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Adhesive Type, Application Mode and Composite Preheating Influence Temperature Changes Across Different Dentin Thicknesses

Keywords

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ABSTRACT

Objectives. To evaluate the effect of universal adhesive type/mode and bulk-fill composite preheating on temperature changes (ΔTs) across two different dentin thicknesses.

Methods. Eighty dentin discs (2mm thickness) were randomly divided into 8 groups (n=10) based on adhesive type (All Bond Universal-ABU or Scotchbond Universal Plus-SBUP), adhesive mode (self-etching-SE, or etch-and-rinse-ER), and composite preheating (non-preheated, or preheated). K-type thermocouple wire was used to record ΔTs during adhesive light-curing (ΔT1), composite application (ΔT2), and composite light-curing (ΔT3). After recording of ΔTs, 2mm dentin discs were reduced to 1mm thickness, and experiment was repeated. Statistical analysis was performed using ANOVA/Tukey tests ($\alpha = 0.05$). Results. Dentin thickness significantly affected ΔTs (P<.001), with 1mm thickness showing significant increase. Neither composite preheating, nor adhesive type/mode significantly affected temperature changes (P>0.05). Both ABU/SE and SBUP/ER in preheated composite groups showed no significant difference (P>0.05) between 2mm (2.81±0.85°C and 1.51±0.89°C, respectively) and 1mm thicknesses (3.52±0.46°C and 2.38±0.94°C, respectively) in ΔT2. ΔT3 was significantly higher than ΔT1 and ΔT2 regardless of the dentin thickness (P<0.05). Conclusion. Composite light-curing increased temperature beyond the limit that pulp can withstand, regardless of dentin thickness. Clinical Relevance. Preheated bulk-fill composite is safe for restoring deep cavities, but caution is needed during light curing.

INTRODUCTION

Resin-based composites (RBCs) are widely used for restoring carious posterior and anterior teeth due to their excellent chemical and mechanical properties, durability, and esthetics.[1,2] However, they require dental adhesives for effective bonding to cavity walls. Universal adhesives, as one-step self-etching (SE) systems, enable bonding for both direct and indirect restorations and can also function as two-step etch-and-rinse (ER) adhesives when enamel and dentin are pre-etched with phosphoric acid etching.[3]

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Restoring deep posterior cavities with RBCs presents challenges, including inadequate polymerization due to limited light penetration and poor adaptation to cavity walls due to high viscosity.[4,5] To enhance depth of cure and reduce chair time, bulk-fill composites were developed, allowing RBC placement in a single 4 mm layer without compromising mechanical properties.[6]

To improve the adaptation of high-viscosity resin-based composites (RBCs), preheating before placement has been suggested. Preheating reduces viscosity, enhances flowability, and increases polymerization temperature, accelerating radical and monomer mobility.[7] This results in a higher degree of conversion and improved physical and mechanical properties.[8] The recommended preheating temperature ranges from 50 to 70°C, which is generally well tolerated by sound tooth structure.[9]

Dental pulp is a highly vascularized tissue with an average temperature of 35°C.[5] Due to its sensitivity, cavity preparation and restoration procedures, especially without strict clinical precautions, can compromise pulp vitality.[5] Zach and Cohen[10] demonstrated that pulpal temperature increase of 11°C and 16°C led to irreversible damage in 60% and 100% of specimens, respectively. The primary mechanisms of pulpal damage include protoplasm coagulation, increased outward fluid flow from tubules, vascular injury, and tissue necrosis.[5]

The microstructure of a human tooth is essential for its protective mechanisms against various stresses, including thermal stress.[11] Dentin, a biological composite with 30% organic content and elongated, inverted cone-shaped dentinal tubules, serves as a barrier that protects the pulp from external influences.[12] Studies on thermal behavior have shown that microstructural arrangement significantly affects thermal diffusivity.[13,14] As a result, the thermophysical properties of a tooth can vary across different layers and exhibit anisotropic characteristics within the same layer.[13,14]

Residual dentin thickness is a key factor in pulpal protection, as thinner dentin increases stress transmission during restorative procedures.[14-16] However, many studies on heat transmission and temperature changes in dentin have overlooked the influence of dentin thickness.[15,17]

However, concerns persist regarding the direct placement of preheated RBCs on dentin, particularly in deep cavities, due to potential heat stress and pulpal damage from the exothermic polymerization reaction during light curing.[10,18] The cumulative heat buildup during adhesive and RBC placement has been largely overlooked.[17] Dental restorative procedures can generate significant heat, increasing the risk of pulpal injury.[15] Additionally, the effects of adhesive application mode, monomer infiltration, and filler type and content, particularly those of the newly introduced universal adhesive (*Single Bond Universal Plus*), on heat transmission through varying dentin thicknesses have not been thoroughly investigated.

This study aimed to evaluate the impact of universal adhesives types/application modes, and bulk-fill composite preheating on temperature changes across two different dentin thicknesses. The null hypothesis tested is that universal adhesives/application modes, and bulk-fill composite preheating will not influence temperature changes after adhesive light curing, after the application of preheated bulk-fill composite, and after the light curing of bulk-fill composite across two different dentin thicknesses.

METHODS

A bulk-fill resin composite, and two universal adhesives were used in this study. Material, abbreviations, chemical composition, lot # and manufacturers are listed in Table 1.

Table 1. Material, Abbreviations, Chemical Composition, Lot # and Manufacturers.

Material	Abbreviations	Chemical Composition	Lot #	Manufacturers
x-tra fil (Photo-polymerized micro-hybrid bulk-fill resin composite caps, shade universal).	XTF	Bis-GMA, UDMA, TEGDMA and Barium boron alumino-silicate glass. Filler content: 86% by wt.	2146655	VOCO GmbH, Cuxhaven, Germany.
All-Bond Universal (ultra-mild universal adhesive, pH 3.2).	ABU	Bis-GMA, 10-MDP, 2-HEMA, ethanol, water, and photo-initiator.	2300010910	Bisco; Schaumburg, IL, USA.
Scotchbond Universal Plus (mild universal adhesive, pH 2.7).	SBUP	MDP phosphate monomer, Dimethacrylate resins, HEMA, Vitrebond™ Copolymer, Filler, Ethanol, water, Initiators and silane.	8664889	3M ESPE, St Paul, MN, USA.
Meta Etchant (37% Phosphoric acid etchant gel).		Phosphoric acid, water, xanthan gum.	2010121	META BIOMED CO., Ltd, Republic of Korea.

Bis-GMA: Bisphenol A-glycidyl methacrylate, UDMA: Urethane dimethacrylate, TEGDMA: Triethylene glycol dimethacrylate, MDP: Methacryloyloxydecyl dihydrogen phosphate, HEMA: Hydroxylethyl methacrylate

SAMPLE SIZE CALCULATION

The sample size was calculated using G*Power 3.1.9.4. The means and standard deviations from a previous study that evaluated the effect of different bulk-fill composites and dentin thickness on intra-pulpal temperature changes were used as a reference to calculate the total sample size.[19] Since dentin thickness was a dependent variable, a total sample size of 64 dentin discs was determined, with an effect size of 1.39, a power (1-ß) of 0.90, and a confidence level of 95%. To account for structural variability in dentin, the sample size was increased by 20% per group resulting in a total of 80 dentin discs evaluated in this study.

PREPARATION OF DENTIN DISCS

A total of 80 freshly extracted maxillary premolars were collected from patients undergoing orthodontic treatment, following ethical approval (Approval No. FDASU-Rec ER072416) from the Ethics Committee Board, Faculty of Dentistry, Ain Shams University. The teeth were thoroughly cleaned under running water to remove blood, and soft and hard tissue residues were eliminated using a hand scaler. They were then stored in a saline solution (El Fath for Drugs and Cosmetics Industry, Egypt) at 4°C for a maximum of three months post-extraction.

The occlusal enamel of all 80 premolars was removed to the level of the central occlusal groove using a low-speed abrasive disc (Coarse Polishing Discs, TOR VM, Russia) under continuous water irrigation. The occlusal surfaces were carefully examined to ensure complete enamel removal, with any remaining enamel eliminated by wet grinding using #180 SiC paper. A second horizontal cut, parallel to the first, was made to separate the roots and obtain dentin discs approximately 2 mm thick. The dentin thickness was verified using a precision caliper (TOTAL DIGITAL CALIPER INOX, China), with an average thickness of 2 ± 0.08mm.

STUDY DESIGN

The 2 mm dentin discs were randomly assigned to eight experimental groups (n = 10/group) based on two experimental factors: adhesive type/mode (ABU/ER, ABU/SE, SBUP/ER, and SBUP/SE) and resin composite preheating (preheated or non-preheated). To evaluate the effect of dentin thickness, adhesive and composite application procedures were initially performed on the 2 mm dentin discs, and temperature changes were recorded. After data collection, the composite build-ups were removed using an abrasive bur. Subsequently, for each group, the same 2 mm dentin discs (n = 10) were wet-ground with #180 SiC paper to reduce their thickness to 1 mm. The adhesive and composite procedures, along with temperature measurements, were then repeated on the 1mm dentin discs. The study design and experimental procedures are shown in Figure 1.

EXPERIMENTAL INTRA-PULPAL CIRCULATION ASSEMBLY

An artificial pulp chamber assembly was custom designed to simulate intra-pulpal circulation and temperature *(Figure 2)*. A rubber-based impression material (ZETAPLUS C Silicone, Zhermack SpA, Italy) was used to create a hollow cylinder with a top opening, where dentin discs were positioned. Three circular openings were incorporated at the bottom of the cylinder to facilitate fluid circulation and temperature monitoring.

A standard infusion set (*Figure 2a, 2d*) with a 21-gauge (blue) infusion tube, measuring 15 cm in length, was vertically fixed at the left opening using cyanoacrylate adhesive *(Figure 2d)*. One end of the tube extended inside the cylindrical cavity, while the other was connected to a one-liter bottle *(Figure 2a)* containing a mixture of 10% glycerin and distilled water to simulate blood. The flow rate remained constant throughout the experiment. A second infusion tube was fixed at the right opening to allow fluid egress. At the center opening, a K-type thermocouple wire (UT320D Mini Contact Type Thermometer, Generic, China) was inserted into the cylindrical cavity, ensuring contact with the middle of the dentin disc base for precise temperature measurements *(Figure 2f)*.

HEAT TRANSMISSION TESTING

Immediately before bonding procedures, each occlusal dentin surface was prepared using a superfine grit abrasive bur (five strokes) and abundant water irrigation to create a clinically relevant smear layer. Each prepared dentin disc was then fixed on top of the rubber assembly using cyanoacrylate adhesive. To maintain a physiological temperature inside the pulp chamber, the fluid temperature was set to 28°C (±1°C) at the start of each experiment. The baseline temperature (T0) was measured using a K-type thermocouple wire and recorded.

For the ABU/ER group, dentin discs were acid-etched with 37% phosphoric acid gel for 15 seconds, rinsed for 30 seconds, and blot-dried. The adhesive was applied using an application brush and agitated over the dentin surface for 15 seconds. A second coat was then applied and agitated for another 15 seconds. The adhesive was air-dried for five seconds following the manufacturer's instructions and light-cured for 10 seconds using an LED curing unit (SDI Radii Plus, SDI Limited, Bayswater, Victoria, Australia) with an output of 1500 mW/cm² and a wavelength of 440–480 nm. For the ABU/SE group, the same bonding procedure was followed, except the acid-etching step was omitted.

For the SBUP/ER group, acid etching was performed as described for ABU/ER. The adhesive was applied in a single coat, agitated for 20 seconds, air-dried for 5 seconds, and light-cured for 10 seconds using the LED curing unit. For the SBUP/SE group, the adhesive was applied following the SBUP/ER protocol, except that the acid-etching step was omitted.

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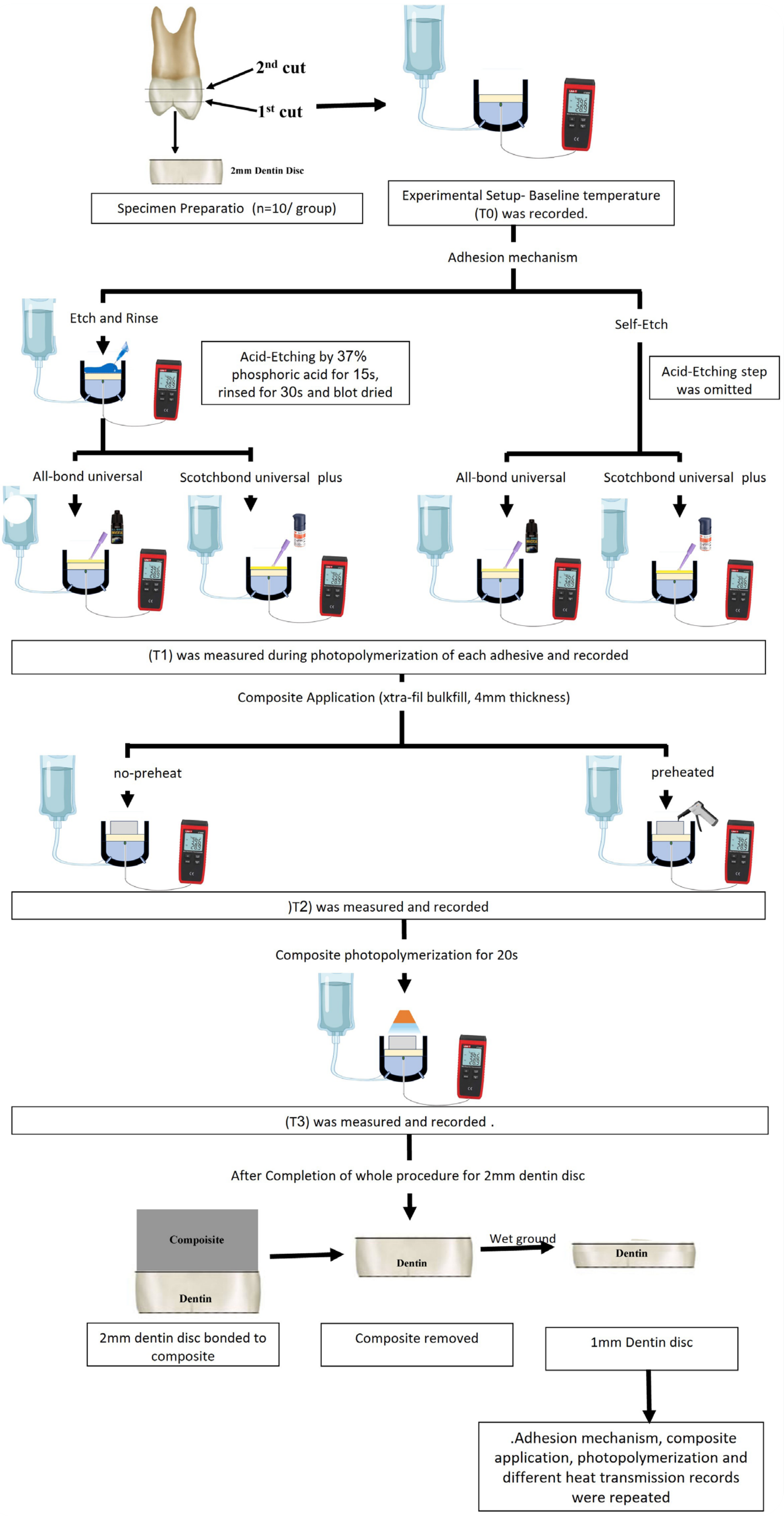

Figure 1: Graphic flowchart showing the study design and experimental procedures.

During the adhesive light-curing process, the temperature (T1) was measured and recorded.

For the non-preheated bulk-fill composite, the composite compule was loaded into the applicator, and the material was directly applied onto the polymerized adhesive in a 4 mm layer. The composite thickness was verified using a periodontal probe (Lascod Zeffiro, Florence, Italy). At this stage, the temperature (T2) of the non-preheated composite was measured and recorded.

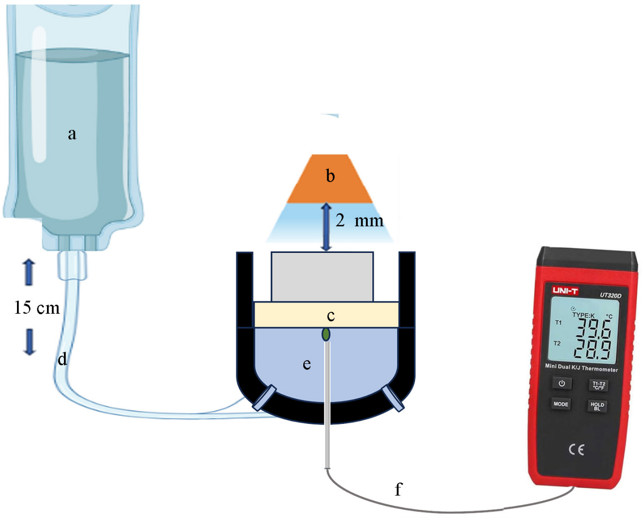

Figure 2: Schematic view of the test setup a) 10%glycerin mixed with distilled water, b) Curing unit, c) Dentin disc, d) infusion, e) Water circulation and f) Thermocouple.

For the preheated RBC, the compule was attached to the VisCalor® bulk dispenser (VOCO GmbH, Cuxhaven, Germany) and heated for 70 seconds at 65°C using the second heating mode, following the manufacturer's instructions. The preheated composite was then directly applied onto the polymerized adhesive. At this stage, the temperature (T2) of the preheated composite was measured and recorded.

Both non-preheated and preheated bulk-fill composites were light-cured for 20 seconds at a 2 mm distance from the top surface of the composite. At this stage, the temperature (T3) was measured and recorded.

After completing the adhesive and composite applications and recording the temperature through dentin (T1, T2, and T3), the composite build-ups were removed using high-speed abrasive burs (R&S Diamond Bur-F1 R, DIATECH, USA). The 2 mm dentin discs were then wet ground using #180 grit SiC paper to reduce their thickness to 1 mm. The final dentin thickness was verified using a digital caliper. The adhesive and composite application procedures, along with temperature measurements, were then repeated for the 1 mm thick discs. Temperature change (ΔT) was calculated by subtracting the initial temperature (T0) from each subsequent recorded temperature (T1, T2, and T3).

STATISTICAL ANALYSIS

Numerical data were assessed for normality using the Shapiro-Wilk test. After confirming a normal distribution ($p > 0.05$), data were presented as mean ± standard deviation (SD). Levene's test verified homogeneity of variance ($p > 0.05$). A three-way ANOVA analyzed the effects of dentin thickness, adhesive type/mode, and composite preheating on temperature changes (ΔT1, ΔT2, and ΔT3). Repeated measures ANOVA compared temperature changes within groups. One-way ANOVA with Tukey's HSD *post hoc* test evaluated the effect of adhesive type/mode and composite preheating within each temperature change at 2 mm and 1 mm dentin thicknesses. A paired t-test compared temperature changes between 2 mm and 1 mm thicknesses within each group. The significance level was set at $\alpha = 0.05$. Statistical analysis was performed using IBM® SPSS (Version 22, SPSS Inc., Chicago, IL).

RESULTS

The three-way ANOVA revealed that factors "dentin thickness" "composite preheating", and "dentin thickness × adhesive type/mode × composite preheating" significantly influenced temperature change ($p < .001$, $p = .032$, and $p < .001$ respectively). However, "adhesive type/mode" had no significant effect on temperature change ($p = .145$).

At a thickness of 2 mm (*Table 2*), repeated-measures ANOVA showed that ΔT3 exhibited the highest temperature change compared to ΔT1 and ΔT2, regardless of the adhesive type/mode and composite preheating ($p < 0.05$). Among the three temperature changes (ΔT1, ΔT2, and ΔT3), the ABU/ER group with preheated composite exhibited significantly higher ΔT1, ΔT2, and ΔT3 values compared to ABU/ER and ABU/SE with non-preheated composite, as well as SBUP/ER and SBUP/SE with preheated composite ($p < 0.05$). The ABU/ER and ABU/SE groups with non-preheated composite, along with SBUP/ER and SBUP/SE with preheated composite, exhibited the lowest temperature change values.

At a thickness of 1 mm (*Table 3*), repeated-measures ANOVA showed that ΔT3 exhibited the highest temperature change, regardless of the adhesive type/mode and composite preheating ($p < 0.05$). Significant differences were observed among ΔT1, ΔT2, and ΔT3 for ABU/SE mode and SBUP/ER mode when the composite was preheated ($p < 0.05$), with ΔT2 showing the lowest values and ΔT3 showing the highest values. For the ΔT1, ΔT2, and ΔT3, the highest temperature change was recorded with SBUP/ER when the composite was not preheated, while the lowest value was recorded with ABU/ER when the composite was preheated ($p < 0.05$).

Dentin thickness (*Table 4*); no significant difference was observed in ΔT2 between 2 mm and 1 mm thicknesses for ABU/SE and SBUP/ER when the composite was preheated ($p > 0.05$). Similarly, no significant difference was found in ΔT3 between 2mm and 1 mm dentin thicknesses for ABU/ER when the composite was preheated ($p > 0.05$). However, a significant difference was observed between 2mm and 1mm thicknesses ($p < 0.05$), with the highest temperature change recorded at 1mm dentin thickness in the remaining experimental groups.

DISCUSSION

Preheating direct RBCs is a well-known technique aimed at improving their adaptation to cavity walls and margins.[20] However, it is crucial to avoid excessive temperature increases during restorative procedures, especially in deep cavities. Zach and Cohen[10] reported that pulpal tissues cannot tolerate a

Table 2. Means ±SD in C° for the effect of composite preheating and adhesive type/mode on ΔT1, ΔT2, and ΔT3 and the effect of temperature change (ΔT) within each composite preheating and adhesive type/mode for 2 mm dentin thickness.

Dentin thickness	Composite preheating	Adhesive type/mode	ΔT1	ΔT2	ΔT3
2mm	Non-Preheated	ABU/ER	1.58±0.74 $^{c\ A}$	1.58±0.74 $^{b\ A}$	4.31±1.03 $^{bc\ B}$
		ABU/SE	1.46±0.50 $^{c\ A}$	1.46±0.50 $^{b\ A}$	3.51±0.57 $^{c\ B}$
		SBUP/ER	2.34±0.96 $^{abc\ A}$	2.34±0.96 $^{ab\ A}$	5.25±1.16 $^{abc\ B}$
		SBUP/SE	2.79±1.07 $^{ab\ A}$	2.79±1.07 $^{a\ A}$	4.91±1.24 $^{abc\ B}$
	Pre-heated	ABU/ER	3.36±0.69 $^{a\ A}$	3.19±0.54 $^{a\ A}$	6.42±1.36 $^{a\ B}$
		ABU/SE	2.36±0.53 $^{abc\ A}$	2.81±0.85 $^{a\ A}$	5.63±0.78 $^{ab\ B}$
		SBUP/ER	1.78±0.44 $^{bc\ A}$	1.42±1.03 $^{b\ A}$	4.66±1.54 $^{bc\ B}$
		SBUP/SE	1.35±1.14 $^{c\ A}$	1.27±1.02 $^{b\ A}$	4.18±1.89 $^{bc\ B}$

Means with same lower-case letters within each column showed no statistically significant difference at p=0.05.
Means with same upper-case letters within each row showed no statistically significant difference at p=0.05

Table 3. Means ±SD in C° for the effect of composite preheating and adhesive type/mode on ΔT1, ΔT2, and ΔT3 and the effect of temperature change (ΔT) within each composite preheating and adhesive type/mode for 1 mm dentin thickness.

Dentin thickness	Composite preheating	Adhesive type/mode	ΔT1	ΔT2	ΔT3
1mm	Non-Preheated	ABU/ER	4.25±1.34 $^{ab\ A}$	4.25±1.34 $^{ab\ A}$	8.20±2.15 $^{ab\ B}$
		ABU/SE	3.24±0.91 $^{bc\ A}$	3.24±0.91 $^{bcd\ A}$	6.52±1.57 $^{bc\ B}$
		SBUP/ER	5.44±2.13 $^{a\ A}$	5.44±2.13 $^{a\ A}$	10.02±3.45 $^{a\ B}$
		SBUP/SE	4.39±1.39 $^{ab\ A}$	4.39±1.39 $^{ab\ A}$	6.67±1.13 $^{bc\ B}$
	Pre-heated	ABU/ER	1.89±0.64 $^{c\ A}$	1.68±0.60 ^{d} A	5.25±1.75 $^{c\ B}$
		ABU/SE	4.91±1.11 $^{ab\ A}$	3.52±0.46 $^{bc\ B}$	7.30±1.64 $^{abc\ C}$
		SBUP/ER	3.81±1.73 $^{ab\ A}$	2.17±1.10 $^{cd\ B}$	7.54±2.41 $^{abc\ C}$
		SBUP/SE	4.14±1.26 $^{ab\ A}$	3.22±1.23 $^{bcd\ A}$	6.96±1.40 $^{bc\ B}$

Means with same lower-case letters within each column showed no statistically significant difference at p=0.05.
Means with same upper-case letters within each row showed no statistically significant difference at p=0.05

temperature increase of 5.5°C or higher in the pulp chamber. Prolonged temperature rise can lead to permanent changes in pulp tissue with a temperature rise to 42°C sustained for one minute considered harmful to the pulp.[21] A recent review indicated that factors such as light-curing of composite materials could raise the pulp chamber temperature beyond the critical threshold that pulp tissue can withstand.[15]

The study results partially supported the null hypothesis, as the factors “dentin thickness” and “composite preheating” had a significant effect on temperature changes, while the factor “adhesive type/mode” did not have a significant effect on temperature changes. Dentin has a thermal conductivity ranging from 0.11 to 0.96 W/mK[22,23] and a thermal diffusivity of approximately 0.48 $Wm^{-1}K^{-1}$, indicating good thermal insulating capabilities for pulp protection.[11] The study results showed variations in ΔT1 for both 2 mm and 1 mm dentin thicknesses, even though the bulk-fill composite was not applied at this stage. It has been reported that the porous tubular structure of dentin affects both its thermal conductivity and diffusivity[13,14], suggesting variations in the thermophysical properties within a tooth. This suggests that the variations were not only present within

Table 4. Means ±SD in C° for the effect of dentin thickness within each heat change (ΔT), composite preheating, and adhesive type/mode combinations.

Heat change	Composite preheating	Adhesive type/ mode	2mm	1mm	P value
ΔT1	Non-Preheated	ABU/ER	1.58±0.74	4.25±1.34	<.001
		ABU/SE	1.46±0.50	3.24±0.91	<.001
		SBUP/ER	2.34±0.96	5.44±2.13	.003
		SBUP/SE	2.79±1.07	4.39±1.39	.025
	Pre-heated	ABU/ER	3.36±0.69	1.89±0.64	.002
		ABU/SE	2.36±0.53	4.91±1.11	<.001
		SBUP/ER	1.78±0.46	3.81±1.63	.004
		SBUP/SE	1.35±1.14	4.14±1.26	.001
ΔT2	Non-Preheated	ABU/ER	1.58±0.74	4.25±1.34	<.001
		ABU/SE	1.46±0.50	3.24±0.91	<.001
		SBUP/ER	2.34±0.96	5.44±2.13	.003
		SBUP/SE	2.79±1.07	4.39±1.39	.025
	Pre-heated	ABU/ER	3.19±0.54	1.68±0.60	<.001
		ABU/SE	2.81±0.85	3.52±0.46	.072
		SBUP/ER	1.42±1.03	2.17±1.10	.164
		SBUP/SE	1.27±1.02	3.22±1.23	.002
ΔT3	Non-Preheated	ABU/ER	4.31±1.03	8.20±2.15	.001
		ABU/SE	3.51±0.57	6.52±1.57	.001
		SBUP/ER	5.25±1.16	10.02±3.45	.002
		SBUP/SE	4.91±1.24	6.67±1.13	.013
	Pre-heated	ABU/ER	6.42±1.36	5.25±1.75	.164
		ABU/SE	5.63±0.78	7.30±1.64	.031
		SBUP/ER	4.66±1.54	7.54±2.41	.012
		SBUP/SE	4.18±1.89	6.96±1.40	.007

p value1 represents paired t-test between 2 mm and 1 mm

a single tooth but could also occur between different teeth, which may explain the variations in ΔT1 observed among different adhesive type/mode combinations. The remaining dentin thickness remained after excavation and its microstructure are crucial factors that can affect its thermal insulation capacity.[11] It was reported that there was an inverse relationship between remaining dentin thickness and pulpal temperature increase, indicating higher risk of pulpal injury in deep cavities.[24] Moreover, reducing dentin thickness to 1 mm resulted in less thermal insulation and higher ΔT during restorative procedure. Heat flow through dentin was directly related to its thermal conductivity and diffusivity but inversely related to its thickness.[15] While 2 mm of dentin thickness over the pulp is considered a sufficient heat barrier,[24] the temperature changes during light-curing of bulk-fill composite in this study exceeded the pulp's tolerance threshold, regardless of dentin thickness.

Light-curing of adhesives and composites poses a risk to pulpal health[25,26] due to the significant heat changes during the procedure. Studies by Yasa, *et al.*[27] and Lau, *et al.*[15] found that the rise in temperature during polymerization of RBCs is attributed to the exothermic polymerization reaction and heat emitted from the light-curing unit, exceeding the pulp's biological threshold.[25,28] Previous research reported an increase in temperature during RBCs polymerization ranging from 4.4°C to 9.3°C, consistent with the results of this study, showing an increase in temperature during RBC polymerization ranging from 3.1°C to 10.02°C.[29] This indicates that heat generated by the light-curing unit may cause a risk to the pulp, especially when the remaining dentin thickness is 1mm or less from the pulp. The *in vitro* simulation of the cooling effect of pulpal circulation in this study and the low heat capacity of RBCs may explain the reduction in temperature change between preheated and non-preheated groups.

In this study, two universal adhesives were tested in both SE and ER modes. In the SE mode, the smear layer was preserved within the hybrid layer safeguarding the dentin mineral content.[30] Conversely, in the ER mode, the smear layer was completely removed depleting the dentin of its mineral content and exposing the collagen matrix.[31] The exposed matrix required full infiltration by the adhesive resin to create a thermal insulating hybrid layer.[32-34] Among the adhesive types/modes examined, only ABU/ER showed no significant difference between 2 mm and 1 mm in ΔT3 when composite was preheated and light cured. ABU is a low-viscosity adhesive with a relative density of 0.9-1 g/cm^3,[35] while SBUP is a high-viscosity adhesive with a density of approximately 1.1 g/cm^3 .[36] These characteristics of ABU account for its superior ability to penetrate demineralized dentin, forming a heat-resistant hybrid layer.[33,34] In contrast to the findings of this study, Algamaiah *et al.*,[17] reported that adhesives with low-viscosity monomers led to higher temperature changes, attributed to increased heat transmission through the low dentin thickness (1 mm). This discrepancy may be due to the variations in adhesive systems used and their application modes. Additionally, the use of ABU/ER resulted in lower temperature changes in DT1, DT2, and DT3, especially when the composite was preheated, compared to SBUP/ER at 1 mm dentin thickness. This difference may be linked to the variations in chemical compositions between the two adhesives tested. According to the manufacturer of SBUP, it contains polyalkenoic acid copolymer (PAC) and fillers, unlike ABU. Adhesives containing PAC and MDP monomer have shown superior adhesion to dentin compared to PAC-free adhesives.[37] However, Yoshida, *et al.*[38] suggested that PAC might compete with MDP for calcium binding sites on dentin, potentially hindering the formation of the polymerized adhesive layer and hybrid layer. Additionally, it was reported that the inclusion of fillers within the adhesive may contribute to its high thermal conductivity.[39] According to the manufacturers of the two tested adhesives, SBUP contains silica fillers, whereas ABU is considered filler-free.

The study found no significant effect between the two adhesive type/mode combinations regardless to ΔT. Despite the increase in ΔT1 for SBUP/ER at the 1 mm thickness, the change in temperature during light curing of both adhesives regardless of the mode of the application did not exceed the critical temperature change threshold of 5.5°C reaching the pulp.[10] Both adhesives in this study are universal adhesives containing MDP monomers. The MDP monomer reacts with calcium in dentin to form an ionic bond, which enhances stable bond formation. Pre-etching of dentin removes the surface and subsurface calcium, potentially impairing the formation of the ionic bond in MDP-containing adhesives.[40] However, the formation of thick hybrid layer with long resin tags of the universal adhesives utilized the etch-and-rinse mode was reported in previous studies.[41,42] In the SE mode, acid monomers may diffuse beyond the hybrid layer and react with hydroxyapatite to create a stable organic complex known as the "acid-base resistant zone".[43] This zone could provide an additional protective layer, reducing heat transmission through dentin.[28] Fluctuations in temperature changes were observed among the tested adhesives, especially in ΔT3. Some results indicated an increase in temperature changes when adhesives were used in the ER mode, while others showed the opposite trend. This suggests that factors such as composite preheating or composite light-curing may influence the temperature changes, but there is no single factor that consistently controls the increase or decrease in temperature changes. This indicates that factors other than adhesives and their application modes may have influenced the temperature measurements, potentially masking the true effect of the adhesives and application modes. Further investigation is needed to clarify this explanation.

Preheating of RBCs has been found to improve their mechanical properties, reducing viscosity and improving flowability, which can lead to better marginal adaptation and reduced marginal leakage.[44] The results showed that upon the placement of preheated RBC, minimal temperature change was observed. However, in some adhesive/mode combinations, a decrease in ΔT2 was noted. This suggests that, despite the temperature increase during the application of preheated composite, preheating bulk-fill resin composite poses no risk to pulpal health as long as the temperature rise does not exceed the critical threshold of 5.5°C. These finding agreed with the results of Karacan and Ozyurt,[5] despite variations in the preheating bulk-fill RBC types. It was noted that the actual temperature of composite materials delivered was lower than the set temperature on heating device due to the composite's low heat capacity, leading to rapid cooling.[45] Marcondes, *et al.*,[46] reported a significant temperature drop in preheated composite materials within seconds after removal from the heating device. When the preheated bulk-fill composite was applied over a Mylar strip, the measured temperature was 50% (32.5±2.1°C) of the dispenser actual temperature (65°C). This discrepancy in actual and delivered temperatures may be attributed to the low heat capacity of the RBC and the presence of composite material within a plastic compule that may act as a heat barrier to prevent excessive temperature rise. The x-tra fil composite has a high filler load of 70.1 Vol%, consisting of barium, boron alumino-fluoro-silicate glass fillers. Yasa *et al*.[27] observed that the temperature increase during polymerization of bulk-fill RBC materials was influenced by the low filler Vol% content of barium and alumino-fluoro-silicate fillers. The filler Vol% directly corelates with the exothermic reaction of RBCs during light-curing.[27] An exothermic reaction is "chemical reaction in which the material releases energy when exposed to heat or light".[47,48] According to Yasa, *et al*.,[27] materials with high filler content show lower exothermic reaction during preheating. The x-tra fil composite, with a high filler Vol% likely has reduced energy release from its exothermic reaction during preheating.

This study demonstrated that light curing of bulk-fill composite is a critical factor that can potentially cause pulp damage, particularly at lower dentin thicknesses. A minimally invasive caries removal approach could help preserve sufficient dentin thickness to protect the pulp. Additionally, the minimum light curing time required for optimal polymerization of composite restorations should be carefully considered to minimize temperature rise through dentin reaching the pulp. The use of a filled hydrophobic adhesive layer with adequate thickness may also help reduce temperature rise through dentin. However, further research is needed to evaluate these factors, as they were not tested in this study.

This was an *in vitro* study conducted on dentin discs, which may not fully represent the role of intra-pulpal microcirculation in heat dissipation. Intraoral thermal regulation mechanisms rely on the tooth's thermophysical properties, such as dentinal fluid flow, which can enhance heat dissipation and help regulate temperature changes within the pulp.[15] The overall impact of pulpal blood flow on heat dissipation is uncertain due to relatively low blood flow.[14] Periodontal ligaments may also help limit intra-pulpal temperature increases by promoting heat convection.[15]

CONCLUSIONS

Under the limitations of this study, the following conclusions could be suggested:

1. Both 2mm and 1mm dentin thicknesses failed to prevent temperature rise during composite light curing.
2. Since the temperature increase from x-tra fil composite exceeded the critical threshold for pulp tolerance, protecting the pulp from thermal damage during light curing is essential.
3. The x-tra fil composite can be safely applied in deep cavities in its preheated form.
4. The temperature fluctuation during the application of x-tra fil resin composite was found to be adhesive/mode dependent.

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