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BOUILLAGUET, Serge, *et al*.

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Reference

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Thermal Risks from LED- and High-Intensity QTH-Curing Units during Polymerization of Dental Resins

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Abstract: The aim of this study was to test the ability of an infrared (IR) camera to assess temperature changes and distributions in teeth below restorations when quartz-tungsten-halogen (QTH) and light-emitting diode (LED) curing lights were used to photopolymerize the restorative material. Our hypothesis was that the higher power density and broader spectral distribution of the QTH source would cause greater increases in tooth temperature than the LED source, and that these differences would be best demonstrated with the IR camera. Cavities were prepared on human third molars and restored with a resin composite restorative material. The material was light-cured using three light-curing sources using several exposure times. The external (outside the tooth) and internal (inside the pulp chamber) temperature changes during polymerization of the composite material were recorded over 360 s with thermocouples and an IR camera. Using thermocouples the maximum increase in external temperature ($+17.7°C$) was reported for the Swiss Master light after 20 s of curing time while the minimum temperature rise ($+7.8°C$) was reported for the Freelight 2. Whereas a $2.6°C$ increase in internal temperature was observed after curing 20 s with the Freelight 2, $7.1°C$ was reported after 60 s of light exposure to Astralis 10. Infrared images showed similar trends in external–internal rises in temperature as the thermocouples, although temperatures measured by the IR were generally higher. These results indicate that the higher power density QTH sources caused greater increases in tooth temperatures than the LED source and that thermocouples may underestimate the heat applied to the tooth. © 2004 Wiley Periodicals, Inc. J Biomed Mater Res Part B: Appl Biomater 72B: 260–267, 2005

Keywords: photopolymerization; composites; infrared thermography; temperature; dentin

INTRODUCTION

Today's esthetic dental restorative techniques rely on light-curing sources to activate polymerization of resin composites used either as direct filling materials or luting agents for the restoration of teeth. Wavelengths of 400 to 500 nm (blue light) activate camphorquinone–amine photoinitiation systems contained in most current dental resins.[1] Blue light is used to excite the camphorquinone, leading to the production of free radicals responsible for initiating the polymerization process. Quartz-tungsten-halogen (QTH) lamps are the most frequently used sources for light curing. Typically, 500 to 800 mW/cm^2 of light for 30 to 40 s is necessary from QTH sources to polymerize composites to a depth of 2 mm, but the amount of curing time also is a function of type, shade, and thickness of the material.[2] Therefore, larger, deeper, darker restorations require longer exposures, multiple curing cycles, or curing of multiple layers of composite material. Newer QTH sources with intensities in excess of 1500 mW/cm^2 have been developed to cure thicker layers of composite in shorter periods of time.

QTH lamps use a tungsten filament heated to 2000°C to 3000°C, which emits a white light covering a large range of wavelengths including the infrared. Thus, QTH light must be filtered to eliminate unwanted wavelengths outside the 400 to 500 nm (blue light) range, and only a small fraction of the light produced from this source is used for polymerization

and a large amount of energy is transformed into heat.[3] Heat has been shown to degrade light filters and bulbs and consequently the efficiency of QTH curing units over time.[4]

Recent designs in light-curing units have focused on light-emitting diodes (LEDs) in the blue range.[5] LEDs use junctions of doped semiconductors (p-n junctions) based on gallium–nitride to produce blue light. Previous studies have confirmed that LEDs are more efficient than QTH lamps in converting energy to light and that their light emission more closely matches the absorption spectrum of camphorquinone.[6] Furthermore, LEDs do not generate infrared wavelength, have a constant light output, and have a longer life expectancy than QTH sources.[7] Other research also has shown that the intensity of the newest LEDs is comparable to QTH light sources.[8] Regardless of the amount of infrared energy transmitted from the curing source, polymerization of light-activated resin composites always results in a temperature increase in the material caused by both the exothermic polymerization reaction and the light energy absorbed during irradiation.[9, 10] Temperature increases up to 20°C have been measured during light-induced polymerization within the composite resin.[11,12] The amount of heat generated also depends on the bulk of the composite and the rate at which it polymerizes.

Based on an early report from Zach and Cohen many authors have assumed that 5°C to 15°C elevation in pulpal temperature will irreversibly damage the pulpal tissues.[13] Hussey and colleagues also have reported that the dental pulp may be endangered by the temperature rise that occurs during light curing.[14] Other studies have shown that intrapulpal temperature rises during light curing are low because dentin is an excellent thermal insulator.[15] However, the increased power of recently developed light-curing units (> 1500 mW/cm^2) has renewed concerns about the biological safety of curing units, especially when they are used in deep cavities with little remaining dentin thickness. Hannig and Bott reported that photopolymerization with high energy output curing units causes significantly higher pulp chamber temperature changes as compared to the conventional curing units.[16] However, they also pointed out that the temperature changes measured *in vitro* with thermocouples cannot predict temperature changes *in vivo* because thermocouple measurements cannot monitor heat conduction within the tooth during *in situ* resin polymerization. To gain more detailed information about temperature distribution and temperature changes within the tooth, we hypothesized that an infrared (IR) camera might be more useful. Infrared cameras have previously been used to assess temperature changes during the polymerization process *in vivo* and *in vitro*, but not during *in situ* resin polymerization with QTH and LED curing units.[14,17]

The primary aim of the current study was to test the utility of an IR camera to assess temperature changes and distributions in teeth during photopolymerization of dental resin restorative materials. We used QTH and LED curing units, with the expectation that the higher power density and broader spectral distribution of the QTH source would cause greater increases in tooth temperature than the LED source.
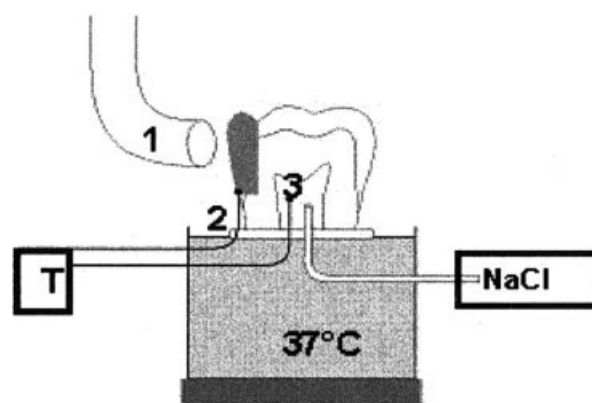

Figure 1. Schematic diagram of the set up used for temperature measurements with thermocouples. The perfused tooth (0.09 g/L NaCl) was cemented to an acrylic base and placed over a thermally regulated water bath. The distance between the tip of the light-curing unit (1) and the restorative material was constant (2 mm). The external temperature rise during the polymerization of the composite was measured with a thermocouple secured at the bottom of the cavity (2). The thermocouple located inside the pulp chamber (3) was used to monitor internal temperature changes during light curing.

The utility of the IR camera technique would allow better, more detailed assessment of new curing sources and restorative materials, and would be applicable *in vitro* as well as *in vivo*.

MATERIALS AND METHODS

Class II slot cavities were prepared on the proximal–occlusal surface of six freshly extracted caries-free human third molars previously stored in 4°C isotonic sodium chloride containing 0.2% sodium azide. The remaining dentin thickness between pulp chamber and axial wall of the proximal box after cavity preparation was 2 mm (assessed by radiographs). The roots were cut at the CEJ and the coronal pulp was removed with small forceps. Each tooth was then cemented with cyanoacrylate to a $2 \times 2 \times 0.4$ cm piece of plexiglass penetrated by polyethylene tubing. These tubes were used to perfuse the pulp chamber with a solution of sodium chloride (0.09 g/L) and to insert a K-type thermocouple inside the pulp chamber (TCA; K-type, Thermocoax, Suresnes, France; Figure 1). This thermocouple was used to measure the internal temperature of the specimen. A second thermocouple was secured on the enamel surface of the tooth and was used to monitor the external temperature of the tooth. The thermocouples were attached to the temperature recorder connected to a PC for data acquisition and storage (Fluke Hydra 2620A and Hydra logger, Fluke Corporation, Everett, WA, USA). Briefly, the Hydra Logger converts voltage from thermocouples directly into temperature readings and downloads data for archiving and graphical representations. To keep the ambient temperature as constant as possible (37°C ± 0.1°C), the sample tooth was placed over a thermally regulated water bath (Bioblock Scientific, AM3001K, Illkirch, France). A

TABLE I. Curing Light (Name, Manufacturer, Source, and Output)

Light Source	Manufacturer	Type	Light Guide Diameter	Power Density (mW/cm^2)
Astralis 10	Ivoclar-Vivadent (Schaan, LI)	QTH bulb (100 W)	12 mm	1200 mW/cm^2
Swiss Master Light	EMS (Nyon, CH)	QTH bulb (340 W)	11 mm	3000 mW/cm^2
Freelight 2	3MESPE (Seefeld, D)	1 LED	8 mm	1000 mW/cm^2

2-mm thick increment of composite resin (Tetric Ceram A 2, Lot E31083, Ivoclar-Vivadent, St Jorioz, France) was condensed into the cavity and polymerized without using a bonding agent. Although this procedure differed from clinical use, previous reports have shown that the absence of a bonding agent does not significantly influence the amount of heat transmitted to surrounding tissues during polymerization.[16] In the absence of bonding agent, the cured composite is easily removed from the cavity and the tooth can be re-used to repeat different experimental conditions with the same specimen. This strategy allowed six measurements on six different teeth for each curing condition to be performed.

Three light-curing sources were used in the current study (Table I). The Astralis 10 is a high-power curing light equipped with a 100-W quartz-halogen bulb (QTH) and features four different power programs. Only the high-power program that provides a minimum of 1200 mW/cm^2 of light was used in the current study. Light curing with the Astralis 10 was for 20, 40, and 60 s. The Swiss Master light (EMS, Nyon, CH) is a QTH curing unit equipped with a 320-W quartz-tungsten-halogen bulb emitting 3000 mW/cm^2 of blue light with the fast-cure program. The light guide of the Swiss Master light is equipped with a water cooling system to avoid excessive temperatures during light curing. Irradiation times were 5, 10, and 20 s. The Freelight 2 (3M-ESPE, St. Paul, MN, USA) is a high-intensity LED light-curing unit which can deliver a light intensity of 1000 mW/cm^2. Light curing with the Freelight 2 was performed for 20, 40, and 60 s. The irradiance and intensity of each curing unit were controlled using a a fiber optic spectrometer sensitive in the 190 to 850 nm wavelength range (AVANTES, AVS-USB2000, Eerbeek, The Netherlands).

For measurements of temperature rise, the tip of the light-curing unit was placed at a distance 1 mm from the tooth sample, and the external and internal temperature changes during polymerization of the composite material inside the cavity were continuously recorded over 360 s. This time interval was selected to allow the samples to return to the initial temperatures after exposure to the light source. The maximum temperature rise was determined from these curves ($n = 6$). Mean values and standard deviations were calculated for each condition and analyzed by one-way ANOVA and multiple comparison tests (Fisher least significant difference LSD; $p < 0.05$).

After completion of the thermal measurements with thermocouples, the tooth samples were sectioned in two halves with a low-speed diamond saw (Isomet, Buehler) for the infrared thermography analysis (Figure 2). The sectioned tooth was repositioned 1 mm above the water bath with the crosscut section parallel to the surface of the water and the thermographic camera Avio TST-2000ST (Avio Tech, Japan) was located perpendicular to the cross-section of the tooth. To ensure the light was entering the sample exclusively from the half section of the light guide, a light shield was cemented to the upper part of the light guide. The composite material was then inserted into the cavity and the samples were irradiated for 20, 40, and 60 s. The temperature distribution within the sample during light curing was monitored by the camera and thermal images were obtained at different time point intervals (5, 10, 20, 40, and 60s). The thermal image achieved is a visual representation of the temperature distribution on the sample surface. Images were imported into an image processing and analysis program (Scion Image, Scion Corporation, Frederick, MA, USA). A transparent image representing the general outline of the tooth including the cavity wall and the pulp chamber was pasted onto the IR image to determine the exact location of these different structures. Measurements of colors inside the pulp, at the cavity floor, inside the composite material, and outside the tooth were made using the color picker tool. When using this tool, pixel values are displayed in the information window as
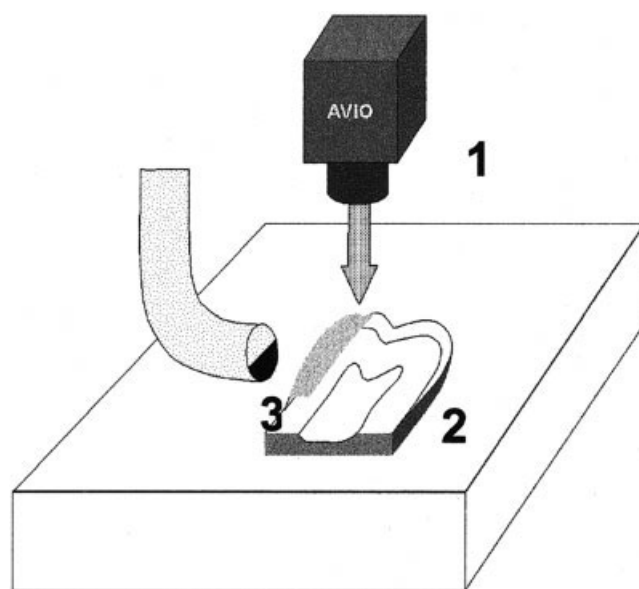

Figure 2. Schematic diagram set up for the IR camera measurement of the tooth temperature. The IR camera (1) is located perpendicular to the tooth section (2) which is placed 2 mm above the water level. The radiation shield (3) was used to limit the radiation from the light guide only on the input face of the composite.

TABLE II. Temperature Rise (± SD) Induced by Curing Lights, Thermocouple Measurements

Light Source	Irradiation Time (s)	External Temperature Rise (°C)	Internal Temperature Rise (°C)
Astralis 10	20	+ 9.65 (± 2.7)	+ 3.30 (± 0.7)
	40	+ 10.83 (± 2.5)	+ 5.12 (± 1.3)
	60	+ 13.05 (± 4.1)	+ 7.10 (± 1.1)
Swiss Master Light	5	+ 10.85 (± 3)	+ 2.62 (± 0.2)
	10	+ 14.64 (± 4.2)	+ 3.29 (± 0.6)
	20	+ 17.72 (± 4.1)	+ 5.80 (± 1.0)
Freelight 2	20	+ 7.80 (± 2.3)	+ 2.63 (± 0.3)
	40	+ 9.53 (± 1.8)	+ 3.98 (± 0.8)
	60	+ 11.03 (± 1.6)	+ 5.09 (± 0.6)

Mean temperature rise ($n = 6$) recorded after light curing. Within each light source and location linked values are not significantly different (one-way ANOVA and Fisher LSD multiple comparison test; $p < 0.05$)

RGB values. A regression analysis was performed to verify the linear relationship between color measurements (RGB values) and temperature scale given by the IR camera image. The relationship between RGB values and temperatures was as shown by the formula: $f(y) = 0.1319 * y + 29.217$ with $R^2 = 0.99$.

RESULTS

For all curing units, increasing irradiation time always increased the external temperature of the tooth measured with thermocouples (Table II). The minimum temperature rise ($+7.8°C$) was observed after curing the composite material for 20 s with the Freelight 2. The maximum increase in external temperature ($+17.7°C$) was reported for the Swiss Master light after 20 s of curing time. However, temperature rises among most curing conditions were not significantly different (multiple comparison tests, LSD $p < 0.05$). For all curing conditions, internal temperatures increased from baseline after exposure to light. Whereas a 2.6°C increase in internal temperature was observed after curing 20 s with the Freelight 2, 7.1°C was reported after 60 s of light exposure to Astralis 10. Although there were some exceptions, the temperature rises recorded under the different curing conditions were significantly different (Table II).

Comparing the 20-s exposure for the different lights, peak temperatures after irradiation differed significantly on the external and internal portions of the tooth (Figures 3–5). All external peak temperatures were reached 10 s after exposure to the light, and these temperatures decreased rapidly with time. Nearly 50% of the heat was dissipated 40 s after light exposure and a progressive return to baseline temperature
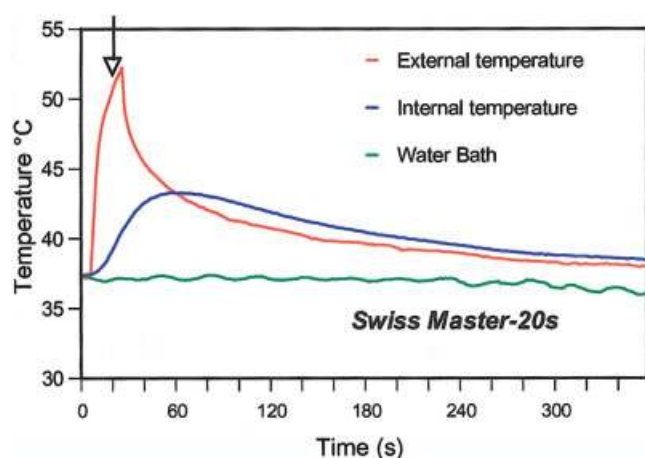
Figure 3. Temperature changes (°C) observed in the restored specimen after 20 s exposure to the Astralis 10. The external temperature is shown on the upper curve, the internal temperature is shown on the middle curve. The bottom curve shows the temperature in the water bath. Arrows indicate the end of exposure to light. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Figure 4. Temperature changes (°C) observed in the restored specimen after 20 s exposure to the Swiss Master light. The external temperature is shown on the upper curve, the internal temperature is shown on the middle curve. The bottom curve shows the temperature in the water bath. Arrows indicate the end of exposure to light. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]
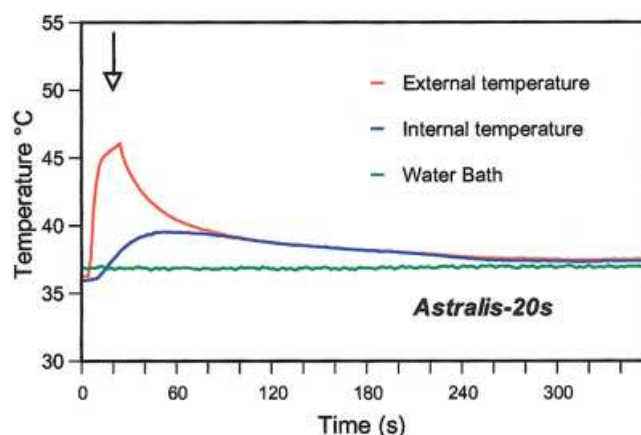
Figure 5. Temperature changes (°C) observed in the restored specimen after 20 s exposure to the Freelight 2. The external temperature is shown on the upper curve, the internal temperature is shown on the middle curve. The bottom curve shows the temperature in the water bath. Arrows indicate the end of exposure to light. [Color figure can be viewed in the online issue, which is available at www.interscience. wiley.com.]
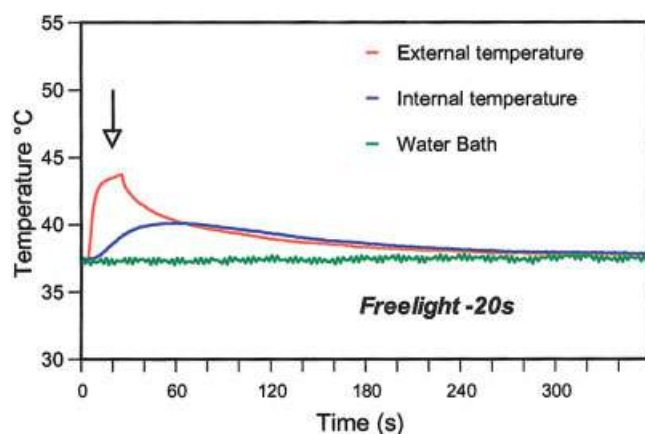
was observed after 4 min. Temperature curves recorded by the internal thermocouple showed a progressive rise in temperature reaching a plateau approximately 20 s after the end of light exposure. The internal temperature remained elevated at the same level for 20 to 40 s and returned to baseline temperatures after 4 min.

The results of IR measurements are shown in Table III. The minimum increase in external temperature (+8.1°C) was observed after curing the composite material for 20 s with the Freelight 2. The maximum increase in external temperature (°18.5°C) was reported for the Swiss Master light after 20 s of curing time. For all curing conditions, internal temperatures also increased from baseline after exposure to light. A 2.7°C increase in internal temperature was observed after curing 20 s with the Freelight 2 and 6.9°C was reported after 60 s of light exposure to Astralis 10. Although there were some exceptions, the temperature rises recorded under the

different curing conditions were not significantly different (Table II). For most curing conditions, the external–internal temperatures measured by the IR method were higher than those measured with thermocouples. However, in most instances, the differences between the two techniques was less than 1°C.

Infrared imaging provided far more information about the temperature profiles in teeth than the thermocouples. Analysis of these images confirmed that the higher power density QTH sources caused greater increases in tooth temperature than the LED source and that increasing exposure to light increased temperature of the tooth (Figures 6–8). Infrared images also showed that external temperatures were consistently lower than temperatures recorded inside the composite material and that heat was also able to propagate towards the deeper part of the tooth down to the pulp chamber. For example, Figure 6(a) is an IR camera image of a sample tooth exposed for 5 s to the Swiss Master light. The temperature outside the tooth (external temp) increased from 31.4°C to 43.9°C. The highest temperature recorded in the composite was 55°C and the temperature at the cavity floor was 45.9°C. The temperature in the pulp chamber was 33.4°C. When exposure to the light was doubled (10 s), the external temperature remained approximately the same (44.4°C) but the temperature of the composite increased up to 57.4°C [Figure 6(b)]. The temperature at the cavity floor was 47.4°C and pulpal temperature was 34.4°C. When the experiment was repeated on the same tooth with an exposure to light of 20 s [Figure 6(c)], the external temperature further increased up to 45.7°C with a peak temperature in the composite of 56.7°C. The temperature at the bottom of the cavity was 46°C and the pulpal temperature rose to 38.5°C. These detailed assessments of temperature profile were not possible with the thermocouple measurements.

In comparison, Figures 7 and 8 illustrate the elevations in temperature observed after light curing 20 s with Astralis 10 and Freelight 2, respectively. Light curing with the Astralis 10 source increased the external temperature of the tooth by 9.1°C (from 31.2°C to 40.3°C) and the temperature within the

TABLE III. Temperature Rise (± SD) Induced by Curing Lights, IR Measurements

Light Source	Irradiation Time (s)	External Temperature Rise (°C)	Internal Temperature Rise (°C)
Astralis 10	20	+ 10.15 (± 2.4)	+ 3.50 (± 0.9)
	40	+ 11.98 (± 2.1)	+ 5.48 (± 1.3)
	60	+ 13.67 (± 2.1)	+ 6.92 (± 2.1)
Swiss Master Light	5	+ 11.39 (± 1.9)	+ 2.85 (± 1.4)
	10	+ 15.35 (± 3.3)	+ 3.53 (± 0.4)
	20	+ 18.48 (± 3.3)	+ 5.66 (± 0.7)
Freelight 2	20	+ 8.08 (± 2)	+ 2.68 (± 0.3)
	40	+ 10.83 (± 1.1)	+ 4.83 (± 0.8)
	60	+ 12.02 (± 0.7)	+ 5.39 (± 0.6)

Mean temperature rise ($n = 6$) recorded after light curing. Within each light source and location linked values are not significantly different (one-way ANOVA and Fisher LSD multiple comparison test, $p < 0.05$)
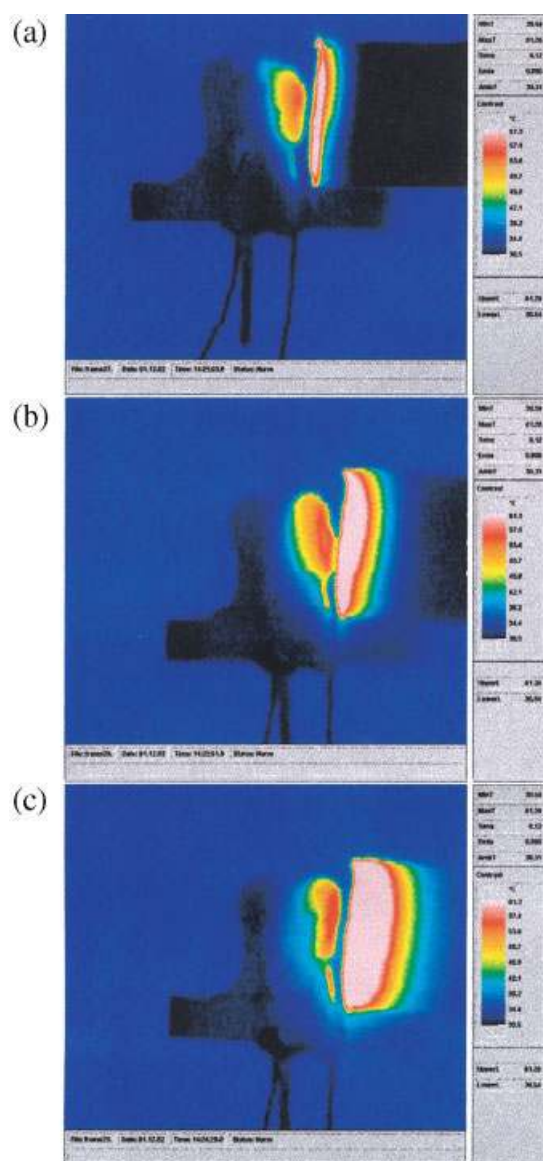
Figure 6. (a) IR image of a tooth exposed to 5 s of Swiss Master light. The temperature outside the tooth (external temp) increased from 31.4°C to 43.9°C. The highest temperature recorded in the composite was 55°C and the temperature at the cavity floor was 45.9°C. The temperature in the pulp chamber was 33.4°C. (b) After 20 s of exposure to the light, the external temperature remained stable (44.4°C) but the temperature of the composite increased to 57.4°C. The temperature at the cavity floor was 47.4°C and pulpal temperature was 34.4°C. (c) With a 20-s exposure to light, the external temperature further increased up to 45.7°C with a peak temperature in the composite of 56.7°C. The temperature at the bottom of the cavity was 46°C and the pulpal temperature was 38.5°C. [Color figure can be viewed in the online issue, which is available at www.interscience. wiley.com.]

pulp by 4.2°C (from 31.2°C to 35.4°C). The highest temperature measured in the composite material was 46.6°C. Under similar exposure durations, light curing with the Freelight 2 source produced much less heat than the QTH curing units, with a 7.2°C rise in external temperature (from 31.2°C to 38.4°C) and a 2.7°C rise in pulpal temperature (from 31.2°C to 33.9°C).
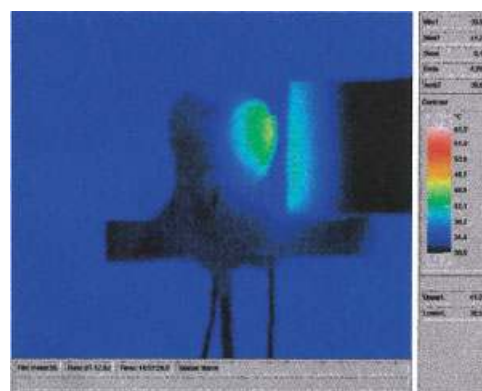

Figure 7. The IR image shows that light curing with Astralis 10 for 20 s increased the external temperature of the tooth by 9.1°C (from 31.2°C to 40.3°C) and the internal temperature by 4.2°C (from 31.2°C to 35.4°C). The highest temperature measured in the composite material was 46.6°C. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

DISCUSSION

The IR camera measurements successfully mapped surface temperatures during light curing and correlated reasonably well with thermocouple measurements. For many years, thermocouples have been used for temperature measurements during cavity preparation using lasers[18, 19] or diamond instruments[20] and during light-curing composite restorative materials.[16,21] In the current study, only the tip of the external thermocouple was exposed to the light to avoid heating of the connectors and metallic wires. To maintain the internal thermocouple in intimate contact with the dentin without using any intermediate agent that might interfere with the conduction of heat, sodium chloride solution, which has a thermal conductivity value similar to dentin, was used as a conducting medium.[15] Because the volume of fluid inside the pulp chamber was small, temperature measurements made inside the
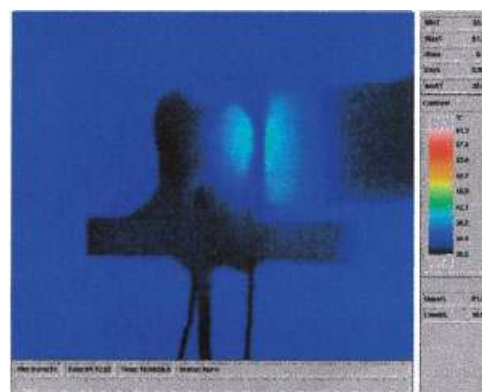

Figure 8. Light curing with Freelight 2 produced much less heat, with a 7.2°C rise in external temperature (from 31.2°C to 38.4°C) and a 2.7°C rise in internal temperature (from 31.2°C to 33.9°C). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

pulp chamber were probably not affected significantly by the pulpal fluid volume.

Infrared thermography detects infrared radiation and isothermal contour lines can be mapped on the surface of a body. For many years, IR thermography has been used successfully for measuring the temperature in materials, tissues, or organs.[22,23,24] Although most heat from the light likely propagates into dental substrates, the dissipation of heat in the ambient air cannot be ruled out. A similar interpretation has been made by Uhl and colleagues (2003) when measuring temperatures in resin composites during light curing.[10] The absence of complete agreement between thermocouple measurements and IR measures after longer periods of exposure to light is not fully understood. However, this result could be explained by the progressive change in temperature and emissivity of the irradiated specimen which affects the energy emitted by the tooth surface and consequently infrared detection.[25]

Infrared images from the current study suggest that thermocouples may underestimate the temperature applied to the tooth much of the time. Therefore, it is likely that a higher temperature is generated and applied to the tooth than assumed by thermocouple measurements used in previous studies. This result is in agreement with previous work on temperature changes during root canal treatment or postspace preparation.[21,26] Infrared images also revealed more detailed information about temperature distribution and temperature changes within the restoration during *in situ* polymerization.

Using IR imaging, the highest temperature rises were recorded inside the composite material and not outside the tooth. This finding can probably be explained by the exothermic polymerization process of the resin material which increased the heat applied internally.[11,12] Although the temperatures recorded inside the composite material remained stable after 5, 10, or 20 s of irradiation with the Swiss Master light, internal temperatures progressively increased with longer exposures to the light [Figure 6(a–c)]. This observation confirms that heat can accumulate inside dental tissues whereas most of the heat applied externally is easily dissipated. An interesting observation made from the IR images is the inhomogenicity of the distribution of heat inside the pulp chamber during light curing. Figure 7 shows an example of the difference in temperature increase at a localized spot of the dentin–pulp interface exhibiting a peak temperature of 36.9°C compared to the mean temperature recorded inside the pulp chamber (35.5°C). Although the biological effects of these localized, short-term temperature increases are not known, they are assumed to be undesirable especially when temperatures exceed 44°C for any length of time. A previous study has shown that moderately increasing temperatures increase pulpal blood flow which in turn compensates for the increases in temperature, but that higher temperatures result in a rapid breakdown of pulpal microcirculation.[27] Other studies have shown that temperature rises do affect cellular metabolism and function, even in the absence of a complete destruction of the cells.[28–31] It can be assumed that the temperature during the polymerization of the composite material should be kept as low as possible to avoid any risk of adverse thermal effects to the dental pulp.[32]

Although most temperature rises measured in the pulp chamber remained below 5.5°C, it must be noted that the conduction of heat across the tooth during light curing will occur until a thermodynamic equilibrium is reached.[33] One simple calculation used to estimate the conduction of heat whenever a temperature difference exists between two solids is given by the Fourier law $Q = (\Delta T) \cdot R^{-1}$, where the thermal resistance $R = Lk^{-1}$ (L is the thickness of the sample and k is the thermal conductivity value of the dentin). Using this formula, it can be extrapolated that, in presence of 1 mm of remaining dentin thickness, the mean temperature increase in the pulp chamber would have been of about +6.6°C, 11.6°C, and 5.2°C after 20s of light exposure to the Astralis 10, Swiss Master Light, and Freelight 2, respectively. Thus, photocuring blue light sources may not be as innocuous as has been assumed by the dental profession.

In summary, the current study indicates that photocuring blue light sources increase temperatures in tooth tissues during *in situ* polymerization of restorative materials. It was clear that the higher power density QTH sources caused greater increases in tooth temperatures than the LED source. Although the exact value of the critical temperature that causes irreversible pulpal damages remains controversial, it can be assumed that excessive temperature rises during photocuring of the composite materials should be avoided. In that sense, the Freelight 2 LED curing unit exhibited the most favorable characteristics.

REFERENCES

1. Stansbury JW. Curing dental resins and composites by photopolymerization. J Esthet Dent 2000;12:300–308.
2. Rueggeberg FA, Ergle JW, Mettenburg DJ. Polymerization depths of contemporary light-curing units using microhardness. J Esthet Dent 2000;12:340–349.
3. Yap AU, Soh MS. Thermal emission by different light-curing units. Oper Dent 2003;28:260–266.
4. Miyazaki M, Hattori T, Ichiishi Y, Kondo M, Onose H, Moore BK. Evaluation of curing lights used in private dental offices. Oper Dent 1998;23:50–54.
5. Whitters CJ, Girkin JM, Carey JJ. Curing of dental composites by use of InGaN light-emitting diodes. Optics Letters 1999;24:67–68.
6. Bennett AW, Watts DC. Performance of two blue light-emitting-diode dental light curing units with distance and irradiation-time. Dent Mater 2004;20:72–79.
7. Nomura Y, Teshima W, Tanaka N, Yoshida Y, Nahara Y, Okazaki M. Thermal analysis of dental resins cured with blue light-emitting diodes (LEDs). J Biomed Mater Res (Appl Biomater) 2002;63:209–213.
8. Uhl A, Siguschb BW, Jandt KD. Second generation LEDs for the polymerization of oral biomaterials. Dent Mater 2004;20:80–87.
9. Shortall AC, Harrington E. Temperature rise during polymerization of light-activated resin composites. J Oral Rehabil 1998;25:908–913.

10. Uhl A, Mills RW, Jandt KD. Polymerization and light-induced heat of dental composites cured with LED and halogen technology. Biomaterials 2003;24:1809–1820.

11. Hofmann N, Hugo B, Klaiber B. Effect of irradiation type (LED or QTH) on photo-activated composite shrinkage strain kinetics, temperature rise, and hardness. Eur J Oral Sci 2002;110:471–479.

12. Knezevic A, Tarle Z, Meniga A, Sutalo J, Pichler G, Ristic M. Degree of conversion and temperature rise during polymerization of composite resin samples with blue diodes. J Oral Rehabil 2001;28:586–591.

13. Zach L, Cohen G. Pulp response to externally applied heat. Oral Surg Oral Med Oral Pathol 1965;19:515–530.

14. Hussey DL, Biagioni PA, Lamey PJ. Thermographic measurement of temperature change during resin composite polymerization in vivo. J Dent 1995;23:267–271.

15. Goodis HE, Pashley DH, Stabholtz A. Pulpal effects of thermal and mechanical irritants. In: Hargreaves KM, Goodis HE, editors. Seltzer and Bender's Dental pulp. Carol Stream, IL: Quintessence Publishing Co.; 2002. p 371–388.

16. Hannig M, Bott B. In-vitro pulp chamber temperature rise during composite resin polymerization with various light-curing sources. Dent Mater 1999;15:275–281.

17. Anic I, Pavelic B, Peric B, Matsumoto K. In vitro pulp chamber temperature rise associated with the argon laser polymerization of composite resins. Lasers Surg Med 1996;19:438–444.

18. Oelgiesser D, Blasbalg J, Ben-Amar A. Cavity preparation by Er-YAG laser on pulpal temperature rise. Am J Dent 2003;16:96–98.

19. Chang JC, Wilder-Smith P. Laser-induced thermal events in empty and pulp-filled dental pulp chambers. Lasers Surg Med 1998;22:46–50.

20. Ottl P, Lauer HC. Temperature response in the pulpal chamber during ultrahigh-speed tooth preparation with diamond burs of different grit. J Prosthet Dent 1998;80:12–19.

21. Loney RW, Price RB. Temperature transmission of high-output light-curing units through dentin. Oper Dent 2001;26:516–520.

22. Lipski M, Wozniak K. In vitro infrared thermographic assessment of root surface temperature rises during thermafil retreatment using system B. J Endod 2003;29:413–415.

23. Benington IC, Biagioni PA, Briggs J, Sheridan S, Lamey PJ. Thermal changes observed at implant sites during internal and external irrigation. Clin Oral Implants Res 2002;13:293–297.

24. Dbrowskia M, Dulski R, Mudab S, Zaborowskib P, Pogorzelski C. The use of thermovision camera to observe physiological and pathological conditions of oral cavity mucous membrane. Infrared Phys Technol 2002;43:265–269.

25. Inagashi T, Katashi K. Errors in infrared thermography. In: Maldague XPV, technical editor, Moore PO, editor. Non destructive testing handbook, 3rd ed. Vol. 3. Infrared and thermal testing CD-ROM. Columbus, OH: American Society for Non Destructive Testing; 2001. p 131–159.

26. Hussey DL, Biagioni PA, McCullagh JJ, Lamey PJ. Thermographic assessment of heat generated on the root surface during post space preparation. Int Endod J 1997;30:187–190.

27. Raab WHM. Temperature related changes in pulpal microcirculation. Proc Finn Dent Soc.1992;81(Suppl 1):469–479.

28. Noda M, Wataha JC, Kaga M, Lockwood PE, Volkmann KR, Sano H. Components of dentinal adhesives modulate heat shock protein 72 expression in heat-stressed THP-1 human monocytes at sublethal concentrations. J Dent Res 2002;81:265–269.

29. Bornman L, Baladi S, Richard MJ, Tyrrell RM, Polla BS. Differential regulation and expression of stress proteins and ferritin in human monocytes. J Cell Physiol 1999;178:1–8.

30. Wataha JC, Lockwood PE, Lewis JB, Rueggeberg FA, Messer RLW. Biological effects of blue light from dental curing units. Dent Mater 2004;20:150–157.

31. Wataha JC, Lewis JB, Lockwood PE, Hsu S, Messer RLW., Rueggeberg FA, Bouillaguet S. Blue light differentially modulates cell survival and growth. J Dent Res 2004;83:104–108.

32. Baldissara P, Catapano S, Scotti R. Clinical and histological evaluation of thermal injury thresholds in human teeth: a preliminary study. J Oral Rehabil 1997;24:791–801.

33. Vavilov VP. Heat transfer (part 1). In: Maldague XPV, technical editor, Moore PO, editor. Non destructive testing handbook, 3rd ed. Vol. 3. Infrared and thermal testing CD-ROM. Columbus, OH: American Society for Non Destructive Testing; 2001. p 791–801.