Effect of light curing with and without an external cooling system on composite temperature rise in resin composite

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KEYWORDS
Composite Resins; Curing Lights, Dental; Temperature.

ABSTRACT
Objectives: This study aimed to assess the effect of light curing with/without an external cooling system on composite temperature.
Materials and Methods: In this in vitro, experimental study, A3 shade of Luna composite resin was applied into 40 molds which were randomly assigned to two groups (n=20). In the control group, composite specimens were cured with a quartz-tungsten-halogen (QTH) curing unit for 40 seconds without an external cooling system; while, the specimens in the test group were cured with the same curing unit attached to an external cooling system for 40 seconds. Temperature change in composite specimens after 20 and 40 seconds of light curing was recorded by a thermometer attached to the molds, and analyzed by the generalized estimating equation (GEE) (alpha=0.05).
Results: A significant increase in temperature was recorded in the control group ($P<0.0001$) and the highest temperature (38°C) was recorded at 40 seconds. A significant increase in temperature was also recorded in the test group ($P<0.0001$) and the highest temperature (26°C) was recorded at 20 seconds, which remained almost constant for the rest of the curing time. The temperature was significantly higher in the control group than the test group at both 20 ($P<0.0001$) and 40 ($P<0.0001$) seconds.
Conclusion: The present results showed temperature rise of composite resin in the process of light curing by a QTH curing unit. Using an external cooling system significantly decreased the temperature rise.

Introduction

Composite resins are extensively used in restorative dental procedures due to increased patient demands for tooth-colored restorations and optimal clinical service of composite restorations [1]. Light-polymerizing resins have revolutionized dental practice. Light-curing units are currently a must-have in all dental clinics. However, the interactions of curing light and resin cements are complex, and in need of further investigations [2]. Quartz-tungsten-halogen (QTH) light curing units were the first light curing devices used in dentistry, operating with a low voltage of 35 W to 150 W. QTH curing units are still used in many dental offices. Although QTH curing lights have a wide emission spectrum, over 70% of their energy input is converted to heat, which causes pulpal temperature rise. The first generation of light emitting diode (LED) curing units was introduced as "cold lights" to the market. The manufacturers claimed that these lights would cause insignificant pulpal temperature rise in comparison with QTH curing units. Later on, it was found that the claims regarding low heat generation of the primary LED units were the result of their low radiant power output and not light emission. The second generation of LED units had higher radiant power output, a cooling fan, and heat absorbents; nonetheless, they still had a relatively narrow emission spectrum.

The first and second generations of LED curing units only emit blue light with a wavelength > 420 nm; they can exclusively activate the camphorquinone resin component, and cannot activate alternative initiators. To overcome this problem, third-generation curing units were introduced that had a wide emission spectrum. However, if the internal optic of the curing unit does not have a proper design, the output light would not be homogenous, and would result in variable microhardness across the composite specimen [2]. Increased output light is probably responsible for the pain experienced by patients after composite restoration of their teeth, which is due to thermal, osmotic, and mechanical stimuli causing fast movement of dentinal fluid in dentinal tubules [3]. Overheating of the pulp is a serious problem and can cause inflammatory reactions, histopathological changes, vascular rupture, and cell death [4]. Overheating of the pulp can occur in light curing, polishing of restorations, and light-assisted bleaching [5]. The magnitude of pulpal temperature rise by light curing depends on the duration of radiation, power, energy output, and light intensity of curing unit, residual dentin thickness, type of composite resin and its thickness, and exothermic reactions that occur during resin polymerization. Curing units with higher output probably generate greater heat, and destructive temperature rise may occur during photo-polymerization of resin [6-9].

Less heat is generated during curing of darker composite shades, but the temperature remains high for a longer period of time because light penetration decreases, and polymerization occurs at a slower pace in darker composite shades. Curing of some bulk-fill composite resins causes greater temperature rise compared with conventional composites applied incrementally by the layering technique. Also, curing of flowable composites generates greater heat due to higher resin volume [10]. Further attention should be paid to the type of light curing unit and light exposure protocol in areas where the pulp is at higher risk of thermal damage, as in deep cavities with a thin layer of residual dentin. The magnitude of temperature rise in teeth with deep cavities is much higher than that in sound teeth. Moreover, return to baseline temperature after irradiation takes longer in teeth with deep cavities. In such teeth, it is recommended to air-cool the tooth during exposure from the opposite side. Also, high-volume suction may be used for cooling of teeth. Air-cooling can lower the pulpal temperature both during and after light exposure. Given that a suitable equipment is used for this purpose, light intensities higher than 1200 mW/cm^2 may be used for irradiations longer than 15 seconds [2].

The wavelength of irradiated light should match the required absorption spectrum of composite resin to achieve optimal polymerization and ensure minimal pulpal temperature rise [11]. QTH curing units have a wide spectral range and can sufficiently polymerize all types of composite resins. However, LED curing units have a very narrow spectral range around the maximum absorption wavelength of camphorquinone (468 nm) [12]. On the other hand, alternative photo-initiators are used in some composite resins that require a shorter wavelength of light (410 nm) for polymerization, and can be polymerized by LED curing units with wavelengths that do not precisely match their required wavelength. Multi-wave LED curing units (with 2 or more spectral peaks) were recently introduced with a wavelength range of 460 nm (blue) to 410 nm (violet) [13]. These LED units can polymerize composite resins with both types of photo-initiators. However, they may have unequal light distribution and result in subsequent temperature rise in the pulp chamber, if not precisely controlled [14]. Dental pulp is surrounded by dentinal walls, and has a limited blood supply. It has a terminal circulation with no accessory blood supply [15]. Thus, dental pulp has low compatibility, and can be easily injured [16]. It is highly sensitive to temperature rise, and visible light curing units can cause pulpal damage. The adverse effects of heat on dental pulp have been well documented, and it has been confirmed that heat generated by some dental procedures can cause irreversible pulpal damage [17] or even necrosis [18]. Many studies have shown that pulpal temperature rise during restorative procedures can damage the pulp tissue [19-22]. Thus, it appears that a cooling system may be required to minimize pulpal temperature rise and prevent pulpal damage [23]. Nonetheless, no cooling system is routinely used during light curing [24-26].

Considering the risk of pulpal damage due to heat generation and pulpal temperature rise by light curing units, this study aimed to assess the effect of light curing with/without an external cooling system on composite temperature. This study was conducted to answer the question of whether the light curing device increases the temperature of the composite and whether the use of a external cooling system with the light curing device is effective in reducing the temperature of the composite.

Materials and Methods

This in vitro, experimental study was conducted on A3 shade of Luna composite (SDI, Australia).

Sample size

Using formula (1) the sample size was calculated to be 40 specimens assuming alpha=0.05, beta=0.1, and study power of 90% using Med Calc software:

$$n = \frac{(\sigma_1^2+\sigma_2^2)(Z_{1-\frac{\alpha}{2}}+Z_{1-\beta})^2}{\delta^2} \qquad (1)$$

Designing the external cooling system

An air compressor with an air pressure gauge was used for this purpose. It also had a tube, which was connected to the external part of the tip of the curing unit. The QTH curing unit (Coltolux 75, Coltene, Switzerland) was modified such that a switch was incorporated in it. By turning on the curing unit and initiation of radiation, the switch would be automatically activated (when the compressor is turned on), and spray air on the tip of the curing unit and around it, resulting in cooling of the tip and the surrounding areas (Figure 1).

Figure 1.

(A) Air compressor; (B) air gauge; (C) tube for attachment to the tip of the curing unit

The light curing unit was mounted at 1 mm distance from the surface of specimens for the purpose of standardization of the procedure for all specimens (Figure 2).

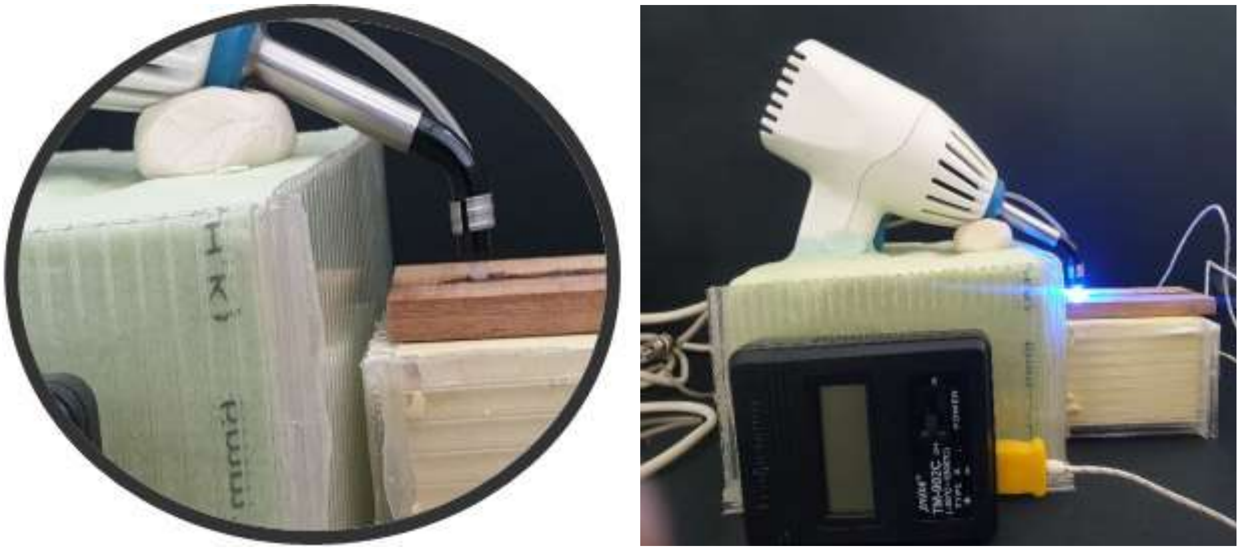

Figure 2.
Light curing unit was mounted at 1 mm distance from the specimens for the purpose of standardization of the procedure for all specimens

Specimen fabrication
Forty molds were fabricated from plastic tubes (ISO13485; ISO9002; TST CE, China) with an internal diameter of 3 mm, an external diameter of 4.1 mm, and 2 mm depth as measured by a digital caliper (Mitutoyo, Japan). A3 shade of Luna composite resin (SDI, Australia) was applied into the molds. After fabrication of specimens, they were measured again by the digital caliper to ensure their exact dimensions. After application of composite into the molds, they were placed on a perforated PVC sheet that was connected to a thermocouple with a brass sensor with 4.1 mm diameter, which was attached to a thermometer (Figure 3).

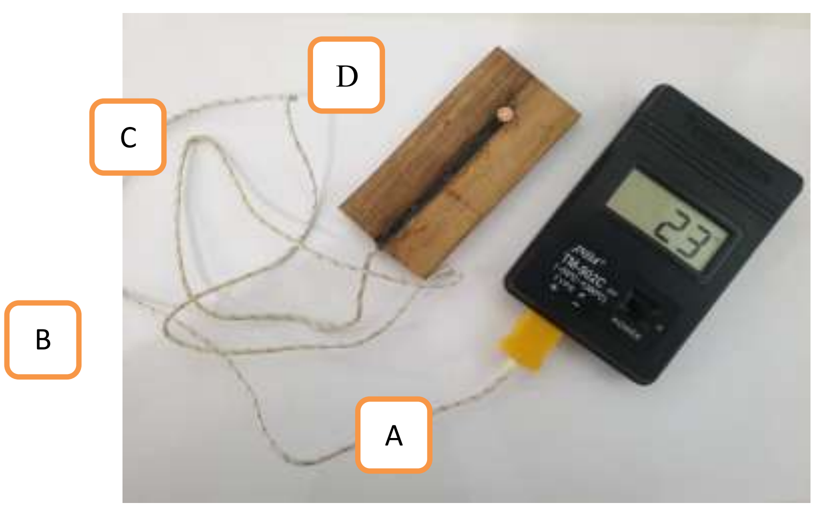

Figure 3.
(A) Thermometer; (B) thermocouple; (C) PVC sheet; (D) brass sensor connected to the thermocouple

Composite specimens were then randomly assigned to two groups (n=20). In the control group, the specimens were cured with a QTH curing unit (Coltolux 75, Coltene, Switzerland) with 1 mm distance from the composite surface for 40 seconds. The temperature change of composite specimens was recorded after 20 and 40 seconds of curing. The same process was performed for the test group specimens with the difference that the external cooling system was turned on upon initiation of light irradiation, and temperature of specimens was recorded after 20 and 40 seconds of curing by the thermocouple. The recorded temperatures were compared between the two groups.

Statistical analysis

The Kolmogorov-Smirnov test showed that the data did not have a normal distribution ($P<0.05$). Thus, data were analyzed by non-parametric generalized estimating equation (GEE) using SPSS version 24 (SPSS Inc., IL, USA) at 0.05 level of significance to answer the question of whether the light curing device increases the temperature of the composite and whether the use of a external cooling system with the light curing device is effective in reducing the temperature of the composite.

Results

This study assessed the effect of light curing with/without an external cooling system on composite temperature. A significant increase in temperature was recorded in the control group and the highest temperature (38°C) was recorded at 40 seconds. A significant increase in temperature was also recorded in the test group and the highest temperature (26°C) was recorded at 20 seconds, which remained almost constant for the rest of the curing time. At both 20 and 40 seconds, the temperature was significantly higher in the control group than the test group.

Table 1 shows the measures of central dispersion for the temperature of specimens in the two groups at different time points. GEE showed a significant change in temperature at different time points during the curing process in the control group ($P<0.0001$) such that the highest temperature (38°C) was recorded at 40 seconds. In other words, temperature rise was 15°C, compared with baseline. In the test group, a significant change was noted in temperature during the curing process ($P<0.0001$). The highest temperature was recorded at 20 seconds (26°C), and the temperature remained constant until 40 seconds. The temperature rise at 20 and 40 seconds was 3°C compared with baseline.

Table 1.

Measures of central dispersion for the temperature (°C) of specimens in the two groups (n=20) at different time points

Group	Time		Minimum	Maximum	Mean	Std. Deviation
Control	0 S	Temp	23	23	23.00	0.00
	20 S	Temp	29	30	29.89	0.32
	40 S	Temp	37	38	37.78	0.42
Test	0 S	Temp	23	23	23.00	0.00
	20 S	Temp	25	26	25.83	0.38
	40 S	Temp	25	26	25.83	0.38

The baseline temperature of the two groups was the same (23°C) ($P>0.999$). The temperature was significantly higher in the control group than the test group at both 20 seconds ($P<0.0001$; 6-7°C temperature rise in the control group versus 2-3°C in the test group) and 40 seconds ($P<0.0001$; 14-15°C temperature rise in the control group versus 2-3°C in the test group).

Figure 4 shows the trend of thermal alterations in the two groups. As shown, the trend of temperature change was ascending in the control group, and the temperature increased with time. In the test group, the trend of temperature change was ascending until 20 seconds but with a slower gradient that that of the control group. At 20 seconds, the temperature reached a plateau and remained constant until 40 seconds.

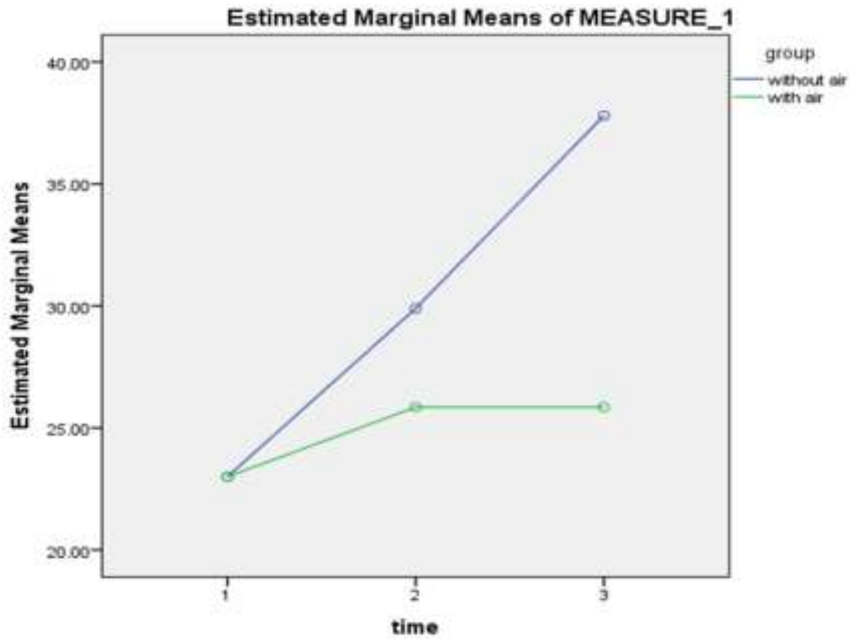

Figure 4.
Trend of thermal alterations in the two groups

Discussion

With the increasing demand for dentistry, the aesthetic qualities of composite resins have made them among the most widely used restorative materials today. Beyond their aesthetic appeal, composite resins can bond to enamel and dentin using adhesives, which helps reinforce the remaining tooth structure. Most contemporary composites rely on light-curing systems for polymerization. Achieving optimal mechanical properties in restorations requires adequate curing and a high level of resin polymerization. For a long time, continuous-intensity quartz-tungsten-halogen (QTH) devices were the sole light source available for curing resins. However, in recent years, various devices and polymerization techniques have been introduced. Light-curing lamps produce heat as a result of their design, but this heat does not directly cure the composite resin. Instead, the curing process depends on the visible light emitted by the light-curing device (27). The dental pulp is highly susceptible to cavity preparation and restoration for several reasons. It is encased within rigid dentin walls, comprises a relatively high amount of tissue with limited vascular supply, and relies on terminal circulation without collateral blood flow (15). Consequently, the pulp is described as a "low-compliance system," making it prone to damage from trauma (16).

Due to its low-compliance nature, the pulp is especially vulnerable to temperature increases, raising concerns that visible light-curing (VLC) lamps may harm it. The thermal effects on pulp tissue have been extensively studied. Zak and Cohen found that 60% of tested samples failed to recover after experiencing a 20°F rise in internal pulp temperature (4). Mousavi-Nasab and colleagues demonstrated that during photopolymerization, the temperature increase in the first layer of conventional composites under the soft-start mode was greater than that observed in bulk-fill composites under the continuous light-curing mode. Furthermore, conventional composites exhibited a higher degree of conversion (DC) compared to bulk-fill composites (28). Winiger and colleagues found that all LED light-curing modes significantly raised pulp temperature, with high-energy curing modes causing temperature changes of 5.5°C or more, which could potentially harm the pulp (29). Seol and colleagues showed that under constant irradiation and fixed curing times, the temperature increase was slower and less pronounced. Over 20 seconds, the temperature rise decreased by 50% when irradiation energy was kept constant. Additionally, light-curing with reduced irradiation energy resulted in lower heat transfer, minimizing the risk of pulp damage (30). Baraga and colleagues revealed that simulating pulp microcirculation could dissipate heat generated during resin light-curing, leading to smaller temperature increases (31). Hosseini-Far and Lashkarizadeh observed that the degree of conversion for bulk-fill composites was unaffected by the light-curing device type. These composites achieved clinically acceptable degrees of conversion at both the surface and a depth of 4 mm (32). In 1961, Foote and colleagues concluded that dental procedures could cause tooth temperature increases sufficient to trigger irreversible pulp changes (17). Brännström and colleagues suggested that the heat reaching the pulp in older teeth might be enough to induce pulp necrosis (18). Research by Schuchard and Watkins (19), Hamilton and Cramer (20), Wood and Deitz (21), and Morant (22) all highlighted the potential harm of temperature increases during restorative procedures. These studies mainly focused on temperature rises during cavity preparation, whereas the current study investigated temperature changes during composite curing. Lloyd and Brown reported that when resin bonding agents are applied to teeth with a history of prior restorative treatments, the curing temperature poses a greater risk to the pulp (33). Watts and colleagues emphasized the importance of using a liner to protect the pulp from thermal shocks caused by certain resin composites. If the material itself produces heat during curing, it can intensify the effects of the lamp's heat and lead to pulp damage (34).

Lloyd and colleagues also noted that prolonged light exposure during curing causes a temperature rise, potentially reaching up to 21.4°C, depending on the composite and light-curing device used. This is especially critical for posterior composites, where restoration depths may range from 7 to 11 mm. Consequently, manufacturers recommend layering materials during curing, which can extend the process to 2–4 minutes (35). Bodkin and Sheer evaluated two VLC lamps and determined that they generate enough heat to damage the pulp. They also recommended implementing monthly temperature checks as new units are introduced (36). Basiani and colleagues observed that visible light-activated composites produce more heat than chemically cured materials (37). In 1985, the ADA Council on Dental Materials, Instruments, and Equipment highlighted that the differences in heat generation exist among curing systems and composites, with some capable of producing enough heat to affect the pulp (38). The degree of polymerization in light-cured composites varies based on factors like wavelength, light intensity, the curing unit tip's size and position, and the material's thickness, color, and composition. The heat generated during light-curing raises concerns about its impact on pulp tissue. Since monitoring pulp temperature changes under various light-curing protocols is challenging, this study used composite specimens with a fixed thickness of 2 mm rather than natural teeth. Temperature changes were recorded with the curing light alone and when combined with a cooling system. Traditional restorative techniques produce heat, making cooling systems essential to minimize or eliminate heat generation and reduce pulp damage (23). However, cooling devices are rarely used during the restorative phases of prepared cavities, despite the potential harm to the pulp during this stage (24–26).

Given the introduction of resin composite restorative systems and the heat generated during their placement, this study aimed to assess the temperature increase caused by VLC lamps. The investigation measured temperature changes in composite specimens exposed to light-curing for 20 and 40 seconds, both with and without air cooling, to evaluate whether the light-curing process raised the temperature and whether air cooling mitigated this effect. A study by Winiger and colleagues on four types of light-curing devices found that all LED curing modes significantly increased pulp temperature. High-energy curing modes caused temperature rises of 5.5°C or more, posing potential harm to the pulp (29). Our findings were similar. Using a QTH light-curing device with consistent irradiation intensity, the temperature in composite specimens increased, with a higher rise observed at 40 seconds compared to 20 seconds, and the 20-second temperature higher than the baseline. Goodis and colleagues also concluded that light-curing raised the pulp chamber temperature, with the extent depending on the remaining thickness of dentin and enamel. Higher temperatures were recorded in teeth with thinner dentin layers, and more heat was generated at 60 seconds compared to 20 seconds. However, air cooling applied at the contact point between the light-curing tip and the tooth reduced the recorded temperature under all conditions and durations (39). Our study confirmed these observations. In our investigation, using a cooling system with the light-curing device for 20 seconds caused a slight temperature increase relative to the baseline, but it was minimal compared to the group without cooling. At 40 seconds, the temperature remained nearly stable with no significant rise. Conversely, in the non-cooled group, the temperature increased significantly over 40 seconds. This study concluded that light-curing raises the temperature in composite specimens, with prolonged curing times resulting in greater temperature increases. However, using air cooling effectively prevented significant temperature rises, demonstrating its potential to reduce heat generation during light-curing.

Conclusion

The present results and those of the abovementioned studies all highlight the need for an external cooling system during light curing. In the present study, A3 shade of composite was used since evidence shows that darker shades of composite experience smaller temperature rise but maintain the temperature for a longer period of time. The situation is reverse for lighter shades. Thus, an intermediate shade was selected for this study. Future studies are required on the efficacy of the designed cooling system for reduction of temperature rise in tooth specimens caused by other types of curing units.

References

1. Heintze SD, Rousson V. Clinical effectiveness of direct class II restorations - a meta-analysis. J Adhes Dent. 2012 Aug;14(5):407-31.
2. Ritter AV, Busheii LW, Walter R. Sturdevant's Art and Science of Operative Dentistry 7th Edition. 2016 (pp. 177-203)
3. Swift EJ Jr. Causes, prevention, and treatment of dentin hypersensitivity. Compend Contin Educ Dent. 2004 Feb;25(2):95-106, 109; quiz 110.
4. Zach L, Cohen G. Pulp response to externally applied heat. Oral Surg Oral Med Oral Pathol. 1965 Apr;19:515-30.
5. Kodonas K, Gogos C, Tziafas D. Effect of simulated pulpal microcirculation on intrapulpal temperature changes following application of heat on tooth surfaces. Int Endod J. 2009 Mar;42(3):247-52.
6. Yazici AR, Müftü A, Kugel G, Perry RD. Comparison of temperature changes in the pulp chamber induced by various light curing units, in vitro. Oper Dent. 2006 Mar-Apr;31(2):261-5.
7. Choi SH, Roulet JF, Heintze SD, Park SH. Influence of cavity preparation, light-curing units, and composite filling on intrapulpal temperature increase in an in vitro tooth model. Oper Dent. 2014 Sep-Oct;39(5):E195-205.
8. 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 Mar;35(3):238-45.
9. Leprince J, Devaux J, Mullier T, Vreven J, Leloup G. Pulpal-temperature rise and polymerization efficiency of LED curing lights. Oper Dent. 2010 Mar-Apr;35(2):220-30.

10. Balestrino A, Veríssimo C, Tantbirojn D, Garcia-Godoy F, Soares CJ, Versluis A. Heat generated during light-curing of restorative composites: Effect of curing light, exotherm, and experiment substrate. Am J Dent. 2016 Aug;29(4):234-2240.
11. Leprince J, Devaux J, Mullier T, Vreven J, Leloup G. Pulpal-temperature rise and polymerization efficiency of LED curing lights. Oper Dent. 2010 Mar-Apr;35(2):220-30.
12. Jandt KD, Mills RW. A brief history of LED photopolymerization. Dent Mater. 2013 Jun;29(6):605-17.
13. Strassler HE, Price RB. Understanding light curing, Part I. Delivering predictable and successful restorations. Dent Today. 2014 May;33(5):114, 116, 118 passim; quiz 121.
14. Rueggeberg FA. State-of-the-art: dental photocuring--a review. Dent Mater. 2011 Jan;27(1):39-52.
15. Seltzer S, Bender IB. The dental pulp 3 rd ed. Philadelphia: JB Lipplncott. 1984 (pp. 195-7)
16. Van Hassel HJ. Physiology of the human dental pulp. Oral Surgery, Oral Medicine, Oral Pathology. 1971 Jul 1;32(1):126-34.
17. Pohto M, Scheinin A. Microscopic observations on living dental pulp II. The effect of thermal irritants on the circulation of the pulp in the lower rat incisor. Acta Odontol Scand. 1958 Jan 1;16(3):315-27.
18. Brännström M, Lindén LA, Aström A. The hydrodynamics of the dental tubule and of pulp fluid. A discussion of its significance in relation to dentinal sensitivity. Caries Res. 1967;1(4):310-7.
19. Schuchard A, Watkins C. Temperature response to increased rotational speeds. The Journal of Prosthetic Dentistry. 1961 Mar 1;11(2):313-7.
20. Hamilton AI, Kramer IR. Cavity preparation with and without waterspray. Effects on the human dental pulp and additional effects of further dehydration of the dentine. Br Dent J. 1967 Sep 19;123(6):281-5.
21. Woods RM, Dilts WE. Temperature changes associated with various dental cutting procedures. J Can Dent Assoc (Tor). 1969 Jun;35(6):311-5.
22. Morrant GA. Dental instrumentation and pulpal injury. Part I- Biological and physical factors. J Br Endod Soc. 1977 Jan;10(1):3-8.
23. Langeland K. Histologic evaluation of pulp reactions to operative procedures. Oral Surg Oral Med Oral Pathol. 1959 Oct;12:1235-48.
24. Zach L, Cohen G. Thermogenesis in operative techniques: Comparison of four methods. J Prosthet Dent . 1962 Sep 1;12(5):977-84.
25. Stanley HR. Human Response to Restorative Procedures. Gainesville, FL: Storter Printing Co. 1981 (pp. 15-8).
26. Goodis HE, Schein B, Stauffer P. Temperature changes measured in vivo at the dentinoenamel junction and pulpodentin junction during cavity preparation in the Macaca fascicularis monkey. J Endod. 1988 Jul;14(7):336-9.
27. LLOYD, C.H. (1984): A Differential Thermal Analysis for the Heats of Reaction and Temperature Rises Produced During the Setting of Tooth Coloured Restorative Materials, *J Oral Rehab* 11: 111-121.
28. Sayed Mostafa Mousavinasab , Zahra Taromi , Elham Zajkani. Thermal rise during photopolymerization and degree of conversion of bulk fill and conventional resin composites. Dent Res J (Isfahan) 2020 Aug 14;17(4):293-299. eCollection 2020 Jul-Aug
29. Alexandra Vinagre,[1,*] João C. Ramos,[1,2] Clara Rebelo. Pulp Temperature Rise Induced by Light-Emitting Diode Light-Curing Units Using an Ex Vivo Model. 2019 Feb; 12(3): 411.

30. Jo SA, Lee CH, Kim MJ, Ferracane J, Lee IB. Effect of pulse-width-modulated LED light on the temperature change of composite in tooth cavities. Dental Materials. 2019 Apr 1;35(4):554-63
31. Braga SS, Oliveira LR, Ribeiro MT, Vilela AB, da Silva GR, Price RB, Soares CJ. Effect of simulated pulpal microcirculation on temperature when light curing bulk fill composites. Operative dentistry. 2019 May;44(3):289-301.
32. Hosseinifar Razieh, Lashkarizadeh Lida. Studying the effect of the type and mode of light curing device on the degree of conversion of bulk composites. Journal of Isfahan Dental School [Internet]. 2022;18(2):145-152.
33. LLOYD, C.H. and BROWN, E.A. (1984): The Heats of Reaction and Temperature Rises Associated with the Setting of Bonding Resins, J Oral Rehab 11: 319-324.
34. WATTS, D.C.; HAYWOOD, C.M.; and SMITH, R. (1983): Thermal Diffusion Through Composite Restorative Materials, Br Dent J 154: 101-103.
35. LLOYD, C.H. (1984): A Differential Thermal Analysis for the Heats of Reaction and Temperature Rises Produced During the Setting of Tooth Coloured Restorative Materials, J Oral Rehab 11: 111-121.
36. BODKIN, J. and SHARE, J. (1984): Heat Generation by Composite Light Curing Units Tested in vitro, J Dent Res 63: 199, Abst. No. 258.
37. BASSIOUNY, M.A.; COWPERTHWAITE, G.F.; and CHOHAYEB, A.A. (1983): Temperature/Time Cure Profile of Visible Light Activated Composites, J Dent Res 62: 665, Abst. No. 140.
38. COUNCIL ON DENTAL MATERIALS, INSTRUMENTS AND EQUIPMENT (1985): Visible Light Cured Composites and Activating Units, J Am Dent Assoc 110: 110-113.
39. Goodis, H.E., White, J.M., Andrews, J., Watanabe, L.G. Measurement of temperature generated by visible-light-cure lamps in an in vitro model. July 1989, Pages 230-234.