Effect of pulse-width-modulated LED light on the temperature change of composite in tooth cavities

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ABSTRACT

Objective. The purpose of this study was to investigate the effects of the radiant emittance and cure time of pulse width modulation (PWM)-controlled LED light on the temperature change of composite and dentin.

Methods. Class I cavities (M-D 6 mm, B-L 4 mm, Depth 2.5 mm) were prepared on 30 extracted human molars and vertically sectioned to expose the mesial side of the cavity and tooth. Cavities were filled with Bulk Fill Posterior Restorative (BFP, 3M ESPE) and cured with an LED light. The duty ratio (% of time the light is on) and cure time of the LED light were controlled using an Arduino UNO microcontroller (PWM) as follows (6 groups, n = 5): 10%/100 s, 30%/33.3 s, 50%/20 s, 100%/10 s, Increase mode (0 → 100%)/20 s, and Decrease mode (100 → 0%)/20 s. All measurements were performed at 100 Hz PWM with the constant total radiant exposure. Thermograms of the specimens were recorded using an infrared thermal camera (Vario-Camhr head 700, InfraTec GmbH) for a pre-cure time of 20 s, cure time, and a post-cure time of 100 s at room temperature of 30 ± 0.5 °C. Temperature change data on the composite and dentin surfaces were collected at incremental distances of 0.625 mm and 1 mm from the top of the cavity to the pulp. Data were statistically analyzed using two-way ANOVA and Tukey's *post-hoc* test at α = 0.05.

Results. A rapid temperature increase occurred within the cavity during light curing. The maximum temperature rises (ΔT_{max}) were observed at 0.625 mm apical from the top and middle of the cavity. The ΔT_{max} ranged from 7.62 to 16.74 °C at 0.625 mm apical from the top, 4.83 to 11.39 °C at the floor of the cavity, and 3.16 to 8.09 °C in the dentin 1 mm beneath the cavity base. The ΔT_{max} of composite and dentin increased and the time to reach ΔT = 5 °C decreased with increasing duty ratio at constant radiant exposure. In the Increase mode, ΔT_{max} was lower than that of 50%/20 s mode. The ΔT_{max} in the Decrease mode was similar to that of 100%/10 s mode.

Significance. The PWM-LED curing light system controlled by a microcontroller provided a useful tool of varying the radiant emittance and cure time with constant radiant exposure to evaluate temperature change of composite and dentin. These result will be helpful

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to determine proper curing modes with varying radiant emittance of the LED curing light for decreasing temperature change of composite and dentin. At constant radiant exposure and cure times, the Increase mode showed lower and slower temperature rises than the 50%/20 s and Decrease mode. Within the limitations of this *in vitro* study, when radiant exposure is constant, a curing light with lower radiant emittance can induce relatively low thermal transfer, thereby decreasing the risk of pulpal damage.

1. Introduction

Heat can be produced and transferred within a tooth by various dental instruments and materials during dental treatment. During photo-polymerization of dental composite, heat can be generated from an exothermic chemical reaction within the material and radiance from the curing light [1–3]. Excessive temperature rise during restorative treatment can induce thermal damage to the pulp [4,5]. In a study using monkey teeth, an intrapulpal temperature increase of 5.5 °C led to 15% necrosis of vital pulp [6]. It was later reported, however, that a temperature increase of 11.2 °C in human teeth produced no pulpal damage [7].

In many previous *in vitro* studies, thermistor [8], thermocouple [9–11], differential thermal analysis (DTA) [1,12], and differential scanning calorimetry (DSC) [13] have been used to measure temperature change during light curing of dental composite. Several studies have measured temperature during composite photo-curing using an infrared thermal camera. The camera can measure surface temperatures in a noninvasive way and provide simultaneous two-dimensional thermal distribution images over an extensive area. It was previously reported that composite temperature rise during polymerization in *in vitro* studies using artificial molds was affected by the mode of light application [14,15]. In *in vitro* studies on extracted human teeth, the amount and initial rate of temperature increase were affected by the type and intensity of LED curing light in the composite and at the pulpal side of dentin [16].

Halogen curing lights and LED curing lights with low intensity have been replaced by LED curing lights with high intensity. This raised concern that temperature rise during composite polymerization using high intensity LED curing lights could cause pulpal damage. It was previously reported that composite polymerization using LED curing light generated lower temperature rise compared to halogen curing lights [14]; but this was likely due to the low intensity LED curing lights used at the time in comparison to those currently available. Most researchers have been using commercial curing lights from various companies having varying light intensity and cure times. Therefore, it is not possible to directly compare the results across the studies. To investigate the effect of the light curing mode on the pattern of temperature rise within a composite and tooth, an identical light source with precisely controlled radiant emittance and cure time should be used.

Pulse width modulation (PWM) is a technique used for controlling an analog circuit through the digital output of a microcontroller [17]. Digital signals express analog signals by turning on and off within a set period. Radiant emittance can be controlled by changing the duty ratio, the ratio of on-time to off-time within a single cycle. PWM has the advantage of reducing system noise, cost, and power loss and can be applied to visual and tactile sensing, motion control systems, spectrum imaging systems, and LED intensity control [18,19].

To date, there have been few studies on the effects of radiant emittance and cure time of PWM-controlled LED light on composite temperature change during photo-curing. In an *in vitro* study using PWM technology, PWM lowered the maximum temperature while maintaining the polymerization efficiency of a high-power LED curing light [20]. However, this study only used one optimum PWM mode.

In this study, we developed a custom-made PWM-controlled LED curing light using an Arduino UNO microcontroller. The objective of the study was to investigate the effects of the radiant emittance and cure time of the PWM-LED light on the temperature change of composite and dentin in class I cavities in extracted human molars. We hypothesized that increasing the radiant emittance with constant radiant exposure will result in greater and faster temperature rise of the composite and dentin.

2. Materials and methods

2.1. Composite used in this study

A nano-hybrid composite, Filtek™ Bulk Fill Posterior Composite (BFP, 3M ESPE, St. Paul, MN, USA), with a manufacturer's stated depth of cure of up to 5 mm was used in this study (Table 1).

Table 1 – Composite used in this study.	
Composite (code, shade, lot no.)	Composition
Filtek™ Bulk Fill Posterior Restorative (BFP, A2, N710161)	AUDMA, AFM, DDDMA, UDMA, 20 nm silica filler, 4–11 nm zirconia filler, agglomerated 100 nm ytterbium trifluoride filler (76.5 wt%/58.4 vol%)
Abbreviations: AUDMA, aromatic urethane dimethacrylate; AFM, addition-fragmentation monomer; DDDMA, 1, 12-dodecanediol dimethacrylate; UDMA, urethane dimethacrylate.	

Table 2 – Six experimental groups at constant radiant exposure with varying duty ratio (%), cure time (s), and radiant emittance (mW/cm^2) of the pulse width modulated (f = 100 Hz, period = 10 ms) LED curing light.

Duty ratio (%)	Cure time (s)	Radiant emittance (mW/cm^2)
10	100	112.8
30	33.3	338.4
50	20	564.0
100	10	1128.0
0 → 100 (Increase)	20	0 → 1128
100 → 0 (Decrease)	20	1128 → 0

2.2. Preparation of the PWM-controlled LED curing light

An open-source microcontroller, Arduino UNO (Arduino, Torino, Italy), was used to fabricate the PWM-controlled LED curing light. The digital output of the Arduino UNO turned the NPN transistor on and off (Period = 10 ms) to control the current supplied to the LED (B & Lite, B & L Biotech, Ansan, Korea). This resulted in a frequency of 100 Hz to change the duty ratio and cure time of the curing light (PWM). A signal to select duty ratio and cure time was transferred to the Arduino UNO using a smartphone application and Bluetooth wireless technology. Light curing was initiated using the smartphone (Fig. 1a). The LED probe was composed of a LED emitter (LZ4, LED Engin, Inc., San Jose, CA USA, mean wavelength: 460 nm, maximum current: 1200 mA) and a focusing lens without an optical fiber. The details of the various duty ratios, cure times, and radiant emittances are shown in Table 2. The power of the curing light was measured in contact with a power detector (UP55N-300F-H12, Gentec-EO, Quebec, Canada) and then divided by the cross-sectional area of the curing light tip (diameter = 10 mm) to provide the radiant emittance. The LED light output signals with varying duty ratios were confirmed using a digital oscilloscope (TDS 220, Tektronix, Inc., Wilsonville, OR, USA) (Figs. 1b and 2).
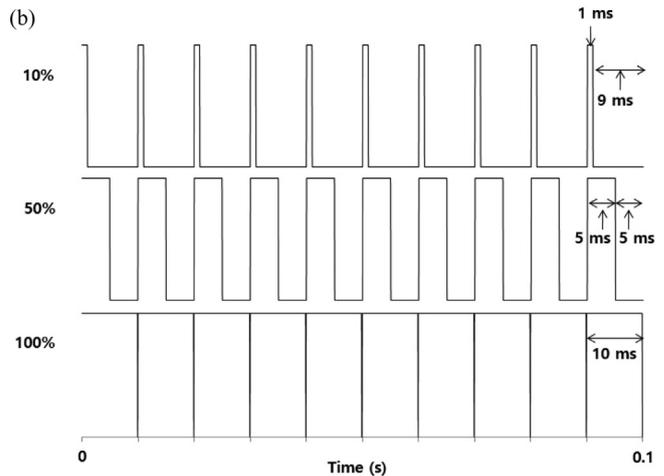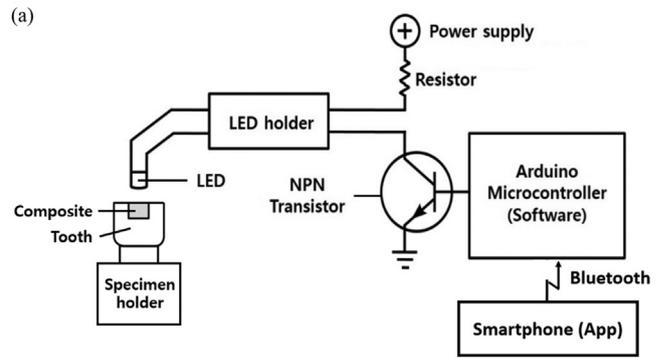

Fig. 1 – (a) Schematic diagram of a custom-made pulse width modulated (PWM)-LED curing system and (b) PWM signals with different duty ratios (10, 50, and 100%) at a frequency of 100 Hz (period = 10 ms).
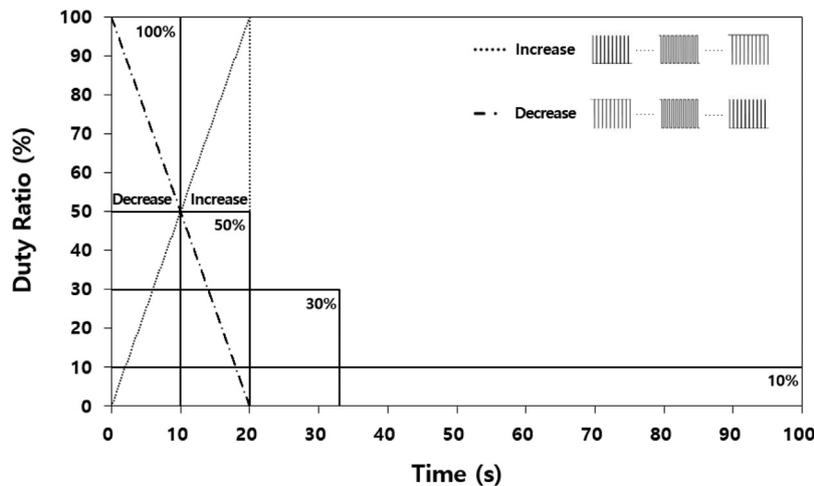

Fig. 2 – Diagram of changing duty ratio (%) and cure time (s) with constant total radiant exposure (product of duty ratio and cure time).
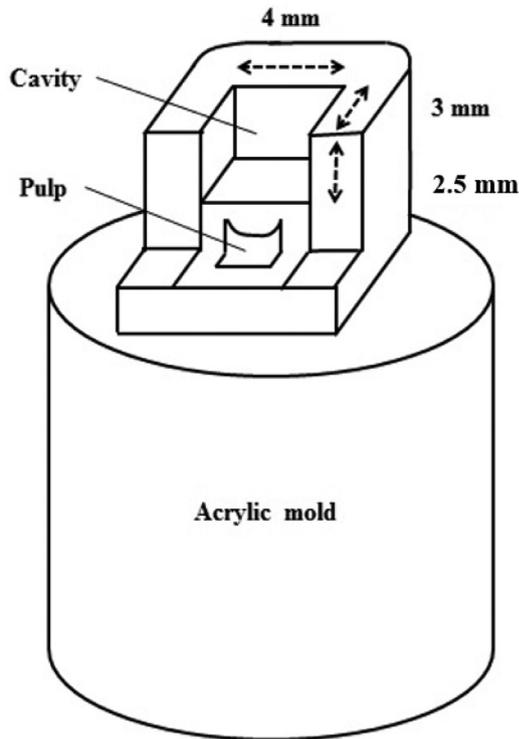
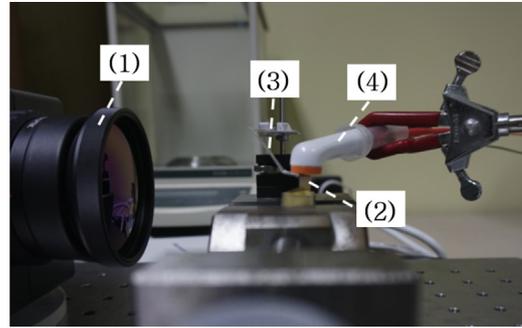Fig. 3 – Schematic diagram of the prepared tooth cavity.

Fig. 4 – Experimental set-up for temperature measurement with a thermal imaging camera. (1) Thermal imaging camera, (2) prepared tooth specimen, (3) radiation shield, and (4) curing light.

cover the bucco-lingual length of the tooth was positioned in contact with the mesial line angle of the cavity (Fig. 4). The infrared imaging camera was equipped with a microbolometer focal plane array detector with a high spatial resolution display (640 × 480 pixel, pixel size 0.25 mm), a spectral range of 7.5–14 μm, and a high resolution of 0.03 °C at 30 °C.

2.3.3. Measurement of temperature changes with varying radiant emittance and cure time of the LED light

After applying Single Bond Universal adhesive (3M ESPE, St. Paul, MN, USA) to the prepared cavity with a rubbing motion (20 s) and photo-curing with the LED curing light (1128 mW/cm^2, 10 s), the specimen was placed in front of the thermal camera.

To investigate the effect of the PWM-LED light on temperature change of the composite and dentin, the duty ratio and

2.3. Temperature measurements during composite photo-curing using thermal image analysis

2.3.1. Preparation of tooth specimens

Thirty extracted, caries-free human molars stored in 0.5% Chloramine-T solution were used for the study. After flattening the occlusal surface of each tooth to standardize the cavity preparation, Class I cavities (mesio-distal 6 mm, bucco-lingual 4 mm, and occluso-gingival 2.5 mm) were prepared using a high-speed handpiece and flat-end cylindrical diamond bur (TF13, Mani, Utsunomiya, Japan). Each tooth was sectioned bucco-lingually along the long axis at the center of the cavity to expose the mesial side of the cavity and tooth and cut horizontally at 3 mm below the CEJ at the mesial aspect (Fig. 3). The prepared specimens were embedded using dental stone in plastic cylinders (15 mm in diameter and 30 mm in height) at 5 mm below the CEJ and stored at 100% relative humidity. Photographs of the sectioned surfaces of all specimens were produced with a digital camera to clarify the cavity outlines of the thermal images.

2.3.2. Thermal imaging apparatus

At a temperature of 30 ± 0.5 °C with 40% relative humidity, an infrared thermal camera (VarioCamhr head 700, InfraTec GmbH, Dresden, Germany) was placed on an optical plate, and each tooth specimen was fixed 8 cm from the lens with the sectioned surface facing the camera. The object emissivity was set at 1.0, the default value for the program. The tip of the curing unit was positioned 1 mm above the occlusal surface of the cavity. To prevent direct light exposure on the mesial surface of the specimen, an opaque paper large enough to
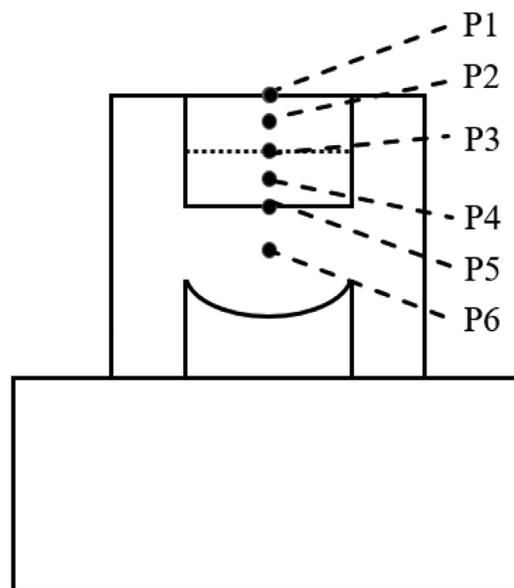

Fig. 5 – Regions-of-interest (ROIs): P1, top center of the cavity; P2, 0.625 mm apical from P1; P3, middle center of the cavity (1.25 mm apical from P1); P4, 0.625 mm coronal from the cavity base; P5, center of the cavity floor; P6, 1 mm apical from P5.
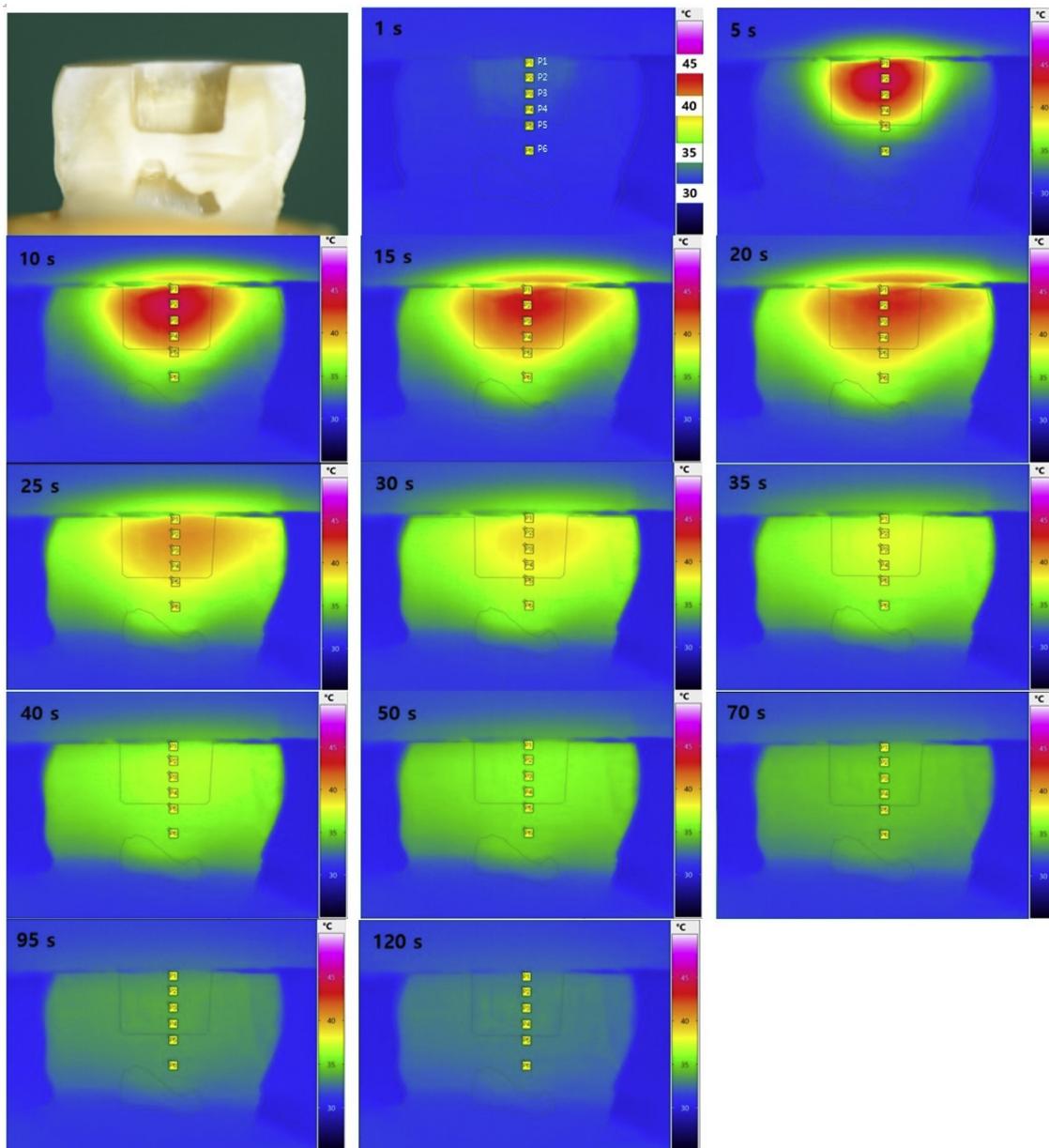
Fig. 6 – Series of representative infrared thermograms of a tooth specimen from the 50%/20 s group at 1, 5, 10, 15, 20, 25, 30, 35, 40, 50, 70, 95 and 120 s after initiating light curing. The outline of the tooth and prepared cavity are superimposed on the thermal images.

cure time of the LED light were changed by the Arduino UNO as follows: 10%/100 s, 30%/33.3 s, 50%/20 s, 100%/10 s, Increase mode (0 → 100%)/20 s, and Decrease mode (100 → 0%)/20 s (Table 2). All measurements were performed at 100 Hz (period of one cycle = 10 ms) while maintaining the total energy (radiant exposure) of the curing light at a constant (Figs. 1b and 2).

Each cavity was bulk filled with BFP by sculpting flat to the open mesial cavity surface and cured using the different duty ratios and cure time settings for each experimental group (n = 5 per group). Thermal images for baseline data was recorded for 20 s, after which the curing light was turned on automatically for each exposure time. The images were continuously

recorded throughout the cure time, and for 100 s after curing. The recordings were performed at a rate of 2 frames/s using the IRBIS-3 professional analysis program (InfraTec, GmbH).

The images were analyzed in the range of 25.0–50.0 °C. Six regions of interest (ROIs) were labeled P1–P6: P1, top center of the cavity; P2, 0.625 mm apical from P1; P3, center of the cavity (1.25 mm apical from P1); P4, 0.625 mm coronal from the cavity base; P5, center of the cavity floor; P6, 1 mm apical from P5 (Fig. 5). The temperature changes at each ROI were measured over time. The maximum temperature rise (ΔT_{max})(°C), and time (s) to reach $\Delta T = 5$ °C were obtained at the ROIs for each group.
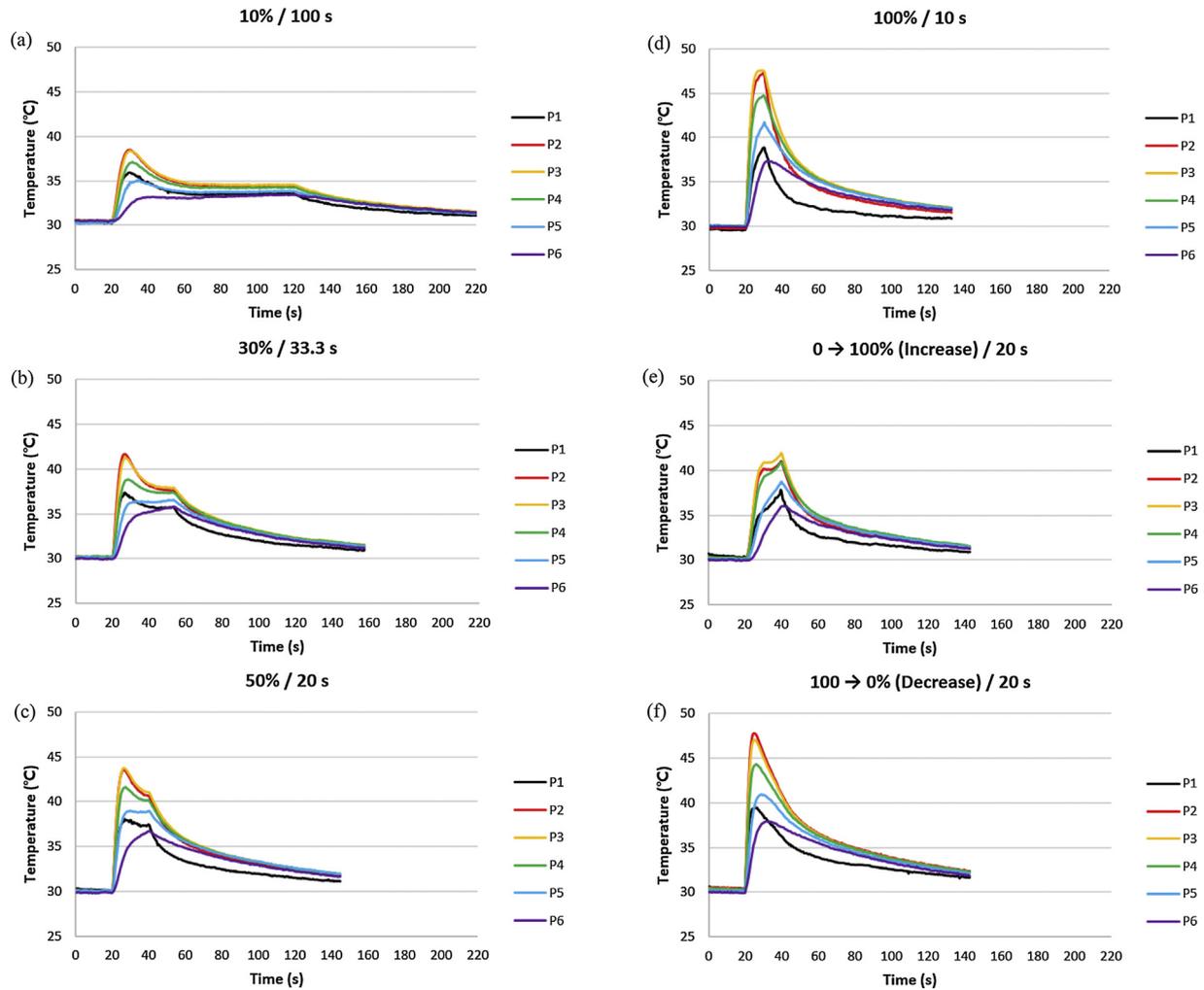
Fig. 7 – Representative curves of temperature change (°C) *vs.* time (s) during photo-curing of BFP composite with varying duty ratios/cure times. (a) 10%/100 s, (b) 30%/33.3 s, (c) 50%/20 s, (d) 100%/10 s, (e) 0 → 100% (Increase)/20 s, and (f) 100 → 0% (Decrease)/20 s group.

2.4. Statistical analysis

Data were analyzed using two-way ANOVA followed by a Tukey's *post hoc* test ($\alpha = 0.05$) to evaluate the statistical significance of ΔT_{max}, and time to reach $\Delta T = 5\,°C$ according to the various curing conditions and ROIs. The analyses were conducted using SPSS software (version 23.0, SPSS Inc., Chicago, IL, USA).

3. Results

Representative infrared thermograms (50%/20 s) are shown in Fig. 6. Rapid localized temperature rises reaching 45 °C were observed at P2 and P3 within the composite 5 s after initiating the light exposure. At 10 s, the regions displaying high temperatures (visualized in pink and red in the thermograms) extended throughout the cavity, subsequently broadening to the outer regions of the lateral walls and reaching approximately 40 °C at the end of the light exposure. Temperatures at

regions below the cavity floor and inside the pulp chamber did not rise above 40 °C and 35 °C, respectively.

After the light exposure ended, a rapid temperature decrease occurred inside the cavity, while a gradual temperature decrease took place on the cavity's outer side. Representative temperature change curves at all ROIs for each group are shown in Fig. 7. The maximum temperature rises, ΔT_{max}, are listed in Table 3. Times (s) to reach $\Delta T = 5\,°C$ at each ROI are summarized in Table 4. ΔT_{max} and time to reach $\Delta T = 5\,°C$ showed an interaction between the duty ratio and ROIs ($p < 0.05$).

Thermal analysis was conducted between ROIs according to duty ratio change. The largest ΔT_{max} were shown at P2 and P3, and the smallest was shown at P6. There were no significant differences in ΔT_{max} at P2 and P3 for the same group ($p > 0.05$). The ΔT_{max} at P2 ranged between 7.62–16.74 °C for all groups. The ΔT_{max} at P5, 4.83–11.39 °C, was significantly higher than ΔT_{max} at P6, 3.16–8.09 °C ($p < 0.05$). The time to reach $\Delta T = 5\,°C$, indicating the initial rate of temperature rise, was relatively short at P2 and P3 and longest at P6 (Tables 3 and 4, Fig. 8).

Table 3 – Mean maximum temperature rises, ΔT_{max} (°C), measured during composite curing.

Group (duty ratio/time)	ROI						Mean
	P1	P2	P3	P4	P5	P6	
10%/100 s	4.91 (0.6)	7.62 (0.6)	7.50 (0.7)	6.36 (0.9)	4.83 (0.7)	3.16 (0.3)	5.73[e]
30%/33.3 s	7.01 (0.4)	11.44 (0.6)	11.14 (0.3)	8.99 (0.3)	6.94 (0.3)	6.00 (0.1)	8.59[d]
50%/20 s	7.78 (0.7)	14.46 (0.6)	14.24 (0.6)	11.61 (0.2)	9.23 (0.4)	7.03 (0.5)	10.72[b]
100%/10 s	9.72 (0.4)	16.44 (0.8)	17.23 (0.4)	14.57 (0.5)	11.39 (0.4)	7.48 (0.3)	12.81[a]
Increase/20 s	8.38 (0.6)	11.79 (0.7)	12.25 (0.6)	11.14 (0.5)	9.16 (0.4)	6.87 (0.7)	9.93[c]
Decrease/20 s	9.54 (0.7)	16.74 (0.6)	16.64 (0.5)	14.43 (0.5)	10.81 (0.8)	8.09 (0.9)	12.71[a]
Mean	7.89[D]	13.08[A]	13.17[A]	11.18[B]	8.73[C]	6.44[E]	

Different superscript lower-case letters indicate a statistically significant difference among groups (within the column, p < 0.05).
Different superscript upper-case letters indicate a statistically significant difference among ROIs (within the row, p < 0.05).

Table 4 – Times (s) to reach $\Delta T = 5$ °C during composite curing.

Group (duty ratio/time)	ROI						Mean
	P1	P2	P3	P4	P5	P6	
10%/100 s	–	4.66 (0.9)	4.58 (0.8)	5.78 (0.7)	–	–	
30%/33.3 s	3.20 (0.5)	1.94 (0.1)	2.28 (0.1)	2.98 (0.2)	6.08 (1.3)	14.66 (1.7)	5.19[c]
50%/20 s	4.36 (0.8)	1.38 (0.1)	1.60 (0.1)	2.08 (0.2)	3.56 (0.3)	9.48 (1.4)	3.74[b]
100%/10 s	2.48 (0.5)	1.08 (0.2)	1.06 (0.2)	1.40 (0.2)	2.52 (0.3)	6.00 (0.6)	2.42[a]
Increase/20 s	5.68 (1.1)	3.72 (0.3)	3.80 (0.4)	4.60 (0.3)	7.38 (0.7)	14.15 (1.0)	6.55[d]
Decrease/20 s	1.62 (0.3)	1.20 (0.2)	1.22 (0.2)	1.48 (0.3)	2.54 (0.2)	5.72 (1.2)	2.30[a]
Mean	3.47[C]	1.86[A]	1.99[AB]	2.51[B]	4.42[D]	10.00[E]	

Different superscript lower-case letters indicate a statistically significant difference among groups (within the column, p < 0.05).
Different superscript upper-case letters indicate a statistically significant difference among ROIs (within the row, p < 0.05).
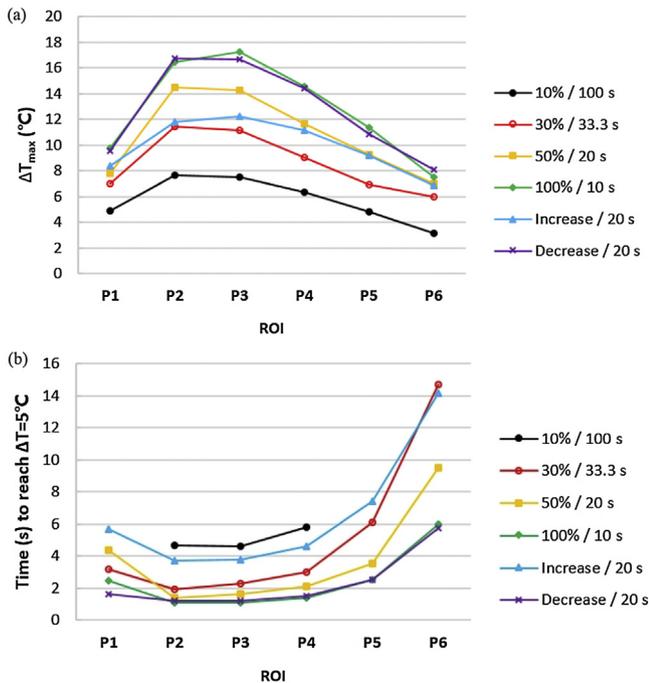

Fig. 8 – (a) Mean maximum temperature rises, ΔT_{max} (°C) and (b) Times (s) to reach $\Delta T = 5$ °C of the specimens at different regions-of-interest (ROIs) with varying duty ratio (%)/cure time (s).

When comparing 10%, 30%, 50%, and 100% duty ratio groups, as the LED light duty ratio increased under constant radiant exposure, ΔT_{max} within the composite and dentin increased, and the time to reach $\Delta T = 5$ °C decreased (Tables 3 and 4, Figs. 8 and 9). The smallest ΔT_{max} was shown in 10% duty ratio group, and the largest was shown in 100% duty ratio group. Except 10% duty ratio group, the time to reach $\Delta T = 5$ °C was shortest in 100% duty ratio group and longest in 30% duty ratio group.

The ΔT_{max} in the Increase mode group ranged between 6.87–12.25 (mean 9.93) °C at all ROIs (Table 3). It was the value between those of 30% and 50% duty ratio groups. Time to reach $\Delta T = 5$ °C in the Increase mode group ranged between 3.72–14.15 (mean 6.55)s at all ROIs (Table 4). It was longer than that of 30% duty ratio group.

The Decrease mode group (100 → 0%) showed a similar temperature change pattern to the 100% duty ratio group for all ROIs. The ΔT_{max} in the Decrease mode group ranged between 8.09–16.74 (mean 12.71) °C for all ROIs, similar to that of 100% duty ratio group (Table 3). The time to reach $\Delta T = 5$ °C of the Decrease mode group ranged between 1.20–5.72 (mean 2.30)s for all ROIs, comparable to that of 100% duty ratio group (Table 4).

To investigate the relationship between radiant emittance and ΔT_{max}, the duty ratio and ΔT_{max} were graphed for varying duty ratios (10, 30, 50, and 100%) (Fig. 9a). To investigate the relationship between radiant emittance and initial rate of temperature rise, the duty ratio and time to reach $\Delta T = 5$ °C were also plotted for varying duty ratios (10, 30, 50, and 100%) (Fig. 9b).
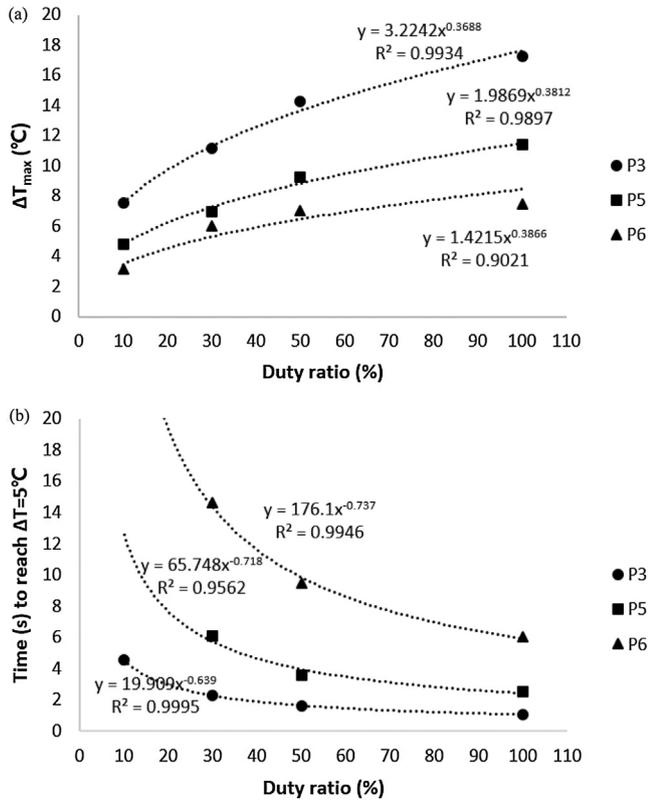
Fig. 9 – (a) Mean maximum temperature rises, ΔT_{max} (°C) and (b) Times (s) to reach $\Delta T = 5\,°C$ of the specimens with varying curing light duty ratio (%) at different ROIs of P3, P5, and P6.

4. Discussion

In the present study, an infrared thermal camera was used to analyze the effects of duty ratio (radiant emittance) and cure time on temperature changes throughout a class I cavity and at the pulpal side of the dentin. The infrared thermal camera enabled real time visualization of the heat flow and temperature distribution in a composite restoration within an extracted tooth. In most previous studies, to modify curing mode, soft start cure or pulse delayed cure technique were used in which the radiant modulation was done in the order of a few seconds with ready-made commercial curing lights. We developed a custom-made PWM-controlled LED curing light using an Arduino UNO microcontroller. This allowed the duty ratio (radiant emittance) and cure time to be precisely controlled at constant radiant exposure, overcoming the limitations of previous studies that used different commercial light curing units. Thus, this is a useful method of varying the radiant emittance and cure time with constant radiant exposure to study temperature change of composite and dentin.

During the photo-curing process, temperature increased over all of the tooth sections and composite surfaces. It took more than 100 s for the transferred heat to dissipate. In the thermal image analysis, higher ΔT_{max} were exhibited at P2 and P3 compared to P1 in all groups. The closer the measurement was to the pulp, the lower was the ΔT_{max} observed. These results can be explained by the thermodynamic poly-

merization kinetics of the composite and heat absorption and radiation by restorative material and tooth structure. The temperature rise in the light-cured composite results from both the exothermic polymerization reaction of the material and the radiant heat from the curing light [1,2,21,22]. The light is scattered by the filler and is diminished as it passes through the composite [23,24]. As the thickness of composite increased with cavity depth, the transmitting light intensity decreased, resulted in decreasing the degree of conversion (DC) and surface hardness at the bottom of the cavity. The intensity of light decreases exponentially by the equation $I_x = I_0 \times e^{-\alpha x}$ (α: attenuation coefficient) when passing through a material with a thickness of x [29]. This attenuation effect could influence the polymerization and ΔT_{max} at different ROIs. Thus, the heat generated by the exothermic polymerization of composite is reduced in deeper areas of the tooth cavity. The radiant heat is reduced by its transmission through the thick composite layer, although a higher ΔT_{max} was exhibited at P2 compared to P1. This is because, while the highest irradiance can be obtained at P1, the radiant heat loss from P1 through the occlusal and lateral surface is higher compared to the loss at P2 through the lateral surface. This is related to the lateral surface exposure of the composite cavity to the thermal camera. Studies that used thermocouples, however, reported that the top of the cavity showed the greatest ΔT_{max} among ROIs [16,25], the highest irradiance was obtained at the occlusal surface, and heat loss from the surface was relatively small due to the confined lateral wall.

In this study, ΔT_{max} at P6 was the lowest and ranged between 3.16–8.09 °C. This may be due to the insulation of dentin between the composite and pulp. It was previously reported that 5.5 °C was the critical threshold of intra-pulpal temperature increase, where irreversible pulp damage could occur [6,26]. If a tooth cavity boundary is located within 1 mm of the pulp chamber, the pulp could be damaged by a temperature rise greater than 5.5 °C during composite polymerization. The microcirculation of pulpal blood flow was stimulated as the intrapulpal temperature rose above 42 °C in vital teeth, leading to heat dissipation that prevents excessive temperature rises in the pulp [4,27]. Therefore, to apply the results from the thermal image analysis to the clinical situation, a careful approach is needed when evaluating the intrapulpal temperature rise and the possibility of pulpal damage in human teeth.

Significant differences were found in ΔT_{max} when varying the LED light duty ratio (10, 30, 50, and 100%) at ROIs between groups ($p < 0.05$). Increasing the radiant emittance at constant radiant exposure caused the ΔT_{max} of the composite and dentin to increase and the time to reach $\Delta T = 5\,°C$ to decrease. The main cause for the temperature rise of the composite and nearby dentin were the polymerization exotherm of the composite and the radiant heat from the light curing unit. However, the heat dissipated from the cavity surface should also be considered. To investigate the relationship between light intensity, polymerization heat, and radiance heat, the theoretical photo-polymerization rate (R_p) due to radical chain polymerization can be expressed using the following equation [28].

$$R_p = k_p\,[M]\,(\Phi I_a/k_t)^{1/2}$$

R_p: rate of polymerization

k_p: rate constant for propagation

[M]: monomer concentration

Φ: quantum yield for initiation

= number of propagating chains initiated per light photon absorbed

$[I_a]$: intensity of absorbed light

k_t: rate constant for termination.

In the above equation, the polymerization rate (∝ polymerization heat) is proportional to the square root of the intensity of absorbed light. Radiant heat from the curing light is also proportional to the intensity of absorbed light. Therefore, as the radiant emittance increased and cure time decreased at constant radiant exposure, both polymerization heat and radiant heat increased. In comparison, the amount of heat released from the surface during the short photo-curing time was relatively small, and the increase in radiant emittance induced a higher ΔT_{max}. As the radiant emittance decreased and cure time increased, polymerization heat and radiant heat decreased. This left enough time for heat release to occur via conduction and radiation. Thus, radiant emittance decrease lowers ΔT_{max}. Using the above equation, as the radiant emittance increased, the time to reach $\Delta T = 5\,°C$, the parameter that indicates the initial rate of temperature rise, decreased.

To investigate the relationship between radiant emittance and temperature change pattern, duty ratio vs. ΔT_{max} and duty ratio vs. time to reach $\Delta T = 5\,°C$ were plotted for varying ROIs (P3, P5, P6) (Fig. 9). Theoretically, the polymerization rate increase is a power function of the square root of light intensity (∝ duty ratio). However, in Fig. 9a, the order of the ΔT_{max} curve was slightly lower than the theoretical order of 0.5 due to heat dissipation. Because time to reach $\Delta T = 5\,°C$ during composite curing and initial polymerization rate are inversely proportional, the results shown in Fig. 9b are reasonable.

The lower ΔT_{max} in lower duty ratio group is not due to low conversion, but because of slow polymerization. According to our previous study [29], Vickers hardness (HV) is positively correlated with the DC. In addition, Bulk Fill Posterior showed no significant difference in HV values with varying duty ratio and cure time, which is due to the constant total light energy (radiant exposure) for all irradiation modes. In present study, we used the same PWM modes (duty ratio and cure time) and LED light as the previous study. So, we can deduce that the final DC would be same for all groups and not have affected the difference of ΔT_{max}. Instead, the rate of polymerization only influenced the difference.

The ΔT_{max} and time to reach $\Delta T = 5\,°C$ showed an interaction between the duty ratio and ROIs (p < 0.05). This may be caused by that the transmitted light intensity was affected by the ROIs.

The Increase mode and Decrease mode groups were established to investigate the effects of continuous radiant emittance changes on the temperature change of the composite. These groups experienced a constant increase or decrease rate (5%/s) when the duty ratio continuously increased from 0 to 100% or decreased from 100 to 0% (mean duty ratio: 50% and cure time: 20 s), respectively.

Regarding the temperature rise in composite and dentin, initial radiant emittance is important factor. The mean duty ratio (radiant emittance) of Increase mode was the same as that of 50% duty ratio group, but the initial radiant emittance in the Increase mode was lower than that of 50% duty ratio group. Therefore, the Increase mode showed lower ΔT_{max} compared to 50% duty ratio group. Time to reach $\Delta T = 5\,°C$ in the Increase mode (6.55 s) was slightly longer than that (5.19 s) of 30% duty ratio group. Until 6.55 s, the mean duty ratio (16.4%) of the Increase mode was lower than that of 30% duty ratio group.

The Decrease mode showed no statistically significant differences in ΔT_{max} and time to reach $\Delta T = 5\,°C$ compared to the 100% duty ratio group. This may be due to their similar initial radiant emittances. The initial fast polymerization rate of the composite during the both of these photo-curing processes, leads to a rapid evolution and build up of temperature.

When comparing three methods at the same cure time (20 s) at P6, the Increase mode showed a lower ΔT_{max} than the Decrease mode group, but a value similar to that of the 50% duty ratio group. When the radiant emittance was doubled and the cure time reduced by half, ΔT_{max} at P1–P5 significantly increased. When the radiant emittance was reduced by half and the cure time doubled, the ΔT_{max} at all ROIs significantly decreased. A small duty ratio was effective in decreasing the temperature rise in dentin, but has limitations in clinical situations in that it requires a longer cure time. It could be a useful method, however, in cases where residual amounts of the remaining tooth are small, and there is a possibility of heat causing pulpal damage due to the close proximity of the heat source to the pulp.

Using a custom-made PWM-controlled LED curing light that precisely controlled duty ratio and cure time, there were differences in temperature change in the composite and dentin, despite the fact that the overall radiant exposure was equivalent. Therefore, increase in radiant emittance of an LED curing light at constant radiant exposure caused a higher ΔT_{max} and a faster initial temperature rise in composites and at the pulpal side of the remaining dentin at the cavity floor. Therefore, the hypothesis is accepted.

In future studies, it would be interesting to investigate the effect of radiant emittance on temperature rise vs. time in vivo using precisely controlled PWM-LED curing light. As we mentioned earlier, in vital teeth, microcirculation of pulpal blood flow facilitates to heat dissipation to reduce risk of thermal damage of pulp. Further studies simulating blood flow in vital teeth are needed.

5. Conclusion

The PWM-LED curing light system controlled by a microcontroller provided a useful tool of varying the radiant emittance and cure time with constant radiant exposure to evaluate temperature change of composite and dentin. These results will be helpful to determine proper curing modes with varying radiant emittance of the LED curing light for decreasing temperature change of composite and dentin.

At constant radiant exposure and cure times, the Increase mode showed lower and slower temperature rises than the

50%/20 s and Decrease mode. Within the limitations of this *in vitro* study, when radiant exposure is constant, a curing light with lower radiant emittance can induce relatively low thermal transfer, thereby decreasing the risk of pulpal damage.

Acknowledgments

REFERENCES

[1] McCabe JF. Cure performance of light-activated composites by differential thermal analysis (DTA). Dent Mater 1985;1:231–4.

[2] Lloyd CH, Joshi A, McGlynn E. Temperature rises produced by light sources and composites during curing. Dent Mater 1986;2:170–4.

[3] Masutani S, Setcos JC, Schnell RJ, Phillips RW. Temperature rise during polymerization of visible light-activated composite resins. Dent Mater 1988;4:174–8.

[4] Hannig M, Bott B. In-vitro pulp chamber temperature rise during composite resin polymerization with various light-curing sources. Dent Mater 1999;15:275–81.

[5] Jakubinek MB, O'Neill C, Felix C, Price RB, White MA. Temperature excursions at the pulp–dentin junction during the curing of light-activated dental restorations. Dent Mater 2008;24:1468–76.

[6] Zach L, Cohen G. Pulp response to externally applied heat. Oral Surg Oral Med Oral Pathol 1965;19:515–30.

[7] 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.

[8] Stewardson DA, Shortall AC, Harrington E, Lumley PJ. Thermal changes and cure depths associated with a high intensity light activation unit. J Dent 2004;32:643–51.

[9] Emami N, Söderholm K-JM, Berglund LA. Effect of light power density variations on bulk curing properties of dental composites. J Dent 2003;31:189–96.

[10] Kleverlaan CJ, De Gee AJ. Curing efficiency and heat generation of various resin composites cured with high-intensity halogen lights. Eur J Oral Sci 2004;112:84–8.

[11] Asmussen E, Peutzfeldt A. Temperature rise induced by some light emitting diode and quartz-tungsten-halogen curing units. Eur J Oral Sci 2005;113:96–8.

[12] Vaidyanathan J, Vaidyanathan T, Wang Y, Viswanadhan T. Thermoanalytical characterization of visible light cure dental composites. J Oral Rehabil 1992;19:49–64.

[13] Vaidyanathan J, Vaidyanathan TK. Computer-controlled differential scanning calorimetry of dental composites. IEEE Trans Biomed Eng 1991;38:319–25.

[14] Uhl A, Mills RW, Jandt KD. Polymerization and light-induced heat of dental composites cured with LED and halogen technology. Biomaterials 2003;24:1809–20.

[15] Al-Qudah AA, Mitchell CA, Biagioni PA, Hussey DL. Effect of composite shade, increment thickness and curing light on temperature rise during photocuring. J Dent 2007;35:238–45.

[16] Kim MJ, Kim RJ, Ferracane J, Lee IB. Thermographic analysis of the effect of composite type, layering method, and curing light on the temperature rise of photo-cured composites in tooth cavities. Dent Mater 2017;33:e373–83.

[17] Barr M. Introduction to pulse width modulation. http://www.embedded.com/electronics-blogs/beginner-s-corner/4023833/Introduction-to-Pulse-Width-Modulation. [Accessed 24 January 2019].

[18] Rusak DA, Kawka EA, Trexler EB. Note: investigation of a null measurement of optical absorbance using a pulse width modulated light-emitting diode. Rev Sci Instrum 2010;81:016107.

[19] Teikari P, Najjar RP, Malkki H, Knoblauch K, Dumortier D, Gronfier C, et al. An inexpensive Arduino-based LED stimulator system for vision research. J Neurosci Methods 2012;211:227–36.

[20] Huang T-K, Hung C-C, Tsai C-C. Reducing, by pulse width modulation, the curing temperature of a prototype high-power LED light curing unit. Dent Mater J 2006;25:309–15.

[21] Smail SR, Patterson CJ, McLundie AC, Strang R. In vitro temperature rises during visible-light curing of a lining material and a posterior composite. J Oral Rehabil 1988;15:361–6.

[22] Hansen EK, Asmussen E. Correlation between depth of cure and temperature rise of a light-activated resin. Scand J Dent Res 1993;101:176–9.

[23] Al-Qudah AA, Mitchell CA, Biagioni PA, Hussey DL. Thermographic investigation of contemporary resin-containing dental materials. J Dent 2005;33:593–602.

[24] Arikawa H, Fujii K, Kanie T, Inoue K. Light transmittance characteristics of light-cured composite resins. Dent Mater 1998;14:405–11.

[25] Kim RJ, Son SA, Hwang JY, Lee IB, Seo DG. Comparison of photopolymerization temperature increases in internal and external positions of composite and tooth cavities in real time: incremental fillings of microhybrid composite vs. bulk filling of bulk fill composite. J Dent 2015;43:1093–8.

[26] Pohto M, Scheinin A. Microscopic observation on living dental pulp. Acta Odontol Scand 1958;16:303–27.

[27] Raab W. Temperature related changes in pulpal microcirculation. Proc Finn Dent Soc 1992;88:469–79.

[28] Odian G. Principles of polymerization. 4th ed. New York: John Wiley & Sons, Inc.; 2004.

[29] Lee CH, Ferracane J, Lee IB. Effect of pulse width modulation-controlled LED light on the polymerization of dental composites. Dent Mater 2018;34:1836–45.