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Thermal Behavior of Dental Composites During Photopolymerization: Effect of Material Type, Increment Thickness, and Light Intensity

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Abstract

Heat generated during photopolymerization of resin-based composites from both the exothermic reaction of the material and the irradiance of light-curing units poses a risk to pulp vitality, especially in deep restorations. This study aimed to evaluate temperature variation (ΔT) during the photopolymerization of different resin composites, considering material type, shade, increment thickness, and light curing unit output. An in vitro experimental study with a factorial design was conducted. Specimens were prepared using 2.0 mm and 4.0 mm increments from conventional (nanohybrid), bulk-fill, and flowable resin composites in different shades (BW, A1, A3, A4, and XB) and different light curing unit output (100% and 50% battery charge). ΔT was measured using a type K thermocouple (Omega Engineering, Norwalk, CT, USA) positioned at the center of each increment. Data were analyzed using four-way analysis of variance (ANOVA) ($\alpha = 0.05$). All groups demonstrated a statistically significant temperature increase ($p < 0.05$), with ΔT values ranging from 3.24 °C to 18.18 °C. Composite type significantly influenced ΔT ($p < 0.001$), with flowable composites showing the highest temperature rise, followed by bulk-fill and conventional composites. Increment thickness also had a significant effect ($p = 0.008$), with 4.0 mm increments producing greater temperature increases. Shade significantly affected ΔT ($p < 0.001$), with the XB shade exhibiting the highest values. Additionally, higher light-curing output (100%) resulted in significantly greater temperature increases compared to 50% output ($p < 0.001$). Photopolymerization temperature rise is influenced by multiple interacting factors. The combination of flowable composites, darker shades, thicker

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increments, and higher curing output may increase thermal risk. These findings should be considered when optimizing clinical protocols to minimize potential pulpal damage.

Keywords: Photopolymerization; Resin-based composites; Restorative dentistry; Temperature variation.

1. Introduction

Contemporary restorative dentistry has evolved significantly with the development of advanced materials and techniques aimed not only at restoring tooth morphology but also at improving durability and biocompatibility with dental tissues [1]. In this context, photopolymerization of resin-based composites is a fundamental step for clinical success, enabling the conversion of monomers into a stable polymeric network [2].

Photopolymerization induces a fundamental structural transformation within resin-based materials. Initially, the organic resin matrix is composed of dimethacrylate monomers and oligomers, such as bisphenol A glycidyl methacrylate (Bis-GMA), urethane dimethacrylate (UDMA), and triethylene glycol dimethacrylate (TEGDMA), arranged in a low-viscosity, loosely associated configuration. Upon light activation, photoinitiator systems generate free radicals that trigger the opening of carbon–carbon double bonds, leading to chain propagation and the formation of long polymer chains. As polymerization progresses, these chains become increasingly interconnected, resulting in a highly cross-linked three-dimensional polymer network. This transition from a dispersed molecular system to a rigid covalent structure is accompanied by a reduction in intermolecular spacing, increased rigidity, and the development of polymerization shrinkage. In resin-based composite materials containing inorganic fillers, these filler particles are simultaneously embedded and mechanically locked within the polymer network through silane coupling agents, forming a reinforced heterogeneous structure that governs the final mechanical and physical behavior of the material [1-5].

However, the polymerization process is associated with heat generation, resulting from both the exothermic reaction and the energy emitted by light-curing units [3]. Previous studies have demonstrated that different light sources and irradiation protocols may lead to significant temperature increases, potentially affecting pulp vitality [4-6].

The rise in temperature within the pulp chamber is a clinically relevant concern, as increases exceeding approximately 5.5°C may cause irreversible pulp damage [7]. Therefore, controlling thermal effects during photopolymerization is essential, particularly in deep cavities with reduced remaining dentin thickness [8]. In addition to pulpal implications, excessive heat generation may also affect the adhesive interface, accelerating degradation processes and potentially compromising long-term restoration performance [9].

Several factors influence heat generation during photopolymerization, including composite type, chemical composition, filler content, translucency, shade, increment thickness, and light-curing unit characteristics [10-13]. Composites with a higher organic matrix content, such as flowable materials, tend to generate more heat, whereas materials with higher filler loading exhibit greater thermal inertia [14].

Moreover, the thickness of the composite increment plays a critical role in thermal behavior, as thinner layers have been shown to produce significantly higher temperature increases compared to thicker increments due to reduced heat dissipation capacity [15].

Bulk-fill composites, on the other hand, have been developed to allow placement in thicker increments, with modified polymerization kinetics that may influence thermal behavior [16]. Although these materials permit increments up to 4 mm, concerns remain regarding heat accumulation in deeper regions, where limited heat dissipation and increased exothermic reaction may result in higher intrapulpal temperature rise [17]. Additionally, composite shade can affect light absorption and energy distribution within the material [18].

Darker shades have been reported to generate and retain more heat than lighter shades, likely due to increased light absorption and reduced light transmission through the material. In contrast, lighter shades may allow deeper light penetration but can still produce significant thermal effects depending on curing conditions [19].

Furthermore, differences in composite formulation, particularly in photoinitiator systems and filler composition, can influence heat generation, as materials requiring higher energy density for polymerization tend to produce greater temperature rises during curing [20].

Despite advances in this field, there is still a lack of studies evaluating these variables in an integrated manner under standardized experimental conditions.

Most available studies have investigated these factors independently, with limited data assessing their combined influence on intrapulpal temperature rise, which is more representative of clinical conditions [15,19-22]. Therefore, this study aimed to assess temperature variation (ΔT) during the photopolymerization of different resin composites, considering material type, shade, increment thickness, and light-curing unit output. The null hypothesis is that there is no change in the temperature of the composite resin during polymerization, regardless the material type, shade and increment thickness.

2. Materials and Methods

2.1. Study Design

This was an in vitro experimental study with a quantitative approach and a factorial design. The ΔT was evaluated according to the following factors: (1) type of resin composite on three levels: conventional nanohybrid, bulk-fill, and flowable; (2) shade of the material on five levels: BW, A1, A3, A4, and XB; (3) height increment on two levels: 2 and 4 mm; and (4) light curing unit output (100% and 50% battery charge).

The sample size was determined based on previous studies evaluating thermal variation during photopolymerization, which commonly employ standardized increments of approximately 2 or 4 mm thickness to simulate clinical conditions, ensuring adequate light penetration and polymerization efficiency. This thickness is widely accepted as the maximum increment for conventional resin composites, allowing reliable comparison of thermal effects during curing procedures [21,22]. Considering a minimum detectable difference of 3°C, standard deviation of 2.5°C, statistical power of 80%, and significance level of 5%, a minimum of 8 specimens per group was required. To increase statistical robustness, 10 specimens per group were included, totaling 240 samples distributed across 24 groups. The experiment was conducted under controlled laboratory conditions, including standardized ambient temperature (23C +/- 2), lighting, and humidity (50%).

Cylindrical specimens were prepared using standardized molds with 2.0 mm diameter and heights of 2.0 mm and 4.0 mm, representing conventional and bulk increments, respectively. The layer thickness was determined by the internal height of the molds. The following methodology was used to ensure and verify the specified thicknesses: (1) the internal height of each mold was measured three times using a digital caliper (Mitutoyo Corp., Kawasaki, Japan) with an accuracy of ±0.01 mm prior to specimen preparation; (2) the composite material was inserted into the mold and gently pressed flat against the top and bottom surfaces of the mold using a glass slide to ensure the specimen conformed exactly to the mold height; (3) any excess material was removed with a scalpel; and (4) after removal from the mold, the final thickness of each specimen was confirmed using the same digital caliper. All molds were positioned on a 10-mm-thick glass plate, which also served as a stable base for thermocouple positioning.

Each mold contained a central channel to allow insertion of a type K thermocouple (Omega Engineering, Norwalk, CT, USA), which was positioned at the geometric center of the composite increment for accurate temperature measurement.

Specimens were prepared using three types of resin composites: a conventional nanohybrid composite (Filtek Z350 XT, 3M ESPE, St. Paul, MN, USA), a bulk-fill composite (Filtek Bulk Fill Posterior, 3M ESPE, St. Paul, MN, USA), and a flowable composite (Filtek Flow, 3M ESPE, St. Paul, MN, USA), in shades BW, A1, A3, A4, and XB. Conventional and bulk-fill materials were inserted using a composite instrument (Suprafill, Dentsply Sirona, York, PA, USA) in a single increment. For flowable composites, due to their low viscosity, the material was directly dispensed through the manufacturer's syringe after positioning the thermocouple. Figure 1 illustrates the experimental design and workflow of the study.

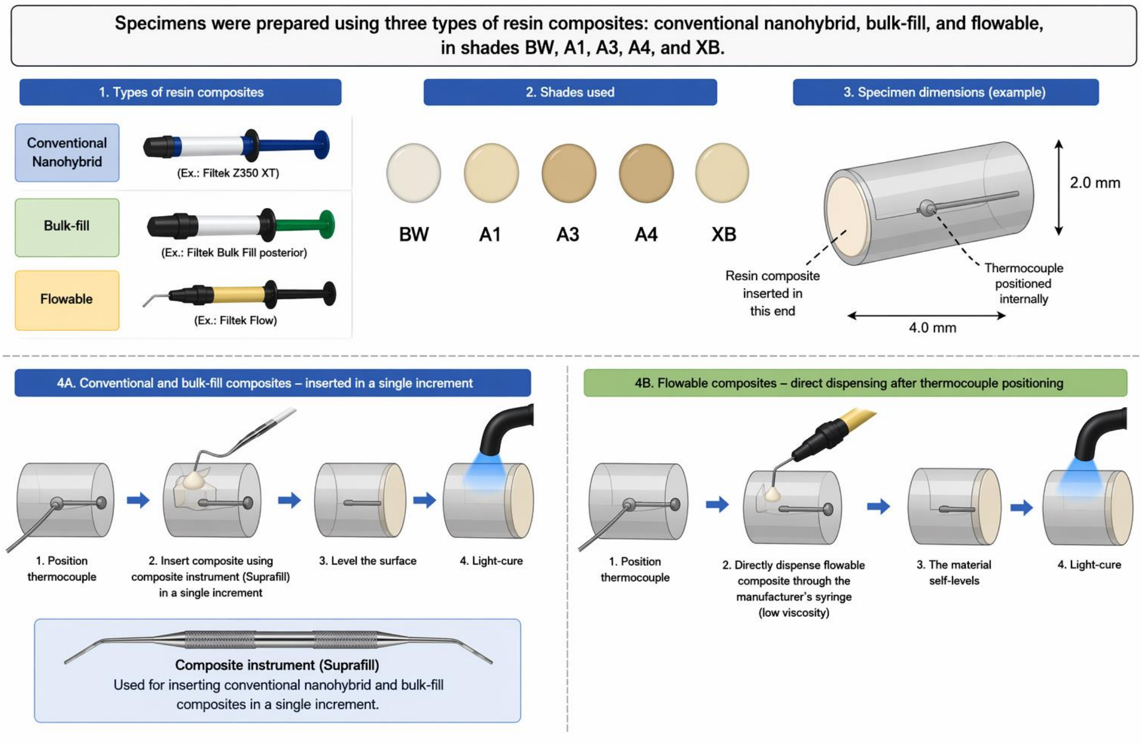

Figure 1. The overall study design.

A glass coverslip (1.0 mm thickness) was placed over each specimen to prevent direct contact between the light-curing tip and the composite surface. Initial temperature was recorded prior to light activation. Photopolymerization was performed using an light emitted diode (LED) polywave light-curing unit (VEGA light-curing unit (Dentac, Istanbul, Turkey)) with a soft start irradiance of 1200 mW/cm^2.

The curing process parameters were standardized according to the manufacturer's recommendations to ensure clinical relevance and reproducibility. No experimental modification of curing time, irradiance, or curing distance was performed. A standardized protocol (20 s of application) was applied for all specimens, with the light guide tip positioned perpendicular to the specimen surface under consistent conditions.

The illumination intensity (irradiance) of the LED light-curing unit was measured using a calibrated Radiometer X (SDI, Victoria, Australia) prior to the experimental procedures. The light guide tip was positioned perpendicular and in direct contact with the sensor surface to ensure standardized and reproducible measurement conditions. Irradiance values were recorded under two conditions: at full battery charge (100%) and at 50% charge, in order to evaluate the effect of power level on light output stability. Three consecutive measurements were performed for each condition, and the mean value was calculated and used for analysis. The radiometer was used according to the manufacturer's instructions to ensure measurement accuracy and consistency. Maximum temperature during curing was recorded, and ΔT was calculated as the difference between peak and baseline temperature.

The chemical composition of the resin composites used in this study is summarized in Table 1. This table includes detailed information on the resin matrix composition, filler type and size, as well as filler loading for each material.

The conventional nanohybrid composite is composed of a dimethacrylate-based resin matrix, including bisphenol A glycidyl methacrylate (Bis-GMA), urethane dimethacrylate (UDMA), triethylene glycol dimethacrylate (TEGDMA), and ethoxylated bisphenol A dimethacrylate (Bis-EMA). Its inorganic phase consists of a hybrid filler system combining non-agglomerated silica nanoparticles (approximately 20 nm), zirconia nanoparticles (4–11 nm), and aggregated zirconia–silica clusters, resulting in a high filler loading that improves mechanical strength and optical properties.

The bulk-fill composite is based on a modified resin matrix containing aromatic urethane dimethacrylate (AUDMA), UDMA, addition–fragmentation monomer (AFM), and 1,12-dodecane dimethacrylate (DDDMA). Its filler system includes silica, zirconia, and ytterbium trifluoride particles, designed to enhance light transmission and allow increased depth of cure in thicker increments.

The flowable composite contains a reduced filler loading and a higher proportion of organic resin matrix, consisting of Bis-GMA, UDMA, and TEGDMA. Its filler phase includes silica and zirconia nanofillers with a lower overall volume fraction, which accounts for its reduced viscosity and improved adaptability but also its distinct thermal behavior during polymerization.

Table 1. Chemical composition of the resin composites used in this study.

Material	Manufacturer	Type	Resin Matrix Composition	Filler Composition	Filler Load
Filtek Z350 XT	3M ESPE, St. Paul, MN, USA	Nanohybrid composite	Bisphenol A-glycidyl methacrylate (Bis-GMA), urethane dimethacrylate (UDMA), triethylene glycol dimethacrylate (TEGDMA), ethoxylated bisphenol A dimethacrylate (Bis-EMA)	Non-agglomerated silica (20 nm), zirconia (4–11 nm), aggregated zirconia/silica clusters	~78.5 wt% (~63.3 vol%)
Filtek Bulk Fill Posterior	3M ESPE, St. Paul, MN, USA	Bulk-fill composite	Aromatic urethane dimethacrylate (AUDMA), urethane dimethacrylate (UDMA), addition–fragmentation monomer (AFM), 1,12-dodecane dimethacrylate (DDDMA)	Silica, zirconia, ytterbium trifluoride	~76.5 wt% (~58.4 vol%)
Filtek Flow	3M ESPE, St. Paul, MN, USA	Flowable composite	Bisphenol A-glycidyl methacrylate (Bis-GMA), urethane dimethacrylate (UDMA), triethylene glycol dimethacrylate (TEGDMA)	Silica, zirconia nanofillers	~65 wt% (~46 vol%)

Although precise proprietary details of filler distribution are not fully disclosed by manufacturers, the information presented is based on technical data sheets and published literature describing the typical nanostructure of these resin-based composites.

2.2. Statistical Analysis

Data were analyzed using SPSS (IBM Corp., Armonk, NY, USA). Normality was assessed using the Shapiro–Wilk test, and homogeneity of variances was verified using

Levene's test. A four-way factorial analysis of variance (ANOVA) was performed to evaluate the effects of composite type, increment thickness, shade, and light-curing output on ΔT, including their main effects. When significant differences were detected, post hoc pairwise comparisons were performed using Tukey's honestly significant difference (HSD) test. A paired t-test was used to compare initial and final temperatures within each group. The level of significance was set at $p < 0.05$.

3. Results

The overall mean initial temperature was 23.32°C (±1.12°C), and the mean final temperature was 31.23°C (±5.32°C), yielding an overall mean temperature increase (ΔT) of 7.91°C (±4.68°C). All groups showed a statistically significant temperature increase during photopolymerization ($p < 0.05$). Composite type significantly influenced ΔT ($p < 0.001$). Flowable composites exhibited the highest ΔT values (mean: 12.52°C ± 3.88°C), followed by bulk-fill (5.76°C ± 1.54°C) and conventional composites (5.46°C ± 1.86°C).

Increment thickness significantly affected ΔT ($p = 0.008$). The 4.0 mm increments resulted in higher temperature increases (9.09°C ± 4.86°C) compared to 2.0 mm increments (6.74°C ± 3.13°C).

Shade significantly influenced ΔT ($p < 0.001$). The XB shade showed the highest temperature rise, followed by A3, whereas BW, A1, and A4 exhibited lower and similar values.

Light-curing output also significantly influenced temperature variation ($p < 0.001$), with specimens cured at 100% output demonstrating higher ΔT values (9.44 °C ± 4.51 °C) compared to those cured at 50% output (6.39 °C ± 3.31 °C).

The lowest ΔT (3.24°C) was observed in the conventional composite (A4, 4.0 mm, 50%), while the highest ΔT (18.18°C) occurred in the flowable composite (A3, 4.0 mm, 100%).

Detailed temperature values for each experimental condition are presented in Table 2, while the mean temperature variations according to the tested variables are summarized in Table 3.

It is important to mention that the temperature variation (ΔT) was calculated for each experimental specimen using the raw temperature data reported in Table 2. The calculation was performed using the equation $\Delta T = Tf - T0$, where T0 represents the initial temperature and Tf represents the final temperature recorded during photopolymerization. Each experimental condition listed in Table 2 corresponds to a single measurement from which ΔT was derived.

To generate the results presented in Table 3, individual ΔT values were grouped according to each experimental factor (composite type, shade, increment thickness, and light-curing unit output). For each group, mean values and standard deviations were calculated from the corresponding individual ΔT values.

For example, in the flowable composite group (Table 2, Groups 17–24), individual ΔT values ranged from 7.07°C to 18.18°C depending on shade, thickness, and curing output. These values were averaged to obtain the mean ΔT reported for flowable composites in Table 2 (12.52°C ± 3.88°C).

Table 2. Temperature variation (ΔT) according to experimental conditions.

Group	Composite	Shade	Thickness (mm)	Output	Initial Temp T0 (°C)	Final Temp Tf (°C)	ΔT (°C)
1	Conventional	BW	2.0	100%	23.94	28.76	4.82
2	Conventional	BW	2.0	50%	22.83	26.97	4.14
3	Conventional	BW	4.0	100%	23.81	32.94	9.13
4	Conventional	BW	4.0	50%	23.70	28.43	4.73
5	Conventional	A4	2.0	100%	23.77	30.52	6.75
6	Conventional	A4	2.0	50%	22.65	27.63	4.98
7	Conventional	A4	4.0	100%	23.54	31.22	7.68
8	Conventional	A4	4.0	50%	23.41	26.65	3.24
9	Bulk-fill	A1	2.0	100%	23.60	29.84	6.24
10	Bulk-fill	A1	2.0	50%	22.91	27.56	4.65
11	Bulk-fill	A1	4.0	100%	23.73	31.88	8.15
12	Bulk-fill	A1	4.0	50%	23.48	27.92	4.44
13	Bulk-fill	A3	2.0	100%	23.68	30.94	7.26
14	Bulk-fill	A3	2.0	50%	22.74	27.96	5.22
15	Bulk-fill	A3	4.0	100%	23.52	32.67	9.15
16	Bulk-fill	A3	4.0	50%	23.33	28.41	5.08
17	Flowable	XB	2.0	100%	22.88	33.61	10.73
18	Flowable	XB	2.0	50%	21.95	29.02	7.07
19	Flowable	XB	4.0	100%	22.71	36.48	13.77
20	Flowable	XB	4.0	50%	22.10	31.35	9.25
21	Flowable	A3	2.0	100%	22.64	35.12	12.48
22	Flowable	A3	2.0	50%	21.83	30.94	9.11
23	Flowable	A3	4.0	100%	22.53	40.71	18.18
24	Flowable	A3	4.0	50%	21.69	30.86	9.1

Table 3. Mean temperature variation (ΔT) according to experimental factors (mean ± SD).

Variable	Category	ΔT (°C, mean ± SD)	p-value
Composite type	Conventional	5.46 ± 1.86	<0.001
	Bulk-fill	5.76 ± 1.54	
	Flowable	12.52 ± 3.88	
Thickness	2.0 mm	6.74 ± 3.13	0.008
	4.0 mm	9.09 ± 4.86	
Output	50%	6.39 ± 3.31	<0.001
	100%	9.44 ± 4.51	
Shade	BW	5.71 ± 2.30	<0.001
	A1	5.82 ± 1.48	
	A3	9.23 ± 4.71	
	A4	5.22 ± 1.61	
	XB	12.28 ± 4.44	

Figure 2 illustrates the effect of the main process parameters of the light-curing unit on thermal behavior (ΔT).

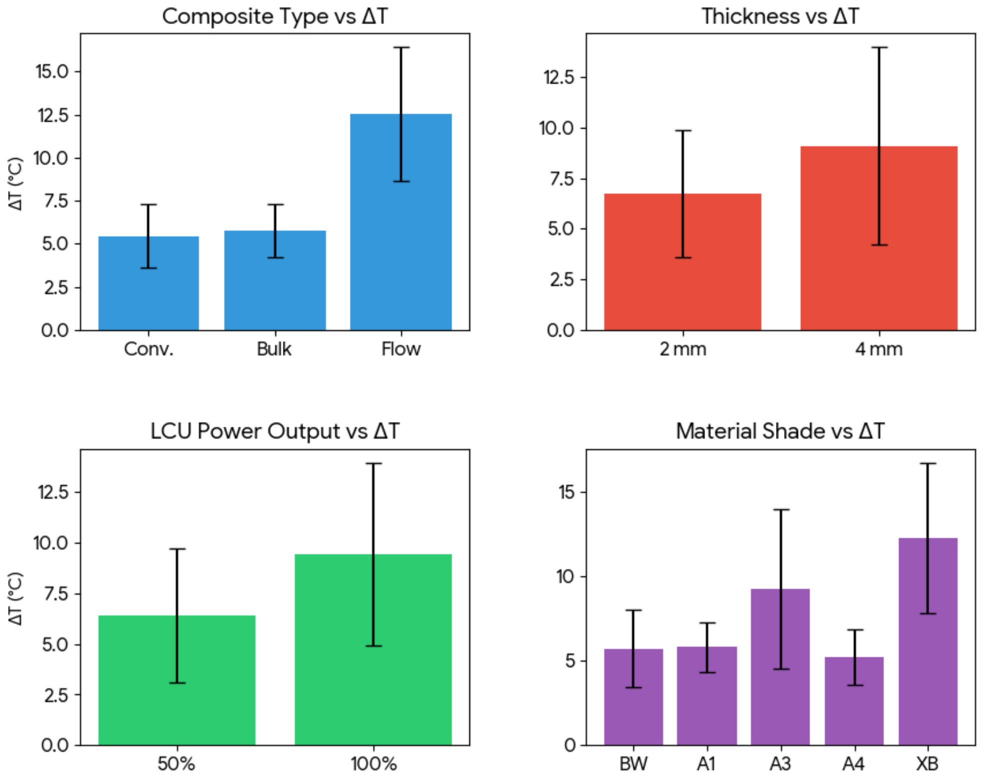

Figure 2. Effect of composite type, thickness, power output, material shade on temperature rise.

4. Discussion

The present study demonstrated that photopolymerization of resin-based composites results in a significant temperature increase, influenced by multiple factors including composite type, increment thickness, shade, and light-curing output. These findings reinforce the multifactorial nature of thermal behavior during restorative procedures and highlight clinically relevant risks associated with certain material and technique combinations [20-22]. Thus, the null hypothesis tested is rejected.

Among the evaluated variables, composite type showed the strongest influence on temperature rise. Flowable composites exhibited significantly higher ΔT values compared to bulk-fill and conventional materials. Flowable composites are resin-based restorative materials characterized by a reduced filler loading and a higher proportion of organic resin matrix, resulting in lower viscosity and increased flowability. This composition enhances their adaptability but also modifies their thermal behavior during photopolymerization. Due to their higher resin content, flowable composites exhibit a greater exothermic polymerization reaction and reduced thermal conductivity compared with more highly filled materials, which limits heat dissipation. As a result, these materials tend to generate higher temperature increases during curing and may present a greater thermal risk, particularly in deep cavities with limited remaining dentin thickness. This behavior can be explained by their lower filler content and higher proportion of organic matrix, which increases the exothermic component of the polymerization reaction. Additionally, their greater translucency may allow deeper light penetration, enhancing the degree of conversion and, consequently, heat generation. Flowable resins also exhibit higher heat release due to increased polymerization shrinkage kinetics and reduced thermal conductivity compared with highly filled materials. Additionally, increased translucency enhances light penetration, resulting in a higher degree of conversion and greater heat generation [23,24].

Bulk-fill composites demonstrated intermediate thermal behavior, which may be attributed to their modified photoinitiator systems and controlled polymerization kinetics. These materials are designed to allow thicker increments while reducing polymerization stress; however, their thermal profile remains dependent on both material composition and curing conditions [25,26].

Increment thickness was another significant factor affecting temperature variation. The higher ΔT observed in 4.0 mm increments can be explained by the larger volume of reactive material, leading to increased total heat release. This finding is consistent with previous studies indicating that greater composite mass intensifies the exothermic reaction and may compromise thermal safety, particularly in deep cavities with limited dentin thickness [27,28]. However, thermal behavior is not solely dependent on material volume. As previously demonstrated, increasing composite thickness may paradoxically reduce surface temperature rise due to light attenuation within the material, which decreases the degree of polymerization in deeper layers [15]. McCabe and Lloyd et al. showed that thicker specimens may exhibit lower surface temperature increases despite increased mass, due to reduced light transmission and energy dissipation through scattering phenomena [29,30]. Similarly, Watts et al. reported that resin composites possess thermal diffusivity comparable to dentin, suggesting that heat dissipation is strongly influenced by surrounding structures rather than material thickness alone [31].

These findings collectively suggest that during incremental placement, the highest pulpal temperature rise may occur during the first increment, where light energy is least attenuated and polymerization is most efficient. This dual contribution of exothermic reaction and light-curing energy explains the complex, non-linear relationship between thickness and temperature increase observed in the present study.

Composite shade significantly influenced ΔT. The XB shade showed the highest ΔT values, followed by A3, whereas BW, A1, and A4 exhibited lower and relatively similar temperature increases. This effect may be explained by differences in light absorption and scattering related to pigment concentration and optical properties of the resin composites. Darker or more chromatic shades contain higher levels of pigments and opacifiers, which increase light absorption and reduce light transmission through the material. As a result, a greater proportion of the curing light energy is converted into heat rather than being uniformly transmitted through the composite. This leads to localized energy accumulation and higher thermal peaks during polymerization. In contrast, lighter shades (BW and A1) allow more efficient light penetration and more homogeneous energy distribution, resulting in lower temperature increases. These findings are consistent with the photophysical behavior of resin composites, where increased chromaticity is associated with greater optical attenuation and higher thermal conversion during light-curing [32-37].

Importantly, this shade-dependent thermal behavior is not solely determined by the nominal shade designation but also by the intrinsic material composition defined by each manufacturer. Contemporary composite systems, such as those developed by Olident, incorporate nano-spherical fillers (<0.2 μm) that enhance surface smoothness and optical properties, as well as refined pigment distributions and refractive index matching strategies. In addition, the use of universal opacity concepts and multi-layered shade systems (including enamel, dentin, and translucent opalescent effects) may further influence light transmission and scattering within the material. These structural and optical modifications, while primarily designed to optimize esthetic outcomes and clinical workflow, may also alter the way light energy is absorbed, transmitted, and converted into heat during polymerization. Consequently, composites with similar shade labels but different formulations may exhibit significantly different thermal responses.

Furthermore, the characteristics of the light-curing unit play an important role in modulating the polymerization process and the associated thermal response of resin-based composites. In the present study, the VEGA light-curing unit (Dentac, Istanbul, Turkey) was selected due to its broad wavelength spectrum and irradiance output within the recommended range for contemporary resin composite systems. This spectral profile ensures compatibility with both camphorquinone-based and alternative photoinitiator systems, promoting efficient light absorption and consistent polymerization across different composite shades and thicknesses [38,39]. As demonstrated by the results, the use of this device enabled controlled and reproducible curing conditions, while confirming that temperature rise remains significantly influenced by irradiance level, reflecting the direct relationship between light energy delivery and thermal behavior.

From a clinical perspective, the optimized emission profile of the VEGA unit may contribute to a more uniform energy distribution within the material, potentially reducing localized heat accumulation. However, the present findings clearly indicate that thermal effects cannot be attributed to the light-curing unit alone. Instead, they are primarily governed by intrinsic material properties, including resin matrix composition, filler content, optical characteristics, and polymerization kinetics. Therefore, while the use of a clinically optimized light-curing unit such as VEGA is essential for ensuring reliable and standardized curing performance, the magnitude of temperature rise is predominantly determined by the characteristics of the composite material and the clinical application technique. Careful control of increment thickness, shade selection, and curing parameters remains critical to minimizing thermal risk and optimizing restorative outcomes.

Light-curing output also significantly influenced ΔT ($p < 0.001$), with specimens cured at 100% output demonstrating higher ΔT values (9.44 °C ± 4.51 °C) compared to those cured at 50% output (6.39 °C ± 3.31 °C). This finding can be explained by the direct relationship between irradiance intensity and the rate of photopolymerization. Higher light-curing output increases photon flux delivered to the resin, accelerating radical formation and increasing the rate of monomer conversion. This more rapid polymerization is associated with a higher exothermic reaction peak, resulting in greater heat release over a shorter time interval. In addition, high irradiance levels increase the energy density absorbed by the resin matrix, which contributes not only to polymerization heat but also to direct thermal transfer from the light-curing unit itself [40,41].

The combination of these two mechanisms, exothermic reaction and external heat input, explains the significantly higher ΔT observed under 100% output conditions. Conversely, reduced irradiance (50%) slows down the polymerization kinetics, allowing more gradual energy dissipation and improved thermal diffusion, thereby limiting peak temperature rise. These findings are consistent with previous investigations demonstrating that increased irradiance is strongly correlated with higher temperature rise and faster polymerization rates, although potentially at the expense of thermal safety in deep cavities with limited remaining dentin thickness [40-44]. Clinically, this highlights the importance of balancing curing efficiency with pulpal safety, particularly when using high-intensity or ultra-fast curing modes in deep restorations.

From a clinical perspective, the results are particularly relevant, as several experimental conditions resulted in temperature increases exceeding the critical threshold of approximately 5.5°C, which has been associated with irreversible pulp damage. This is especially concerning in deep restorations, where the remaining dentin thickness is reduced and the pulp is more susceptible to thermal injury.

Therefore, clinicians should carefully consider the combined effects of material selection, increment thickness, and curing protocol. The use of thinner increments, materials with higher filler content, and controlled light-curing strategies may help reduce thermal risk and improve biological safety.

Importantly, previous investigations have shown that temperature rise during resin composite polymerization has traditionally been measured using thermistors [45], thermocouples [46], differential scanning calorimetry [47], and differential thermal analysis [48], which provide only localized point measurements and may interfere with heat transfer due to direct contact with the material surface. In contrast, infrared thermography offers a non-contact, highly sensitive method capable of detecting small temperature variations (up to 0.1°C) while simultaneously providing a two-dimensional thermal map of the entire surface, allowing a more accurate representation of heat distribution during polymerization. This methodological advantage strengthens the reliability of temperature mapping in future studies compared to conventional point-based techniques [15].

Another important factor influencing the overall performance of resin-based composites is the cohesion between successive material layers, which refers to the integrity of the interlayer polymer network formed during incremental photopolymerization. This cohesion depends on the extent of polymer chain propagation and interdiffusion between the oxygen-inhibited layer of the previously cured increment and the newly applied resin layer. Effective interlayer cohesion occurs when sufficient residual carbon–carbon double bonds remain available at the surface of the underlying layer, allowing chemical bonding and the formation of a continuous crosslinked polymer network. In this context, the process parameters of the light-curing unit play a critical role. Higher irradiance and adequate exposure time enhance the degree of conversion at the interface, improving the availability of reactive groups for bonding and strengthening interlayer integration. Conversely, insufficient light intensity, inadequate curing time, or suboptimal wavelength matching may result in incomplete polymerization of the underlying layer, leading to weak interfacial bonding, microgaps, and potential delamination between increments. Light-curing distance and angulation further modulate this effect by reducing the energy reaching deeper layers, thereby compromising polymer network continuity. In addition, curing mode (continuous versus ramped or pulsed) may influence the kinetics of polymer formation and stress development, indirectly affecting interlayer cohesion. Overall, optimized light-curing parameters are essential not only for maximizing bulk polymerization but also for ensuring strong cohesion between successive layers, which is critical for the long-term mechanical integrity and clinical performance of layered resin-based restorations [37].

Although the present study focused primarily on thermal behavior during photopolymerization, it is important to acknowledge that clinical performance of resin-based composites is also governed by their physicomechanical properties, including wear resistance, surface hardness, and abrasion resistance. These properties are directly influenced by the degree of polymerization, filler-matrix interaction, and thermal stresses generated during curing. Inadequate polymerization or excessive thermal exposure may negatively affect surface integrity, increase susceptibility to wear, and accelerate material degradation under functional loading. Therefore, while temperature rise provides critical information regarding pulpal safety, it does not fully represent the long-term clinical durability of restorative materials. Future investigations should integrate thermal assessment with mechanical testing, such as abrasion resistance and fatigue behavior, to provide a more comprehensive evaluation of resin composite performance under clinically relevant conditions [49].

This study presents limitations inherent to in vitro designs. The absence of dentin and pulpal blood flow eliminates natural heat dissipation mechanisms present in clinical conditions, potentially leading to overestimation of temperature rise. Additionally, light-the battery level was used as an indirect parameter. Future studies should simulate pulpal conditions more closely.

All in all, the increase in photopolymerization temperature is influenced by multiple interacting factors related to material composition, light-curing parameters, and clinical conditions, as extensively reported in previous literature (Table 4) [1-48].

Table 4. Factors influencing temperature rise during photopolymerization.

Factor	Description of influence on temperature rise
Composite resin type (conventional, bulk-fill, flowable)	Flowable composites generate higher temperature due to lower filler content, higher resin matrix proportion, and greater exothermic polymerization. Bulk-fill materials show intermediate behavior due to modified chemistry.
Filler content and filler type	Higher filler loading increases thermal conductivity and reduces temperature rise by dissipating heat more efficiently. Low filler content increases heat accumulation.
Monomer composition (e.g., bisphenol A glycidyl methacrylate, urethane dimethacrylate, triethylene glycol dimethacrylate)	High-reactivity monomers and high resin content increase polymerization rate and exothermic heat release.
Photoinitiator system (e.g., camphorquinone, alternative initiators)	More efficient or higher concentration photoinitiators increase radical formation, accelerating polymerization and heat generation.
Light-curing unit irradiance (light intensity)	Higher irradiance increases energy input, accelerating polymerization kinetics and raising both exothermic and direct thermal contributions.
Exposure time	Longer curing increases total energy delivered, leading to higher cumulative temperature rise.
Light-curing mode (continuous, soft-start, pulse)	Continuous high-intensity modes produce higher peak temperature; ramped or pulsed modes reduce thermal spikes by moderating polymerization rate.
Emission spectrum (wavelength compatibility)	Better match with photoinitiator absorption increases efficiency of polymerization and associated heat generation.
Composite shade (lightness / chroma)	Darker shades absorb more light energy, converting more radiation into heat and increasing temperature rise.
Increment thickness	Thicker increments increase total exothermic reaction due to greater material volume, but may reduce surface heat due to light attenuation.
Distance between light tip and material surface	Increased distance reduces irradiance reaching the material, decreasing polymerization efficiency and temperature rise at the interface.
Cavity configuration and remaining dentin thickness	Thinner dentin increases heat transmission to pulp, reducing thermal insulation and increasing intrapulpal temperature rise.
Thermal properties of surrounding tissues/materials	Dentin and surrounding structures act as thermal barriers; reduced thickness leads to increased heat transfer to pulp.

5. Conclusions

Temperature rise during the photopolymerization of resin-based composites is a multifactorial phenomenon influenced by material properties and curing parameters. The present study demonstrated that composite type, increment thickness, shade, and light-curing unit output all significantly affect thermal behavior.

Flowable composites, thicker increments, darker shades, and higher light-curing intensity were associated with greater temperature increases, reflecting the combined effect of higher exothermic polymerization and light energy absorption. These findings highlight the importance of considering both material composition and curing protocols when performing restorative procedures.

From a clinical perspective, excessive temperature rise may pose a risk to pulpal health, particularly in deep cavities with reduced remaining dentin thickness. Therefore, careful selection of composite materials, optimization of incremental layering, and appropriate adjustment of curing parameters are essential to minimize thermal stress and ensure biological safety while maintaining optimal restorative performance.

Future studies should further investigate these variables under more clinically simulated conditions, including the presence of dentin substrates and pulpal blood flow simulation, to better predict in vivo thermal behavior during photopolymerization.

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