StarDental, Axis Dental, Hu-Friedy, Grobet Vigor, Whip Mix Corp, Kerr, Cole-Parmer, Buehler, GC Corp, Pump Systems Inc, Water Pik Inc, Fougera Pharmaceuticals, Axis Dental, Shofu Dental Corp, Quincy Labs, C&A Scientific, Leco, Lapsphere, Ocean Optics and CMS Dental are not necessarily the official views of, or endorsed by, the U.S. Government, the Department of Defense, or the

Department of the Air Force or the Uniformed Services University. No Federal endorsement of Dentsply, Dentazon, Coltene, Ultradent, Ivoclar, StarDental, Axis Dental, Hu-Friedy, Grobet Vigor, Whip Mix Corp, Kerr, Cole-Parmer, Buehler, GC Corp, Pump Systems Inc, Water Pik Inc, Fougera Pharmaceuticals, Axis Dental, Shofu Dental Corp, Quincy Labs, C&A Scientific, Leco, Lapsphere, Ocean Optics and CMS Dental is intended.

REFERENCES

1. Heintze SD, Rousson V, Mahn E. Bond strength tests of dental adhesive systems and their correlation with clinical results - A meta-analysis. Dent Mater 2015;13(4):423-434.

2. Rueggeberg FA, Cole MA, Looney SW, Vickers A, Swift EJ. Comparison of manufacturer-recommended exposure durations with those determined using biaxial flexure strength and scraped composite thickness among a variety of light-curing units. J Esthet Restor Dent 2009;21(1):43-61.

3. Kutuk ZB, Gurgan S, Hickel R, Ilie N. Influence of extremely high irradiances on the micromechanical properties of a nano hybrid resin based composite. Am J Dent 2017;30(1):9-15.

4. Selig D, Haenel T, Hausnerová B, Moeginger B, Labrie D, Sullivan B, Price RB. Examining exposure reciprocity in a resin based composite using high irradiance levels and real-time degree of conversion values. Dent Mater 2015;31(5):583-593.

5. Asmussen E, Peutzfeldt A. Polymerization contraction of resin composite vs. energy and power density of light-cure. Eur J Oral Sci 2005;113(5):417-421.

6. Watts DC. Reaction kinetics and mechanics in photo-polymerised networks. Dent Mater 2005;21:27-35.

7. CMS Dental Flashmax P3: The world's most powerful curing light. http://www.cmsdental.com/gfx/pdf/FP3_Brochure_PRINT.pdf. Accessed 30 Oct 2017.

8. Valo Instructions for Use https://intl.ultradent.com/au/Product%20Instruction%20Documents/VALO%20Curing%20Light.pdf. Accessed 30 Oct 2017.

9. Coltene Brochure S.P.E.C. 3 LED: Performance without compromise. https://www.coltene.com/fileadmin/Data/EN/Products/Adhesives_Restoratives/Curing_Lights/SPEC3/60018424_09-14_Brochure_SPEC3_EN.pdf. 30 Oct 2017.

10. AAOF Corporate Partner. Cybird XD: Advanced LED curing light. Ortho Technology. http://www.orthotechnology.com/new_products/Cybird_Curing_Light.cfm. Accessed 1 July 2015.

11. Zarpellon DC, Runnacles P, Maucoski C, Gross DJ, Coelho U, Rueggeberg FA, Arrais CAG. Influence of Class V preparation on in vivo temperature rise in anesthetized human pulp during exposure to a Polywave® LED light curing unit. Dent Mater 2018;34(6):901-909.

12. Runnacles P, Arrais CA, Pochapski MT, Dos Santos FA, Coelho U, Gomes JC, De Goes MF, Gomes OM, Rueggeberg FA. In vivo temperature rise in anesthetized human pulp during exposure to a polywave LED light curing unit. Dent Mater 2015;31(5):505-513.

13. Rueggeberg FA, Swift EJ Jr. Exposure times for contemporary composites. J Esthet Restor Dent 2013;25(2):82-84.

14. Park SH, Roulet JF, Heintze SD. Paramerters influencing increase in pulp chamber temperature with light curing devices: curing lights and pulpal flow rates. Oper Dent 2010;35(3);353-361.

15. Kim S. Microcirculation of the dental pulp in health and disease. J Endod 1985;11:465–471.

16. Bouschlicher MR, Rueggeberg FA, Wilson BM. Correlation of bottom to top surface microhardness and conversion ratios for a variety of resin composite compositions Oper Dent 2004;29(6):698-704.

17. Hadis M, Leprince JG, Shortall AC, Devaux J, Leloup G, Palin WM. High irradiance curing and anomalies of exposure reciprocity law in resin-based materials. J Dent 2011;39(8):549-557.

18. Shimokawa C, Sullivan B, Turbino ML, Soares CJ, Price RB. Influence of emission spectrum and irradiance on light curing of resin-based composites. Oper Dent 2017;42(5):537-547.

19. Swartz ML, Phillips RW, Rhodes B. Visible light-activated resins—depth of cure. J Am Dent Assoc 1983;106:634–637.

20. Esthet-X HD High Definition Micro Matrix Restorative. Directions for Use. https://www.dentsply.com/content/dam/dentsply/pim/manufacturer/Restorative/Direct_Restoration/Composites__Flowables/Universal_Composites/EsthetX_HD_High_Definition_Micro_Matrix_Restorative/Esthetx-HD-m3cirgy-en--1402. Accessed 1 Oct 2017.

21. Price RB, Felix CM, Whalen JM. Factors affecting the energy delivered to simulated class I and class v preparations. J Can Dent Assoc 2010;76:a94.

22. Calheiros FC, Kawano Y, Stansbury JW, Braga RR. Influence of radiant exposure on contraction stress, degree of conversion and mechanical properties of resin composites. Dent Mater 2006;22(9):799-803.

23. Asmussen E, Peutzfeldt A. Influence of specimen diameter on the relationship between subsurface depth and hardness of a light-cured resin composite. Eur J Oral Sci 2003;111(6):543-546.

24. Erickson RL, Barkmeier WW, Halvorson RH. Curing characteristics of a composite - part 1: cure depth relationship to conversion, hardness and radiant exposure. Dent Mater 2014;30(6):e125-133.

25. Erickson RL, Barkmeier WW. Curing characteristics of a composite. part 2: the effect of curing configuration on depth and distribution of cure. Dent Mater 2014;30(6):e134-145.

26. Raab WH. Temperature related changes in pulpal microcirculation. Proc Finn Dent Soc. 1992;88 Suppl 1:469-479.

27. Nguyen DP, Motyka NC, Meyers EJ, Vandewalle KS. Depth of cure of proximal composite resin restorations using a new perforated metal matrix. Gen Dent 2018;66(3):68-74.

28. DeWald JP, Ferracane JL. A comparison of four modes of evaluating depth of cure of light-activated composites. J Dent Res 1987;66(3):727-730.

29. Moore BK, Platt JA, Borges G, Chu TM, Katsilieri I. Depth of cure of dental resin composites: ISO 4049 depth and microhardness of types of materials and shades. Oper Dent 2008;33(4):408-412.

30. Lombardini M, Chiesa M, Scribante A, Colombo M, Poggio C. Influence of polymerization time and depth of cure of resin composites determined by Vickers hardness. Dent Res J (Isfahan) 2012;9(6):735-740.

31. Bouschlicher MR, Rueggeberg FA, Wilson BM. Correlation of bottom to top surface microhardness and conversion ratios for a variety of resin composite compositions. Oper Dent 2004;29(6):698-704.

32. Vandewalle KS, Ferracane JL, Hilton TJ, Erickson RL, Sakaguchi RL. Effect of energy density on properties and marginal integrity of posterior resin composite restorations. Dent Mater 2004;20(1):96-106.

33. Savas S, Botsali MS, Kucukyilmaz E, Sari T. Evaluation of temperature changes in the pulp chamber during polymerization of light cured pulp-capping materials by using a VALO LED light curing unit at different curing distances. Dent Mater 2014;33(6):764-769.

34. Zach L, Cohen G. Pulp Response to externally applied heat. Oral Surg Oral Med Oral Pathol1965;19:515-530.

35. Yazici AR, Muftu A, Kugel G, Perry RD. Comparison of temperature changes in the pulp chamber induced by various light curing units, in vitro. Oper Dent 2006;31:261–265.

36. Leprince J, Devaux J, Mullier T, Vreven J, Leloup G. Pulpal-temperature rise and polymerization efficiency of LED curing lights. Oper Dent 2010;35:220-230.

37. Millen C, Ormond M, Richardson G, Santini A, Miletic V, Kew P. A study of temperature rise in the pulp chamber during composite polymerization with different light-curing units. J Contemp Dent Pract 2007;8:29–37.

38. Rajesh Ebenezar AV, Anilkumar R, Indira R, Ramachandran S, Srinivasan MR. Comparison of temperature rise in the pulp chamber with different light curing units: an in-vitro study. J Conserv Dent 2010;13:132–135.

39. Daronch M, Rueggeberg FA, Hall G, De Goes MF. Effect of composite temperature on in vitro intrapulpal temperature rise. Dent Mater 2007;23(10):1283-1288.

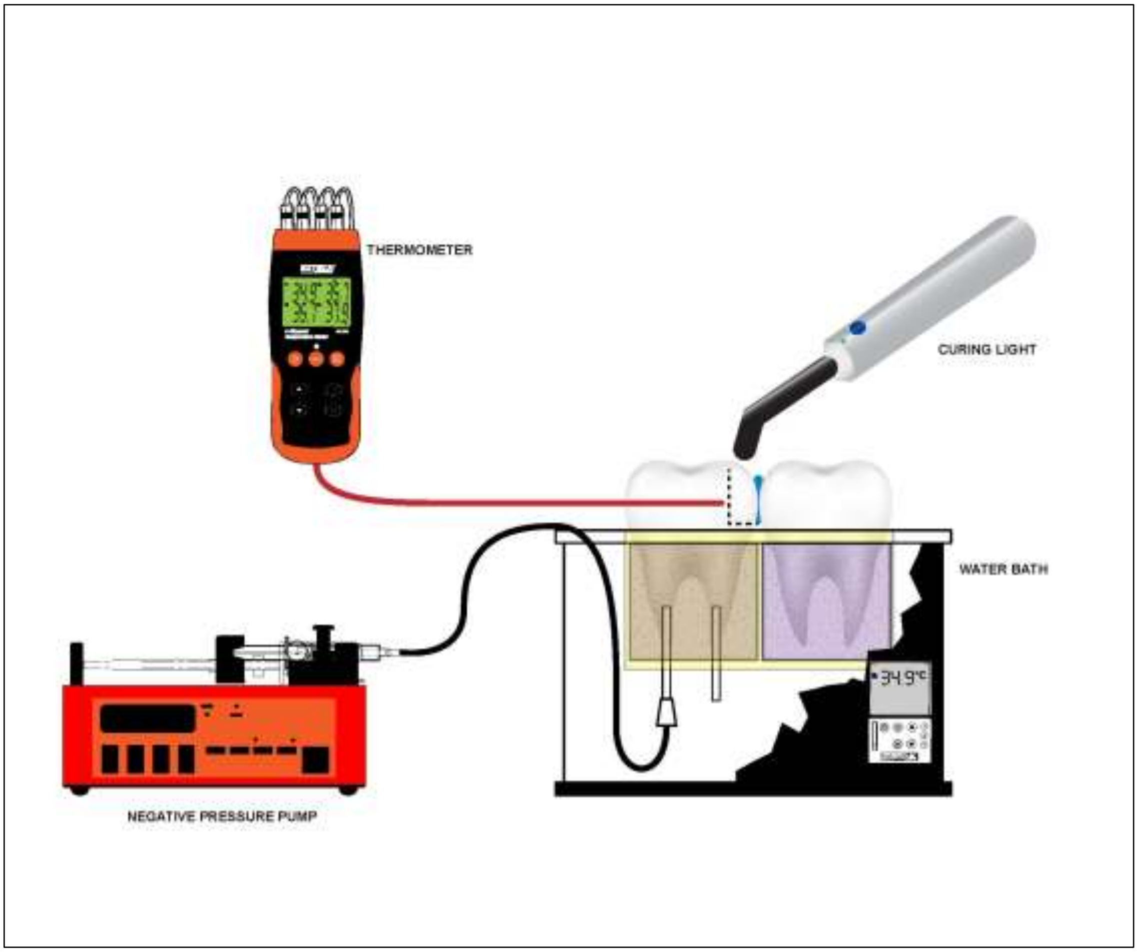

Figure 1. Schematic representation of test assembly

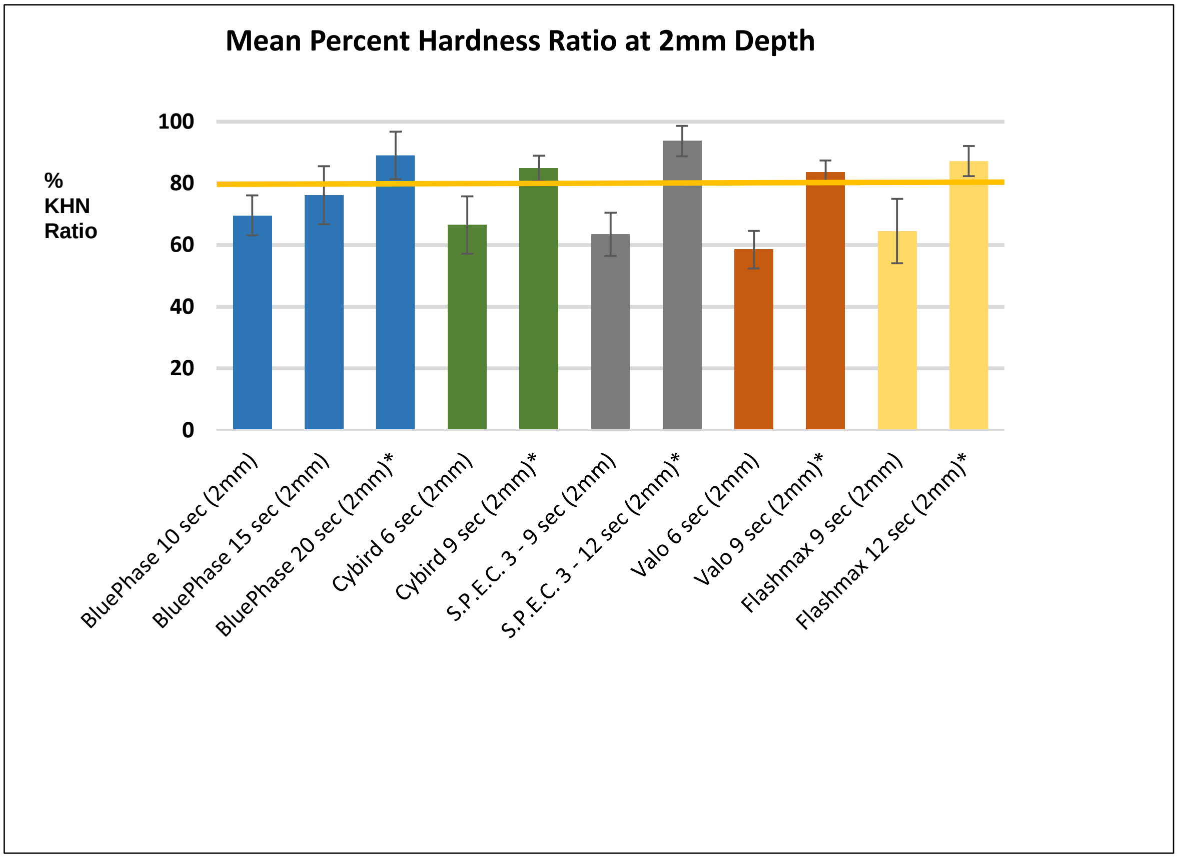

Figure 2. Mean percent hardness ratio at 2mm depth with various exposure times per light-curing unit. Yellow line at 80% indicates threshold for adequate polymerization. Error bars indicate ±1 standard deviation. Asterisk indicates greater than 80% hardness ratio.

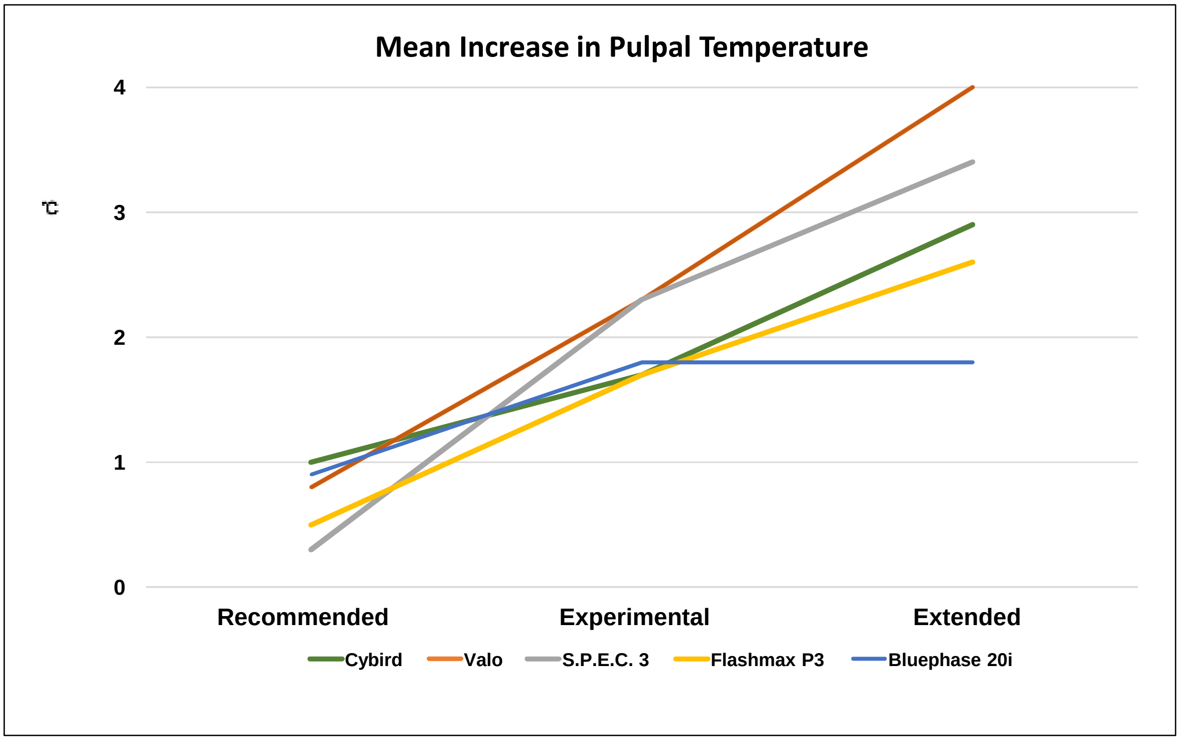

Figure 3. Mean increase in pulpal temperature with the various light-curing units at the Recommended, Experimental and Extended exposure times

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

Table 1. Composition of Esthet-X HD

Light-curing unit	Power (mW)	Irradiance (mW/cm^2)	Mean (st dev) Increase in Pulpal Temperature ºC											
			Recommended				Experimental				Extended			
			Time (secs)	Radiant Exposure (J/cm^2)	↑Pulpal Temp (°C)		Time (secs)	Radiant Exposure (J/cm^2)	↑ Pulpal Temp (°C)		Time (secs)	Radiant Exposure (J/cm^2)	↑Pulpal Temp (°C)	
Cybird	**1404 (24)**	**3179 (53)**	**3**	**9.5 (0.2)**	**1.0 (0.2)**	**Ac**	**9**	**28.1 (0.5)**	**1.7 (0.1)**	**Ba**	**20**	**62.4 (1.1)**	**2.9 (0.1)**	**Cbc**
Valo	**1093 (14)**	**2473 (32)**	**3**	**7.4 (0.1)**	**0.8 (0.1)**	**Abc**	**9**	**22.6 (0.3)**	**2.3 (0.04)**	**Bb**	**20**	**50.3 (0.6)**	**4.0 (0.2)**	**Cd**
S.P.E.C 3	**1336 (69)**	**3024 (156)**	**1**	**3.0 (0.2)**	**0.3 (0.2)**	**Aa**	**12**	**38.9 (2.0)**	**2.3 (0.3)**	**Bb**	**20**	**64.9 (3.1)**	**3.4 (0.4)**	**Ccd**
Flashmax P3	**1194 (11)**	**2702 (24)**	**3**	**8.1 (0.07)**	**0.5 (0.1)**	**Aab**	**12**	**32.2 (0.3)**	**1.7 (0.2)**	**Ba**	**20**	**53.7 (0.5)**	**2.6 (0.1)**	**Cb**
Bluephase 20i	**567 (6)**	**1282 (14)**	**10**	**12.8 (0.1)**	**0.9 (0.1)**	**Ac**	**20**	**25.6 (0.3)**	**1.8 (0.1)**	**Ba**	**20**	**25.6 (0.3)**	**1.8 (0.1)**	**Ba**

Table 2. Mean and standard deviation of power, irradiance, radiant exposure and pulpal temperature increase (°C) for each light-curing unit at various exposure times. Groups with the same lower case letter per column and upper case letter per row are not significantly different ($p>0.006$).