INTRODUCTION

Composite resins have been the restorative material of choice for posterior teeth for many years, because they offer both an extended manipulation time and direct light-curing options. However, their use presents some drawbacks, such as the difficulty of curing in deep cavities due to the limited depth of light penetration. The most common method to overcome this problem is incrementally layering the composite resins to ensure optimized polymerization. However, in dental practice, this procedure is highly time-consuming.

Recent advances in resin-based restorative materials have resulted in the development of bulk-fill composite resins to overcome the need for incremental layering. These materials speed up the restoration process by enabling the placement of up to 4 mm, or sometimes even thicker increments, in a single step. In this technique, composite resins are placed in a maximum of 2-mm thick increments, in order to reduce polymerization shrinkage and minimize internal gap formation. However, in dental practice, this procedure is highly time-consuming.

The aim of this study was to evaluate the intrapulpal temperature changes during the curing of different bulk-fill restorative materials. Ten mandibular molar teeth were selected and occlusal surfaces were removed to obtain a standard 0.5 mm occlusal dentin thickness. Five bulk-fill restorative materials and a conventional resin composite (control) were applied. The intrapulpal temperature changes during the curing of these materials were determined by a device simulating pulpal blood microcirculation. The difference between the initial and maximum temperature values (Δt), was recorded. The data were statistically analyzed with one-way ANOVA and Tukey’s HSD test (p<0.05). There were statistically significant differences between materials (p<0.001). The light-curing bulk-fill restorative materials exhibited the highest Δt values. Equia Forte showed the lowest Δt values among all the groups (p<0.05). Bulk-fill restorative materials causes significantly different temperature changes in the pulp chamber according to curing type. Therefore, clinicians should be considered when using these materials.

Keywords: Bulk-fill, Restorative material, Intrapulpal temperature

Besides composite resins, glass ionomer cements are also widely used in posterior restorations. Glass ionomer cements are known for their chemical adhesion to enamel and dentine. They can continuously release fluoride and show no setting shrinkage under clinical conditions. The major drawbacks of the glass ionomer cements are their lack of physical strength, especially in the initial stage of their setting, their slow setting reactions, and their moisture sensitivity. The poor mechanical properties of the present glass ionomer cements make them unsuitable for posterior teeth restorations in high stress-bearing areas. However, the application of heat from dental curing lamps for one minute can accelerate the setting of the material and improve its early mechanical properties.

In recent years, glass ionomer cement products have become more developed and new systems are becoming available in the market. One such product is the combination of a self-adhesive, chemically cured, highly filled glass ionomer cement with a self-adhesive, light cured, filled resin surface coating. The manufacturers of this system claimed increased fracture toughness, flexural strength, and flexural fatigue resistance compared to conventional glass ionomer materials. Another newly developed glass ionomer-based restorative material, the glass carbomer, was introduced with claims of improved physical characteristics. Its clinical application is similar to that of conventional glass ionomer cements, except that heat application is recommended during the setting reaction. According to the manufacturer, this material sets chemically, and a high output light curing unit with a maximum heat level of 60°C should be applied for optimal setting results.
For many years, the possible damaging effect of the high temperatures associated with restorative treatments on the pulp tissue has been a matter of concern in dentistry. The polymerization process of light-curing materials results in a temperature increase caused by the exothermic reaction of the material and the energy absorbed by the tooth during the irradiation\(^{18}\). The temperature increase during polymerization can result in both reversible and irreversible pulpal inflammation or even necrosis\(^{19,20}\). During this period, several factors can affect the thermal changes in the pulp tissue. There is a positive correlation between the intensity of the light source and the temperature rise\(^{21,22}\). There is also a negative correlation between the heat changes and the remaining dentin thickness\(^{23,24}\), and between the heat changes and the degree of dentin mineralization\(^{25}\). Although dentin has a low thermal conductivity, the potential for pulp damage is greater in deep cavities as the tubular surface area is increased\(^{26,27}\). However, many factors such as the fluid motion in the dentinal tubules, the pulp microcirculation, and the pulpal blood flow may influence the thermal behavior of the dentin-pulp complex\(^{23,28}\). When heat is applied externally, the pulp microcirculation is one of the important factors to be considered in the regulation of the intrapulpal temperature. The lack of a microcirculation mechanism may cause higher measurements in studies evaluating intrapulpal temperature changes\(^{29}\).

In light of these facts, the aim of this in vitro study was to evaluate the intrapulpal temperature changes during the curing/setting process of bulk-fill restorative materials that polymerize differently, using a study model simulating the pulpal blood microcirculation. The null hypothesis was that there would be no significant differences in the alterations to the intrapulpal temperature among the different bulk-fill materials during their curing/setting.

MATERIALS AND METHODS

The present study was approved by the Research Ethics Committee of Sifa University, under report number 352-92. The sample size was calculated at a 95% confidence interval and a significance level of 0.05 (effect size=1.37), according to the study by Savas et al.\(^{29}\). Although their data suggested that a total of 21 specimens would be adequate for analysis, a worst-case scenario was proposed, with an effect size of 0.6. According to the worst-case scenario, the total sample size was calculated as 70 (n=10), considering a 95% power at a significance level of 0.05.

Extracted mandibular molar teeth from humans aged between 18 to 25 (without sex discrimination) (n=10) were used in this study. After the extraction, the gingival and periodontal tissues were removed using a periodontal scaler and the teeth surfaces were cleaned with a pumice slurry. The teeth were then stored in a 0.1% thymol and distilled water solution at room temperature until the test procedure. The roots were removed 2 mm beneath the cemento-enamel junction, and the pulpal remnants were removed. The occlusal enamel was cut 2 mm above the cemento-enamel junction using a water-cooled diamond disc. The exposed dentin surfaces were then abraded with a 600-grit silicon carbide paper under running water to create a uniform occlusal dentin thickness of 0.5 mm. The dentin thickness was controlled.

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**Fig. 1** Schematic representation of the different steps of the experimental setup.
with a precision caliper. A single-tooth model was used to eliminate tooth-related differences. Two notches were prepared at the edge of the occlusal surface to allow for easy removal of the cured material from the tooth after the measurements.

The intrapulpal temperature changes during the curing/setting of the bulk-fill restorative materials were determined with a device that simulated pulpal blood microcirculation\(^{28-30}\). This device consisted of a fixed mechanism providing the circulation of distilled water, at room temperature, with a flow rate of 0.026 mL per min, in the pulp chamber of the specimens\(^{31}\). The flow rate was controlled with a digital infusion flow meter (SK-600II infusion pump, SK Medical, Shenzhen, China). Blood circulation was simulated by the distilled water flow and the fluid pressure was 20 cm H\(_2\)O, to imitate the blood pressure in the pulp. A slot cavity was prepared in the proximal surface of the tooth, and a 0.36-mm diameter J-type thermocouple wire (Omega Engineering, Stamford, CT, USA) was inserted into the occlusal wall of the pulp chamber. The tip of the wire was covered with a silicone heat-transfer compound (ILC P/N 213414, Wakefield Engineering, Beverly, MA, USA).

A light-curing calcium hydroxide cement (Calcimol LC, Voco, Cuxhaven, Germany) was used to fix the wire in contact with the occlusal wall and avoid leakage during the test. The tooth was fixed to the metal base-plate of the device with a light-curing glass-ionomer cavity liner cement (Glass liner, WP Dental, Barmstedt, Germany). The thermocouple wire was connected to a data logger (XR440-M Pocket Logger, Pace Scientific, Mooresville, NC, USA) and a computer.

The temperature increase during the curing/setting process of the materials was recorded. The system is schematically represented in Fig. 1. The materials and product details are summarized in Table 1. A conventional composite resin was also used in the study as a control material. All materials were applied by one operator according to the manufacturer’s instructions at room temperature (24.3±0.1) and after each measurements, it was waited until the specimens cools down to room temperature before undergoing another

### Table 1  The restorative materials and product details used in the study

<table>
<thead>
<tr>
<th>Materials</th>
<th>Type of material</th>
<th>Curing/Setting type</th>
<th>Composition (Filler wt%/vol %)</th>
<th>Manufacturer</th>
<th>Filling procedure (according to manufacturer’s instructions)</th>
<th>Batch no</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equia Forte</td>
<td>Glass ionomer cement</td>
<td>Self-cure</td>
<td>Fluoro alumino silicate glass, apatite, polyacids</td>
<td>GC, Tokyo, Japan</td>
<td>2 min wait for setting</td>
<td>1507029</td>
</tr>
<tr>
<td>GCP Glass Fill</td>
<td>Glass ionomer cement</td>
<td>Light-cure + Heat</td>
<td>Fluoro alumino-silicate glass, apatite, polyacids</td>
<td>GCP-Dental, Elmshorn, Germany</td>
<td>light and heat exposure with a output of 1,400 mW/cm(^2) (max 60°C)</td>
<td>7211953</td>
</tr>
<tr>
<td>Fill-Up!</td>
<td>Bulk-fill composite</td>
<td>Self-cure / Dual-cure</td>
<td>Dental glass, methacrylayes, amorphous silica, zinc oxide (65%/49%)</td>
<td>Coltène, Altstätten, Switzerland</td>
<td>Self curing: 3 min wait for setting</td>
<td>G15729</td>
</tr>
<tr>
<td>Z250</td>
<td>Conventional composite</td>
<td>Light-cure</td>
<td>Bis-GMA, UDMA, Bis-EMA, zirconia/silica (82%/60%)</td>
<td>3M ESPE, St. Paul, MN, USA</td>
<td>20 s light exposure with an output of &gt;400 mW/cm(^2) light curing unit</td>
<td>N581298</td>
</tr>
<tr>
<td>SDR</td>
<td>Bulk-fill composite</td>
<td>Light-cure</td>
<td>Barium-alumino-fluoro-borosilicate glass, Strontium alumino-fluoro-silicate glass, Modified urethane dimethacrylate resin, EBPADMA, TEGDMA, CQ, Photoinitiator, Photoaccelerator, BHT, UV Stabilizer, Titanium dioxide, Iron oxide pigments, Fluorescing agent (68%/45%)</td>
<td>Dentsply, Konstanz, Germany</td>
<td>20 s light exposure with an output of &gt;550 mW/cm(^2) light curing unit</td>
<td>140530</td>
</tr>
<tr>
<td>Filtek Bulk Fill Posterior</td>
<td>Bulk-fill composite</td>
<td>Light-cure</td>
<td>UDMA, Bis-GMA, Bis-EMA(6), TEGDMA, substituted dimethacrylate, ytterbium trifluoride, silane treated ceramic, benzotriazol, ethyl 4-dimethyl aminobenzoate (76.5%/58.4%)</td>
<td>3M ESPE</td>
<td>40 s light exposure with an output of 550–1,000 mW/cm(^2) light curing unit</td>
<td>N651351</td>
</tr>
</tbody>
</table>

Bis-GMA, bisphenol-A-glycidyl dimethacrylate; UDMA, urethane dimethacrylate; Bis-EMA, bisphenol-A-dyethoxy dimethacrylate; EBPADMA, ethoxylated bisphenol A dimethacrylate; TEGDMA, triethyleneglycol dimethacrylate; CQ, Camphorquinone; BHT, butylated hydroxyl toluene
measurement. A special metal matrix tape was used to control the standard 4-mm thickness. While bulk-fill restorative materials were applied on dentin surface in a single layer (4-mm), the conventional composite resin was applied in two increments of 2-mm.

For all light-curing materials except GCP Glass Fill and Fill-up! in dual-cure, a light emitting diode light curing unit in a soft start mode (Bluephase 20i, 850 mW/cm², Ivoclar Vivadent, Schaan, Lichtenstein) was used for the duration recommended by the manufacturer. GCP Glass Fill and Fill-up! in dual-cure were cured using GCP CarboLED (1,400 mW/cm² (max 60°C), GCP-Dental, Elmshorn, Germany) thermo-cure lamp and a light emitting diode light curing unit in a turbo mode (Bluephase 20i, 1,600 mW/cm², Ivoclar Vivadent), respectively, according to manufacturer’s instructions. The light was applied from the top of the matrix band to standardize the irradiation distance.

After the test for each material, the occlusal surface was controlled by a dental loupe (Keeler, Windsor, Berkshire, UK) to confirm the complete removal of the materials, and the surface was cleaned with distilled water and air-dried to remove the debris. The materials could be easily removed through the notches as no bonding agent was applied. The glass ionomer Equia Forte was the last material to be tested among the groups due to its chemical adhesion to tooth structures.

For each material, the initial temperature and the maximum temperature increase were determined during the curing/setting process. In the control group, temperature changes were recorded during polymerization of the two increments. The sampling rate of the data logger was set to one sample every 2 s. The recording duration started with material placement and ended when the temperature started to decrease. The collected data was monitored in real time and transferred to the computer. The difference between the initial and highest temperature values, hereafter defined as the maximum temperature change (Δt), was recorded.

Statistical analysis
The statistical analysis was performed using the IBM SPSS software (Version 20.0, IBM, Armonk, NY, USA). Data were analyzed using a one-way analysis of variance (one-way ANOVA) at a 0.05 significance level followed by post-hoc comparisons with Tukey’s honest significant difference (HSD) test.

RESULTS

The mean maximal temperature change (Δt) values and the standard deviations of the test materials are summarized in Table 2 and Fig. 2. The statistical analysis showed that there were significant differences in the Δt values among the materials (p<0.001). The light-curing bulk-fill restoratives exhibited the highest Δt values while the self-cure glass ionomer-based bulk-fill restoratives had the lowest values (p<0.05). The Δt values of SDR and Filtek Bulk Fill Posterior were 12.82±1.53 and 11.59±2.12°C, respectively, and no statistically significant differences were found among them (p>0.05). GCP Glass Fill presented the highest Δt values (10.74±1.14°C) after the light-curing bulk-fill restoratives. Fill-up! in dual-cure mode (5.00±0.68°C) or self-cure mode (5.31±0.69°C) had significantly lower Δt values than not only the other resin-based materials, but also the control group (p<0.05). Equia Forte showed the lowest Δt values (3.55±0.84°C) among all the groups (p<0.05).

The temperature changes of the materials and intrapulpal temperature drops over time are presented in Figs. 3 and 4.

DISCUSSION

In recent years, bulk-fill restoratives have become the material of choice, particularly in deep cavities, as they reduce the number of steps required for the application, by filling the cavity in a single increment of 4 to 5 mm, and decrease the chair side time. The increased

### Table 2

<table>
<thead>
<tr>
<th>Materials</th>
<th>Temperature change (mean±SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equia Forte</td>
<td>3.56±0.84</td>
</tr>
<tr>
<td>Fill-up! (Dual-cure)</td>
<td>5.00±0.68</td>
</tr>
<tr>
<td>Fill-up! (Self-cure)</td>
<td>5.31±0.69</td>
</tr>
<tr>
<td>Z250</td>
<td>8.22±0.36</td>
</tr>
<tr>
<td>GCP Glass Fill</td>
<td>10.74±1.14</td>
</tr>
<tr>
<td>Filtek Bulk Fill Posterior</td>
<td>11.59±2.12</td>
</tr>
<tr>
<td>SDR</td>
<td>12.83±1.53</td>
</tr>
</tbody>
</table>

Different superscript letters indicate the statistically significant differences.
proximity to the pulp chamber in deep cavities may raise the possibility of damage during the application and polymerization steps. The temperature rise that occurs during the restorative process may be detrimental for the pulpal tissues\textsuperscript{19,20}. In deep cavities, regardless of the composite resin used, the risk of pulpal damage increases because of the temperature changes induced by the light-curing unit\textsuperscript{18,33}. From this point of view, the intrapulpal temperature changes during the curing/setting of different bulk-fill restorative materials were evaluated in this \textit{in vitro} study.

Two different factors cause the increase of temperature during the restorative material applications: the exothermic reaction during the material setting and the heat generated by the light-curing unit\textsuperscript{34,35}. The conversion of the carbon-carbon double bonds during the polymerization of the light-curing materials is an exothermic reaction\textsuperscript{35,36}. The light energy absorbed during the irradiation from the curing source also causes a temperature increase with an exothermic reaction\textsuperscript{34}. The effects of the temperature rise during the polymerization of the materials have been investigated in many studies and temperature rises of up to 20°C have been observed in light-curing materials\textsuperscript{24,35}. Zach and Cohen\textsuperscript{19} reported that the temperature rise during light activation could cause some adverse effects on the pulps of animals. They found that a 5.6, 11.1, and 16.6°C temperature rise in the pulp chamber induced pulp necrosis in 15, 60, and 100% of the teeth, respectively. These results as well as the findings of Pohto and Scheinin\textsuperscript{37}, indicate that the critical temperature for irreversible damage to the pulp begins at 42–42.5°C. Moreover, Eriksson \textit{et al.}\textsuperscript{38} reported that, for a temperature increase of 5°C, a 1-min duration period was the crucial threshold for pulp vitality. The real value of the critical temperature rise that causes pulp damage is still controversial, it can be concluded that the pulp temperature rise should be kept as low as possible during the polymerization of resin materials to avoid any risk of harming the pulp\textsuperscript{18}. For example, Baldissara \textit{et al.}\textsuperscript{39} reported that short-term exposure to thermal increases ranging from 8.9 to 14.7°C did not appear to be a major injurious factor for healthy dental pulp. In our study, the intrapulpal temperatures of the restorative materials were measured in a large mass and a significant temperature rise (over 42.5°C at body temperature) was observed. We observed rises in temperature ranging from 3.5 to more than 12°C in the pulp chamber (Fig. 2). The results demonstrated a rapid temperature rise for light curing materials, occurring as soon as the light source was activated. However, the duration of the temperature change was less than 1 min for all the materials, and the intrapulpal temperature drop was observed only a few seconds after the setting reaction of the materials (Figs. 3 and 4).

Three types of restorative materials (self-cure, dual-cure and light-cure) were used in our bulk-fill groups, as they would be used in clinical practice as well. According to the results of this study, the light-curing materials exhibited a greater increase in temperature compared to the self-cure materials, therefore the null hypothesis was rejected. Both SDR and Filtek Bulk Fill Posterior showed greatest temperature change, whereas the lowest value was found with Equia Forte. The reason for the high temperature change with these materials may be related to their various contents and the effect of the curing lamps. It has been reported that flowable composite resins with low filler content showed higher temperature rises than hybrid composite resins\textsuperscript{40}. SDR has a lower filler content than the other resin-based materials, with 45% (v/v) of barium and strontium alumino-fluoro-silicate glasses fillers. The higher temperature increase observed in the SDR group seems to be related to its low filler content. Previous studies have reported that the exothermic reaction of the resin-based materials during polymerization is proportional to the amount of filler present in the resins\textsuperscript{34,36,40}. Consistent with the reports, the temperature changes in SDR and Filtek Bulk Fill Posterior were higher than Z250 (control group) which was placed incrementally.
Among the glass ionomer cements, Equia Forte (3.55±0.84°C) showed a small internal exothermic setting without the use of the curing lamp whereas greater temperature rise was observed in GCP Glass Fill (10.74±1.14°C) which sets with light curing. These findings are in agreement with those of Gavic et al., which showed that a much greater temperature increase was observed when glass ionomer cements were exposed to curing lamps. Within the bulk-fill composite resin groups, Fill-up! in dual-cure (5.00±0.68°C) or self-cure (5.31±0.69°C) modes showed the lowest temperature rise due to its setting reaction. Briefly, all of these also indicate that the differences of setting reaction and material compositions are important factors inducing the intrapulpal temperature rise.

In previous studies, the temperature increase during the curing of different restorative materials has been measured with a calorimeter, differential thermal analysis, infrared cameras, and thermocouples. In the current study, the thermocouple device, described as a confidential method in previous studies, was selected to determine the temperature changes. In other studies, the tested teeth were positioned inside a tank containing standing water at 37°C without pulpal blood microcirculation. The pulpal blood microcirculation is the main regulatory system for heat distribution in teeth as it is adequate to dissipate the heat transferred by external thermal stimuli to the dentine pulp complex. In the present study, the thermocouple was combined with only a model simulating pulpal blood microcirculation at room temperature. Simulation of pulpal microcirculation by constant 37°C water flow inside the pulp chamber results in better clinical correspondence and future improvements are needed in the circulation apparatus to fix the temperature of water circulated within the pulp chamber to the body temperature of 37°C for a literal simulation. This was not performed in this study to avoid possible temperature fluctuations related to the heating/cooling apparatus.

There are some studies in the literature investigating blood flow rate in the pulp, but there is no consensus about it flow rate. According to Matthews and Andrew, the amount of pulpal blood flow is an average of 40 mL/min per 100 g tissue, and Baik et al. calculated that the flow rate was 0.026 mL/min, a value representing physiologic blood flow through the pulp chamber. So in our study, water circulation in the pulp chamber at a rate of 0.026 mL/min was performed to simulate in vivo conditions.

The thickness of the remaining dentin plays an important role in protection against thermal injuries of the pulp, and showed a negative correlation with the temperature rise during the polymerization of light-curing restorative materials. Although dentin has a low thermal conductivity, pulpal damage risk is potentially higher due to the increasing tubular surface area, especially in deeper restorations. For this reason, the critical dentin thickness for deep cavities was selected to simulate the deep cavity preparation in clinical situations. The intrapulpal temperature change was evaluated under a 0.5 mm dentin thickness to mimic the worst-case scenario. Higher temperature values were recorded in the pulp during the cure of different bulk-fill materials. Therefore, clinicians should take into consideration the application of a cement base or lining materials to the cavity floor in deep cavities to protect the pulp.

The bonding agent application may have a positive effect in reducing the heat transmission under clinical conditions. However, a previous study reported that there was no significant difference in the pulpal temperature rise with and without the application of a dentin-bonding agent. Our preliminary results also showed no statistically significant differences between the temperature changes with and without dentin bonding. Therefore, each material was placed on the same tooth, without any bonding agent, in order to allow easy removal of the materials during repeated measurements in the same tooth. The temperature increase was measured on the same tooth for each material, in order to provide standard tooth conditions and prevent any alteration of the dentin thickness in the samples. This protocol also ensured the same conditions between all the restoratives in this study.

The current study was performed at room temperature in laboratory situations, using a pulpal microcirculation mechanism without fluid motion in the dentinal tubules and the surrounding periodontal tissues. The surrounding periodontal tissues could also promote heat convection in clinical conditions, limiting the intrapulpal temperature change. Therefore, further studies are necessary to evaluate the effects of these limitations on the results of this study.

CONCLUSION

Within the limitations of this in vitro study, the light-curing bulk-fill materials exhibited a higher temperature rise compared to the self- and dual-curing materials. The possibility of pulpal damage caused by temperature rises should be considered when using light-cured bulk-fill materials in very deep cavities.

ACKNOWLEDGMENT

The authors would like to thank Dr. Bilal YASA for his kind help with the statistical analysis.

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