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Light-Curing Dental Restorative Materials: A Literature Review of Thermal Complications

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Abstract

The use of direct resin-based materials has increased primarily due to patient esthetic desires, product improvements, and health concerns with dental amalgam. New visible light-curing resin-based materials are introduced yearly, as manufacturers continue to improve this tooth-colored restorative material. This paper will characterize the heat released during the polymerization of light-curing resin composite and review in vitro and in vivo studies. In addition, the literature on temperature rise during polymerization of light-curing pulp-capping materials, bonding agents, Resin-modified glass ionomer cement (RMGIC), and compomers will be reviewed. The data indicate that the use of light curing sources with high radiant exitance seemed to make a greater temperature rise than the use of traditional sources. Moreover, particular attention should be paid to deep preparations where the thickness of the remaining dentin is minimal.

Keywords: Temperature rise • Dentin • Polymerization • Restorative materials

Introduction

The measure of the amount of total kinetic energy in a substance is known as heat and therefore has the SI unit joule (J) [1]. However, the temperature is defined as the degree of hotness of a substance, and it is measured by different scales such as the Celsius scale (℃) [1,2].

In recent years, aesthetic restorations became very popular. Therefore, light-curing resin-based materials were routinely used as dental restorative material in clinical practice, but the influence of heat released during the polymerization reaction has been reported to be a concern [3]. With advances in modern dentistry, instruments with high-energy output have been widely employed in dental treatments (e.g., Light Curing Units LCUs) so this increased that concern [4].

The heat generated within the tooth during the polymerization of light-curing resin-based materials can cause thermally induced damage to the tooth's hard and soft components [5,6]. Additionally, the temperature rise may induce tooth thermal pain [7]. Therefore, this review highlights the increase of the pulp chamber temperature during the polymerization of light curing materials, their mechanism, influencing factors, and methods to reduce it.

The mechanism of pulp overheating caused by exposure to blue light

When blue light hits the tooth surface, some of the light energy is reflected, some are converted to heat energy, and the rest penetrates the underlying substrate [8]. When blue light reaches the pulp tissue, the photons are strongly absorbed by blood chromophores and partially converted to thermal energy, increasing the pulp temperature [9]. Due to the constant blood flow, the heated chromophores of the absorbed photons quickly displace other, cooler chromophores, thus dissipating most of the heat generated in this tissue. However, it should be emphasized that most of the analyses of the in vivo studies were performed on intact teeth. In this clinical condition, enamel and dentin or a thick dentin barrier can absorb and store heat, protecting the pulp from heat damage [9,10]. Therefore, in teeth with deep cavities and thin pulp floors, we would expect a significant increase in pulp temperature with shorter exposure times.

Effect of blue light on soft tissues

Few data are available in the literature on the effects of LCU light on the temperature of soft tissues such as the gingiva, but studies have raised concerns about the potential damage that light emitted from these LCUs can cause to soft tissues [11,12]. The only report to date that addresses this issue in human soft tissue is that three patients developed lesions in the lower lip at a site that would have been apical of the placed restoration while the rubber dam was in place [13]. An in vivo study performed in swine gingiva recently investigated the temperature rise of the gingival tissue during irradiation with light from an intense polywave® LCU [14]. In that study, exposure to light with a radiant power level of approximately 1,200 MW/cm^2 increased gingival temperature to approximately 41°C. Although the temperature rise that causes severe thermal damage to gingival tissue is not yet known, approximately 67% and 77% of tissue exposed to light for 40 and 60 seconds, respectively, developed gingival lesions. Furthermore, according to the authors, the use of rubber dams did not prevent temperature rise or the development of gingival lesions.

The critical temperature value of pulp damage

A primate study in five rhesus monkeys showed that healthy pulp failed to recover from an intra-pulp temperature increase of 11°C in approximately 60% of the cases, and 15% failed to recover when the temperature increased by 5.5°C [15]. Based on these findings and the lack of similar studies in humans, many authors consider a temperature increase of 5.5°C to be a potential damage threshold for human dental pulp tissue. The effect that neurogenic inflammation leads not only to hyperemia but also to plasma extravasation was demonstrated in the mandibular incisors of wistar rats. The reaction began with hyperemia at 43°C followed by plasma extravasation around 45°C, both of which were unlikely to cause irreversible damage to the pulp, as the inflammation of the interstitial tissue was transient [16]. Various experiments also performed in rat lower incisors showed that stimulation induced by heat 39°C-42°C resulted in a clearly perceptible increase in blood flow velocity. In the case of vital staining, rapid staining of pulp tissue occurred at 42°C-44°C. Stasis and thrombosis leading to circulatory arrest occurred at 46°C-60°C in the exposed pulp, with thermal stimulation durations of 30 seconds. The change led to a circulatory arrest at 46°C in the unexposed pulp, when the temperature increase lasted for 2 minutes [17]. Therefore, the authors believe that the detrimental effects of heat on pulp tissue are related not only to temperature increases, but also to how quickly heat is transferred from the tooth surface to the pulp, and to the duration of thermal stimulation. In summary, the value of the critical temperature rise that causes pulpal damage in human teeth remains unknown, but we must accept that the intra-pulp temperature rise during the setting of the restorative material should be as small as possible.

Temperature rise in the course of the light curing process

Tooth related factors

Structure of human tooth: The thermal behavior of teeth depends on their microstructure and is primarily a heat conduction process coupled with the physiological processes of the tooth [7]. Human teeth are composed of enamel, dentin, cementum, and pulp. Enamel is the most mineralized layer, composed of 96% minerals and 4% water and organic matter [18]. Enamel has a unique microstructure consisting of prisms/rods running nearly perpendicular from the Dentin-Enamel Junction (DEJ) to the tooth surface [19]. This characteristic arrangement of prisms in enamel should have a significant impact on tooth heat transfer.

Dentin is a calcified connective tissue containing an organic matrix of collagenous proteins composed of 70% inorganic and 30% organic matter and water [20]. There are dentinal tubules that radiate from the pulp cavity to the cementum or DEJ [21]. Studies have shown that the number of dentinal tubules increases significantly near the walls of the pulp chamber, whereas the opposite situation has been noted in the region near his DEJ. The thermal conductivity of human dentin decreases with increasing volume fraction of dentin tubules [22]. The flow of dentin fluid within the dentin tubules upon heating can also facilitate heat transfer within the pulp. This characteristic shape of the dentin improves heat transfer to the pulp. Therefore, dentin material is thought to be adapted to transfer more heat to the pulp [23].

The pulp is highly vascularized, with arterial blood vessels entering the crown through the root apex [24]. Pulp blood microcirculation plays an important role in the thermal behavior of teeth. Histophysiological studies showed that the pulpal blood flow velocity is nearly constant in the range of 33°C to 42°C, and increases significantly when the temperature exceeds 42°C. This feature contributes to the thermoregulation of the pulpal soft tissue [16,25]. Blood flow in the pulp acts as a heat sink. However, the effect of pulp blood flow on heat transfer is considered negligible in clinical practice due to the low blood volume in the pulp vessels [26].

Dentition type: The temperature rise in the pulp chamber may differ between primary and permanent teeth due to different microstructures. Reported numbers of tubules per mm^2 of human permanent dentin vary considerably between studies but generally range from 22,000 to 82,900 per mm^2 [27]. There are few published data on the distribution of dentinal tubules in primary teeth. The authors noted that the concentration of dentin tubules in primary teeth was lower than in permanent teeth at the same general locations [28,29].

Several researchers have compared tubule diameters in human permanent and primary teeth dentin. Fromm and Riedel found that dentinal tubule diameters differ significantly between primary and permanent adolescent teeth [30]. Their results showed that the diameter of the permanent teeth was considerably larger, which can be explained by the fact that the primary teeth are relatively thinly covered with enamel. Larger dentin tubular structures in primary teeth than in permanent teeth make them more permeable and more susceptible to thermal stimulation [31].

Cavity preparation-related factors

Remaining dentin thickness: Over the years, estimates of the minimum residual dentin thickness of cavities that do not cause pulpal damage have changed. Stanley suggested that a remaining dentin thickness of 2 mm prevents pulp damage from most restorative materials and procedures [32]. Subsequently, Pameijer reported that a residual dentin thickness of 1 mm was sufficient to protect pulp tissue from the cytotoxicity of glass ionomers modified, zinc phosphate, and resin composite [33]. Murray has shown that a residual dentin thickness of at least 0.5 mm is required to avoid signs of pulpal injury [34].

With respect to composite resin polymerization, various residual dentin thicknesses have been investigated in the literature (Table 1). Comparative studies have shown that the amount of remaining dentin thickness plays an important role in protecting the pulp chamber from temperature rise [35]. Human dentin has a low thermal conductivity, which protects the pulp from overheating [36]. However, there are discrepancies in the thermal conductivity values recorded in the literature, which may be due to differences in tooth morphology such as enamel and dentin structure and thickness, and the thermal conductivity of the tested teeth differences [37]. Because heat flow through dentin is proportional to the thermal conductivity of dentin and inversely proportional to the thickness of residual dentin, deeply prepared teeth with low amounts of residual dentin are at increased risk of pulpal injury. Therefore, residual dentin thickness is one of the important factors in protecting the pulp from thermal damage.

Table 1: Summary of the remaining dentin thickness studied

RDT*	Study
1-0.5	(Guiraldo 2013) [38]
0.5-1-1.5-2	(Hubbezoglu 2013) [39]
1-2	(Yazici 2007) [40]
0.5-1-2	(Da Silva 2010) [41]
0.5-1	(Millen 2007) [42]
1-2	(Buyukkok 2021) [43]
0.5-1	(Karaarslan 2011] [44]
1-2	(Aguiar 2006) [45]
0.58-1.48	(Loney 2001) [46]
1-2	(Botsali 2016) [47]
0.5-1-1.5-2	(Dogan 2009) [48]
2-3-4	(Secilmis 2013) [35]
1-2	(Yazici 2006) [49]

*RDT: Remining Dentin Thickness

Light-curing pulp-capping materials: In deep cavities, pulpal tissue can be attacked by bacterial toxins and heat changes. In such cases, pulp-capping materials can be used to protect the dentin-pulp complex from temperature rise, exhibit antibacterial activity, and block the passage of bacteria into the pulp chamber [50]. Recently, light-curing pulp-capping materials were developed to overcome the drawbacks of traditional calcium hydroxide, such as water solubility, poor bonding strength to hard tooth tissue, and relatively low compressive strength [51]. However, the heat generated during the polymerization of these materials can lead to irreversible pulp damage [52]. Various factors, such as the radiant exitance of the LCU, residual dentin thickness, the distance between the LCU and the material surface, location of the LCU, and exposure time, can influence the degree of temperature increase during the polymerization process of capping material [53-55].

According to Savas light curing causes a lower temperature rise in the presence of cupping materials, which may be primarily due to these materials, and prevents the heat generated by the LCU from being conducted to the pulp chamber [56]. The composition of the capping material affects its thermal properties. Calcium silicate-containing materials have lower specific heat capacities compared to calcium hydroxide-based materials [57]. Specific heat capacity is directly proportional to the thermal conductivity of a material. Therefore, materials with lower specific heat capacities are more insulating.

Light-curing restorative material-related factors

Bonding agent polymerization: Most bonding agents require photoactivation for the polymerization process [58]. However, there are concerns about the potential adverse effects of increased temperature during the photocuring of bonding agents [52]. The lack of studies on the thermal properties of bonding agents makes it difficult to derive recommendations for bonding agents' polymerization, but studies show that photocuring of bonding agents in deep cavities exposes the dentin surface to dangerous temperature rise even the light source away 3 mm from the exposed surface [59,60]. A study by Santini showed a large temperature rise during the curing of the bonding agent and advised physicians to be aware of the potential risk of thermal damage to the pulp when using the new generation of high-output light sources [3].

Interestingly, the authors observed an increase in the temperature rise values recorded during the polymerization of bonding agents compared to those recorded during the resin composite polymerization. Ratih conducted a study investigating the temperature rise in extracted human maxillary premolars using a mesial occlusal preparation. Temperature changes were measured using thermocouples located on the occlusal cavity floor and at the pulp-dentin junction; pre (stage 1), during (stage 2), and post (stage 3) polymerization of the bonding agent. The temperature increase generated in stage 2 is a combination of the exothermic polymerization reaction and radiant heat from the light source, whereas, in the pre-bonding (stage 1) and post-bonding (stage 3), only the light source contributes to the increase in temperature. The authors found no statistically significant difference between stages 1 and 3 [61]. This may be explained by the inability of the bonding agent to reduce the penetration of light into the dentin [62].

Resin composite polymerization

The exothermic polymerization reaction of resin composite: The kinetics of thermal-curing of resin composite has been studied by researchers because polyfunctional monomers are used in applications where the polymerization of resins is performed using heat-curing and thermal initiator systems. Apart from the thermal effects of the LCU, the polymerization reaction is exothermic, mainly contributing to the temperature rise during the early stages of polymerization [55]. Methacrylate-based materials can be polymerized by chemical activation, photoactivation, or both chemical and photoactivation. As the polymerization progresses, C=C (π bonds) are transformed into new C-C (α bonds) [63]. The C-C bond energy is about 350 kJ/mol and the C=C energy is 270 kJ/mol. The energy difference of 80 kJ/mol between the two bonds is dissipated as heat [64]. In dentistry, it may cause thermal damage to the vital pulp. Susceptibility constraints to thermal damage may be due to temperature increases transmitted through the dentin. Thermal damage includes various histopathologic changes of the pulp, resulting in acute inflammation of the pulp, irreversible pulpitis, or pulp necrosis in severe cases [65]. Studies assumed that the exothermic heat generated during isothermal cure is proportional to the number of double bonds reacted in the system. Therefore, a measurement of the heat evolved may be an indication of the degree of conversion [66].

The composition of resin composite

Heat transfer is highly dependent on the composition of the three principal components of the resin composite (organic resin matrix, inorganic filler particles, and silane coupling agent that coats the filler particles for chemical bonding to the resin matrix) [67]. The higher the thermal conductivity, the more easily the temperature rise due to light irradiation or polymerization being transmitted, and the thermal deterioration of the pulp becomes a problem. In other words, it is important to consider the effects of sudden thermal changes when using resin composites containing fillers with a high thermal conductivity as the filler (e.g., alumina: 36 $Wm^{-1}.K^{-1}$). In contrast, silica, which is commonly used as a filler in resin composites, has a relatively low thermal conductivity of 1.38 to 8.0 $Wm^{-1}.K^{-1}$. Inorganic fillers influence heat diffusion within materials through their ability to absorb external energy [66]. Therefore, the matrix-to-filler ratio plays an important role in the temperature rise in the pulp chamber [68].

Regarding monomers, Hori found that the methyl-methacrylate (MMA) based resin, which is based on monomethacrylate, has a higher calorific value than the dimethacrylate-based resin composite because the polymerization chain reaction MMA-based resins are difficult to stop and it is inevitable to use a large amount of resin due to it having a single functional group [69]. The polyfunctional monomers with high molecular weight have a lower number of double bonds relative to the molecular weight, therefore less heat is generated during polymerization, so monomers with a large molecular weight have also found use in recent years [70,71].

Several studies have shown that some composites contain camphorquinone (CQ) co-photoinitiators that cannot be activated by standard Light Emitting Diode (LED) LCUs [72]. As a result, these composites do not reach their maximum degree of conversion. In addition, the polymerization process of a composite using co-photoinitiators is slowed down if irradiated by an LED instead of a halogen LCU [73]. A slower polymerization process means delayed liberated energy from the composite and therefore a slower temperature increases within the restoration.

Type of resin composite

There are many different types of dental resin composites in the market, with different matrix filler components, consistencies, and recommended application methods. A study by Lempel showed that flowable composites should exhibit higher temperature rises than non-flowable materials due to their higher resin content [74]. In other words, flowable resin composites polymerize in a more intense exothermic reaction.

Besides the conventional high-viscosity pastes and low-viscosity flowable resin composite, applied incrementally maximum in two-millimeter-thick layers, the so-called bulk-fill resin composite is increasingly popular among clinicians since these are applicable in a thickness of 4 mm to 5 mm without layering. Although it was reported, that these bulk-filled materials have been reported to exhibit lower polymerization shrinkage, the adequacy of case depth is still controversial [75]. Increasing the thickness of the resin composite layer adversely affects the light transmission and degree of conversion [76]. Thermal stress on pulp tissue is also controversial. Studies have shown that bulk-filled resin composites produce significantly higher pulp temperatures than conventional [77]. On the contrary, some studies have concluded that bulk-filled resin composites can reduce thermal stress on the pulp chamber [78]. The heat generated in bulk-filled resin composites increases as the layer thickness increases. This may be due to the presence of large amounts of monomer in thick materials. Furthermore, the heat generated in the viscous resin becomes increasingly difficult to remove as the volume of the resin material increases [79].

To overcome the failure of composite restorations, which is considered to be one of the most common mechanical limitations [80], fiber reinforcement of conventional dental composites have been introduced. Reinforcement occurs through stress transfer from the matrix to randomly oriented short fibers under load, resulting in high fracture toughness [81]. Investigations show that the increased temperature rise caused by the fiberglass content may be due to the fact that the fiberglass may have stored external (curing light) and internal (exothermic) heat energy [74,82].

The shade of resin composite

There are several ways by which composite shades can be grouped. If grouping is carried out according to the degree of brightness, then the commonly used shades of resin composite are placed in the following order: B1, A1, B2, D2, A2, C1, C2, D4, A3, D3, B3, A3.5, B4, C3, A4, C4. Investigations show that the overall temperature change of the resin composite can be seen to follow the same order. Al-Qudah found that the peak temperature of shades B1 and C2 peak reached after 5 s of curing, whilst shades B3 and A4 peaked after 10 s. This is explained by the fact that light penetrates deeper into the lighter composite (B1 and C2) and initiates a greater polymerization [55]. The darker shades (such as B3 and A4) will take longer to peak because the curing light will not penetrate the darker shades as easily as the lighter shades, so polymerization will slow down. The difference in light transmission between light and dark shades can be related to the presence of different types and content of pigments that control the transmission spectrum of each shade.

Darker shades have a higher temperature than lighter shades. This may indicate a sustained rate of polymerization and heat of reaction of the darker shades during this time interval. This could be due to the presence of a greater amount of residual monomer and free radicals after the initial polymerization peak, as the light took longer to penetrate the darker shades and initiate polymerization. Darker composite shades have been shown to require longer exposures than lighter shades to achieve a comparable depth of cure. Alternatively, darker shades may retain the heat due to the type and content of pigments in the resin matrix.

Resin-modified glass ionomer cements polymerization

Along with the increasing demand for aesthetic restorations, improvements in restorative materials and techniques have led to the introduction of a wide range of resin-containing dental materials (e.g. Resin modified glass ionomer cements RMGIC & Compomers). These materials contain variable proportions of the resin matrix. Since the exothermic reaction is proportional to the amount of resin available for polymerization and to the degree of conversion of carbon–carbon double bonds, then an increase in the pulp chamber temperature is expected for these materials. RMGI contains polycarboxylic acid, modified with methacrylate groups, as well as HEMA and photoinitiators. Several types of polymerizations occur when this material is mixed and light cured. The 2-hydroxyethyl methacrylate (HEMA) will polymerize to form poly HEMA. The modified polycarboxylic acid will copolymerize with HEMA because it contains unsaturated groups. In addition, the modified polycarboxylic acid will further polymerize to form a cross-linked polycarboxylic acid, which should increase the strength of the cement [83]. These polymerization reactions may explain the greater reaction exothermic recorded with RMGI when compared to conventional composite [84].

Compomers polymerization: Polyacid-modified composite resins (compomers) were introduced in 1993 as a new dental material that combines the excellent physical properties of resin composites with the fluoride-releasing properties of glass ionomer cement [85]. Studies reported that the temperature rise of the pulp chamber occurs during the polymerization of all types of light-curing resin-containing restorative materials [86], so a temperature increase during the polymerization of compomers should be expected. Although there are not enough data about the mechanism that cause different temperature increases in the pulp during light curing of different compomers, possibly it is because of the different exothermic reaction of different amount of resin content of the materials.

Additionally, when using colored compomers, the differences in temperature rise values recorded could be attributed to the type and amount of the added pigments. Jafari reported that pigments in darker compomers such as the shade blue absorb more light, thus reducing the depth of penetration of the light into the resin material [87]. Therefore, the blue-shade compomers could cause a lower increase in the temperature of the pulp chamber compared to the other colored compomers [88].

Glass Carbomers polymerization: Glass carbomer is a newly developed restorative material based on glass ionomer cement. Glass carbomer is differing from glass ionomer by its nanosized powder particles and fluorapatite crystals. The addition of fluorapatite was based on the belief that glass ionomers turn into fluorapatite-like material over time [89]. Additionally, Glass carbomers do not contain resins or monomers [90]. The advantages of Glass carbomer over conventional glass ionomer cement include significantly superior mechanical and chemical properties (e.g., strength, shear, and wear) [90,91]. The clinical application of Glass carbomer is similar to that of conventional glass ionomer cement, but heating (60°C, 60 sn) using a special thermocure lamp (Carbo-LED lamp LCU) is recommended during the setting reaction. The beneficial effects of heat on glass ionomers have been documented in recent studies [92]. However, the data show that the use of the Carbo-LED lamp LCU results in an exothermic reaction that increases the temperature of the pulp tissue and thus increases the risk of pulpal damage [93]. Glass carbomer is a relatively new improved restorative material that does not contain resin, monomer, metal, and BPA. Therefore, it deserves a long-term follow-up study of clinical trials.

Curing-light related factors

Light curing units and radiant exitance: Although the heat released during the exothermic reaction of resin composites can contribute to pulp temperature rise, curing lights are still the most important source of temperature rise within the pulp [94,95]. Studies have suggested that the use of Quartz Tungsten Halogen (QTH) and Plasma Arc lights caused higher temperature rise within the pulp chamber in comparison to the first-generation LED [96,97]. At that time, such differences in the temperature rise were attributed to the differences in the curing light outputs as no light was emitted by the LED curing lights in the infrared range compared to the QTH light [96]. It should be noted that the first-generation LED units emitted light with a lower irradiance level than QTH lights [98].

As LED technology advances, high-output light sources have been introduced to reduce clinical times for operators and patients and to achieve a deeper, more effective cure. These new lights have tended to move away from the traditional halogen type to the higher radiant exitance LED source which can have a radiant exitance of up to 1200 mW/cm^2 [96]. Early reports suggest that LED curing units cause less damage to the pulp, but this conclusion should be interpreted with a degree of caution as these early units usually operated in the range of 400mW/cm^2. As a consequence, the heat generated by the light emitted from these high radiant exitance LED devices was comparable to or even higher than the heat generated from QTH lights [42].

In addition, the type of curing light, radiant exposure, radiant exitance values, and light beam profile play an important role in pulp temperature rise [42, 59, 99, 100]. In this regard, curing lights emitting light with higher radiant exitance for longer exposure periods generate more heat than lights with lower radiant exitance values [100]. Furthermore, the design of the LCU has been shown to influence the pulp temperature rise during light exposure. For instance, LED units with diodes placed on the light tip may cause a higher pulp temperature rise [101].

Light curing modes: Studies have shown that the rapid polymerization of resin composites can lead to the formation of short polymer chains, shortening the pre-gel phase, so that the materials cannot adequately absorb the shrinkage stress of polymerization [102]. With a view to controlling the effect of polymerization shrinkage stemming from polymerization contraction stresses recent developments have focused on various alternative irradiation protocols such as soft-start polymerization or pulse mode [103]. Soft-start polymerization is characterized by using an initial low radiant exitance of the curing light followed by a higher radiant exitance [62, 104]. As for pulse mode, it is initiated by a short flash of light followed by a relaxing time of several minutes before the final cure is performed [105]. On other hand, ramp [exponential] curing mode refers to the application of an initial low radiant exitance that is logarithmically increased up to a maximum value, followed by a final high radiant exitance. Finally, pulse delay mode refers to the application of an initial short pulse of light, followed by a waiting time [hiatus] before the final light exposure is performed [106].

These techniques allow the composite resin to flow from the tooth surface, reduce stress, and potentially improve the marginal integrity of the restoration [105,107]. However, if alternative modes were to be used for the polymerization of resin composites in order to realize these advantages, prolonged curing time may be necessary [72], and this may affect pulpal temperatures.

To date, published data are inconsistent with regard to the effect of curing modes on the heat generated by the polymerization of resin composite. Some studies have shown that alternative curing modes generate lower heat than the standard mode, while other studies have shown completely different results (Table 2 a-c). This difference may be because the vast majority of authors concluded their results from experiments that used several extracted teeth. In fact, the thermal conductivity of dentin differs among teeth came from different individuals [108]. Therefore, the results of these studies may be questionable. We can conclude that both the radiant exitance and the total energy delivered to the material have a considerable influence on temperature rise regardless of curing mode.

Table 2a: Summary of studies evaluated the effect of curing modes on the temperature rise.

Curing mode	Study	Curing mode and LCU used	Significant differences in temperature rise values compared with standard mode
Ramp	[Hofmann 2002] [109]	Cycles of exponential energy output automatically increased to full energy within 10 s [1100 mW/cm^2] +10 s full energy using a [LED; Mini LED, Satelec, Merignac, France]	Significantly higher [p<0.05]
	[Atai 2009] [110]	A gradual increase of radiant exitance from 100 mW/cm^2 to full strength during 10 s + full strength of 10 s using an Optilux 501, halogen bulb [Kerr, USA].	Significantly higher [p<0.05]
	[Al-Qudah 2007] [55]	A 20-s mode consists of an initial 10-s ramp cure, from 100 mW/cm^2 to a second output phase in excess of 1000 mW/cm^2 using Optilux 501 [Kerr, Peterborough, UK].	Significantly lower [p<0.01]

Table 2b: Continuing part of the summary of studies evaluated the effect of curing modes on the temperature rise- part II.

Curing mode	Study	Curing mode and LCU used	Significant differences in temperature rise values compared with standard mode
Pulse	[Hofmann 2002] [109]	The cycle consists of 10 successive 1-second flashes at full power pulse activation mode,	No statistically significant [p>0.05]

		with a rest period of 250ms between flashes using a [LED; Mini LED, Satelec, Merignac, France]	
	[Szalewski 2021] [111]	5/10 shots of 1 s [full power with emission of 5/10 successive one-second flashes with a rest of period of 250 ms between each flash] using a Mini LED III Supercharged, Acteon Group, Merignac, France].	No statistically significant [p>0.05]
	[Chang 2013] [112]	Consisted of irradiation with 1200 mW/cm^2 for 0.1 s and a 0.05 s pause alternating for 20 s using a LED [Dr's Light, GoodDoctors Co., Seoul, Korea].	No statistically significant [p>0.05]

Table 2c: Continuing part of the summary of studies evaluated the effect of curing modes on the temperature rise- part III.

Curing mode	Study	Curing mode and LCU used	Significant differences in temperature rise values compared with standard mode
Soft-start	[Chang 2013] [112]	Consisted of increasing power density from 0 to 600 mW/cm^2 for 5 s and thereafter in the full strength of 1200 mW/cm^2 for 15 s using a LED [Dr's Light, GoodDoctors Co., Seoul, Korea].	No statistically significant [p>0.05]
	[Hubbezoglu 2008] [113]	A progressive cycle lasting 20 s using [Mini LED, Satelec, Merignac, France].	Significantly higher [p<0.05]
	[[Dogan 2009] [48]	Radiant exitance increase from 0 to1100mW/cm^2 +1100mW/cm^2 [20seconds]	Significantly higher [p<0.05]

Critical parameters for the use of LCUs

Studies have reported a wide range of heat generated by LCU in the in vitro pulp temperature rise during exposure to curing light (Table 3). Such a discrepancy among results might be related to the variety of LCU types, brands, and irradiances evaluated in those studies, differences in tooth type and anatomy, the presence of cavities either with or without restorative procedures, as well as the thickness of remaining pulpal wall [40,68,99, 114-117]. Those differences between methods do not allow any reliable comparison among studies in order to establish a critical parameter for the use of LCUs to reduce the risk of pulpal damage, several in vitro studies concluded that light emitted from high-power LCUs can be harmful to the pulp depending on the radiant exitance and exposure period [100]. Indeed, based on in vitro results, some authors suggested that the use of LCUs with higher irradiance values than 1,000 mW/cm^2 may harm the pulp tissue [12]. Similarly, other authors advised that clinicians should limit the exposure time to 20 s when the irradiance from LED units is over 1,200 mW/cm^2, while the exposure period should not be longer than 10 s when the LCU irradiance ranges from 2,000 to 3,000 mW/cm^2 [115]. However, in vitro simulation does not reproduce the complexities of an in vivo scenario, which includes the presence of pulp tissue and the dynamic blood flow mechanisms to control pulp temperature [7]. Therefore, care should be taken when interpreting in vitro results.

Runnacles performed an in vivo study to examine the temperature rise of human premolars [100]. In that study, the probe of a temperature acquisition system was inserted within the pulp of anesthetized upper premolars, and a significant rise in pulp temperature was observed when the buccal surface was exposed to light emitted from a polywave® LED unit at varying radiant exposure values. A linear relationship between radiant exposure values (J/cm^2) and pulp temperature rise was established, so the previous in vitro findings that higher irradiance together with longer exposure periods is responsible for higher pulpal temperature rise were confirmed in vivo. However, in contrast to previous in vitro results, longer exposure periods (60 seconds) were required in vivo to cause a pulp temperature rise to values higher than 5.5°C when light with radiant exitance values of approximately 1,200 MW/cm^2 was delivered to intact premolars. The pulp temperature values recorded in vivo were also lower than the in vitro ones from studies simulating pulp flow at varying flow rates, which are known to act as heat sinks [114]. Therefore, the lower pulpal temperature rise observed in vivo confirms that the dynamic changes in the pulp when temperature changes in this tissue occur are crucial when regulating pulp temperature in vivo [118].

Table 3: Summary of the temperature rise values recorded.

Study	LCU	Exposure time [s]	Radiant exitance [mW/cm^2]	Temperature rise [℃]
(Baroudi 2009) [68]	QTH	40	500	1.3
	LED		1100	4.5
(Kodonas 2009) [114]	QTH Diode laser	30 15	1200 2000	7-10.4 10.5-16.6
(Park 2010) [115]	QTH	30	1200	41.4
	LED	60	3000	53.8
(Leprince 2010) [99]	LED	10	1600	3.82-6.91
(Yazici 2006) [49]	QTH	40	550	2.3-2.9
	LED		400	1.4-2.4
	PAC	3	1980	1.6-2.4
(Eldeniz 2005) [119]	LED	40	380	6.04

Methods to reduce the temperature rise

Despite all concerns about increased pulp temperature during LCU light, few attempts have been made to establish alternative approaches to avoid excessive increases in pulp temperature during restorative procedures using LCU [101]. A study of Onisor evaluated the effects of alternative approaches to reduce pulp temperature rise during exposure to LCU light and found that airflow, water, or air/water spray applied during the exposure to LCU light were capable of reducing the pulp temperature rise in extracted molars restored with indirect ceramic restoration [101]. However, the use of water or air/water spray during the exposure of resin composite layers to light on direct restorative procedures should be avoided as water may impair the bonding between the adhesive layer and resin composite, as well as the resin [120]. Therefore, although further in vitro and in vivo studies are still required, directing a stream of air toward the tooth during exposure to light seems promising.

Some clinicians may believe that other methods, such as increasing the distance between the LCU tip and the tooth or reducing the irradiance, can help protect the pulp against thermal injury. However, because the drop in the radiant exitance values with increasing distance between the LCU tip and the tooth may vary among LCUs, such procedures may compromise optimal polymerization of the resin composite in the most difficult regions for the light to reach in the cavity, such as cervical regions of Class II cavity preparations [10,11].

Limitations of current experimental studies

In spite of the extensive research thus far, significant discrepancy still exists between experimental measurements and mathematical modeling. studies reported that the temperature predicted by existing numerical models could not be used directly as temperature changes in vivo [121]. The discrepancy indicates that some of the assumptions made when developing these models are not realistic.

The factors that prohibit the development of a sound and conclusive model include:

- The physical properties of teeth vary in different teeth [incisor, canine, molar] and different donors including ages, sex, and races. Even for a single tooth, its physical properties differ from one layer to another and are anisotropic as well as inhomogeneous in each layer [122,123]. While, in the existing models, teeth are treated as layered materials and assumed to be homogenous, isotropic, and linearly elastic in each layer. Such simplifications lead to an inaccurate presentation of tooth heat transfer and hence prohibit the predictions to be directly used as guidance for clinical applications.
- The thermal boundary conditions in the tooth, especially the part under the gum are too complex to be determined. In the existing models, these boundary conditions have been simplified (e.g., using oral temperature as the constant temperature) [124].

Conclusion

The findings of this review revealed that:

- There were several factors effect on the pulp chamber temperature during the polymerization of light-curing materials.
- Dentin thickness is an important factor to protect the pulp from thermal damage. Therefore, particular attention should be paid to deep preparations where the thickness of the remaining dentin is minimal.
- Among the strategies applied, the use of light-curing sources with high radiant exitance seemed to make a greater temperature rise than the use of traditional sources.
- The clinicians should be aware of the potential thermal hazard to the dental pulp which might arise as the result of the use of light-curing pulp-capping and restorative materials.
- High-powered LCU should be cautiously used for the polymerization of bonding agents in deep cavities.

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