



## Research article

## Real-time pulp temperature change at different tooth sites during fabrication of temporary resin crowns

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## ABSTRACT

**Aim:** To record the pulp temperature at different tooth sites during fabrication of two different temporary crown systems.**Methodology:** Two temporary crown systems were investigated; a conventional direct fabricated and a preformed thermoplastic resin system. Extracted caries-free human teeth (incisor, premolar and molar) were prepared for full coverage ceramic restoration with roots sectioned below the cemento-enamel junction. Thermocouple wires were secured at the surface of crown material, the cut dentine and inside the pulp cavity. Provisional crowns (n = 10/group) from each system were formed prior to placement in a water bath of 37 °C to simulate pulpal temperature. Temperatures were recorded using a K-type thermocouple data logger to collect the mean and peak temperature during crown fabrication. Statistical analysis was carried out on all tested groups and heat flow was calculated.**Results:** For direct fabricated crowns, the mean rise in pulpal temperature recorded was 0.1 °C with the mean temperature range of 37.3 °C–37.8 °C. For the preformed thermoplastic crowns, the mean rise in pulpal temperature recorded was 37.3 °C–45.1 °C. The increase in temperature was significantly higher (6.5 °C for the incisor group, 7.5 °C for the premolar group, and 6.7 °C for the molar group). For both crown systems, the temperature difference between the three different sites; pulp, crown and tooth surface showed a statistical difference (P < 0.01).**Conclusions:** The direct fabrication system showed minimal temperature changes within the teeth, while the preformed thermoplastic fabrication system showed larger temperature change in the teeth.

## 1. Introduction

Temporisation is routinely used to stabilise and protect the prepared tooth crown during fixed restorative dental procedures that require the permanent restoration to be manufactured in the laboratory (Seelbach et al., 2010; Michalakis et al., 2006). A well-established system employed by clinicians include the use of various resin materials to fabricate temporary crowns intraorally (Singh et al., 2015). The polymerisation process of directly fabricated material is known to generate an increase in temperature (Kim and Watts, 2004). Keeping this temperature change in check is critical since a significant increase in temperature could result in reversible or irreversible pulpal inflammation, potentially followed by necrosis of the tooth undergoing restorative treatment (Singh et al., 2015; Abdulmohsen et al., 2016). Previous literature reports that an increase in pulp temperature of 5.5–5.6 °C is sufficient to induce detrimental histological changes in the pulpal tissues (Tjan et al., 1997;

Abdullah et al., 2016). Protection of the dental pulp is particularly important in fixed prosthodontics, since the process of crown preparation inevitably reduces tooth structure that would otherwise help to preserve the pulp from external thermal insults (Tjan et al., 1997; Abdullah et al., 2016). As the enamel/dentine layers get thinner, smaller changes in temperature could cause damage to the dental pulp (Altintas et al., 2008; Seelbach et al., 2010).

Past studies which have investigated temperature changes during restorative procedures have often focused on temporary restorative materials which were used intra-coronally (Michalakis et al., 2006; Singh et al., 2015; Abdullah et al., 2016). Other tooth-shaped preformed materials available are plastic shells, cellulose acetate, or metal in the form of tooth-coloured polycarbonate or polylactic resin crowns or, in aesthetic cases, provisional tooth forms in clear plastic that can be filled with bis-acryl composite resin (Abdulmohsen et al., 2016). The limitation of these commercially-available preformed crowns is that they are

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available in a finite range of sizes with specific tooth anatomy which may increase the chance of an improper fit and an unsuitable contour (Burns et al., 2003). These preformed provisional crowns lack an exothermic reaction unlike the conventional options (Radford and Ricketts, 2011). Recently, newer extra-coronal temporisation materials have become available on the market such as thermoplastic preformed crown systems (Burns et al., 2003; Radford and Ricketts, 2011). These thermoplastic systems have advantages due to their ease of moulding to the shape onto the tooth preparation (Burns et al., 2003; Radford and Ricketts, 2011). The thermoplastic preformed crown is pre-heated extraorally in a water bath to soften the material prior to placement over the tooth preparation and moulding to shape before cooling and hardening. However, a need exists to record potential changes in temperature to the tooth and pulp induced by the thermoplastic fabrication process, since crowns are heated in a water bath with the temperature that is considerably higher than the physiologic temperature.

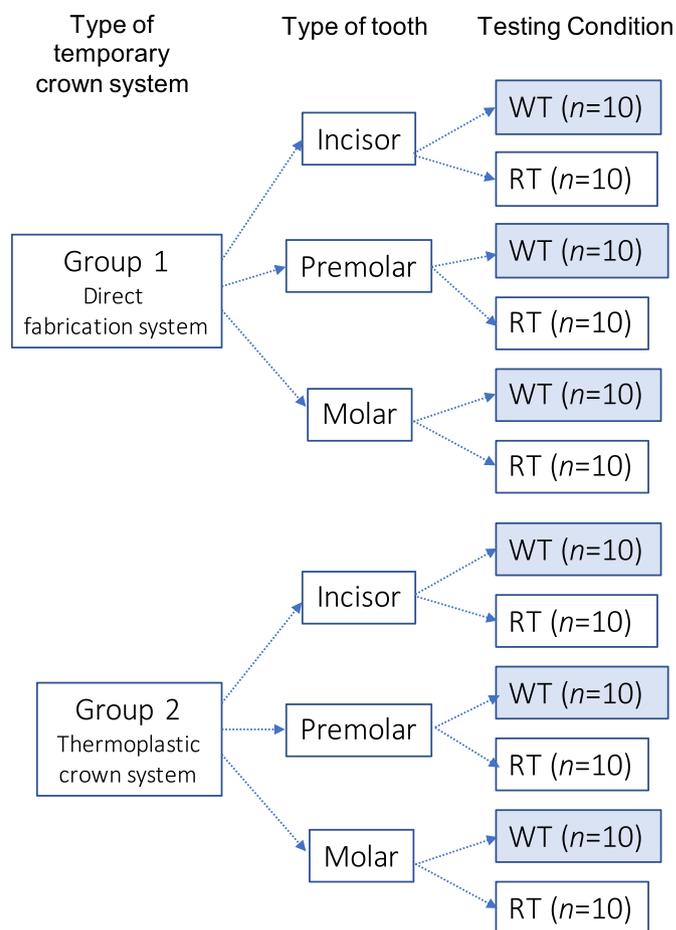
The thermocouple method involves a thermocouple wire connected to an electronic digital thermometer. It is a reliable way to measure temperature change and is commonly employed for measuring heat transfer across tooth structure (Hanning and Bott, 1999; Kim and Watts, 2004). Additionally, a heat-transfer compound injected into the pulp chamber is used to help transfer the heat from the walls of the pulp chamber to the thermocouple (Tjan et al., 1989; Castelnuovo & Tjan 1997). Measurements of heat transfer can be affected by the placement of the thermocouple, which needs to be in the same position at each measurement to minimise any variations in temperature recorded (Kim and Watts, 2004). Radiovisography can be used to determine proper positioning of the thermocouple probe as well as the residual dentine thickness (Abdullah et al., 2016). Often specimens are either prepared in disc shapes which lack in clinical significance (Castelnuovo & Tjan 1997; Kim and Watts, 2004; Singh et al., 2015).

Previous studies which used actual tooth preparation as the test condition, largely employed molars with few studies using premolars and anterior teeth (Tjan et al., 1989; Michalakakis et al., 2006; Daronch et al., 2007). In general, when using tooth specimens, the design had been shaped to represent real case applications by using tooth preparations for either crown or cavity restorations (Hanning and Bott, 1999; Michalakakis et al., 2006; Daronch et al., 2007; Singh et al., 2015). Most studies had small sample sizes ( $n = 5$ ) (Tjan et al., 1989; Castelnuovo & Tjan 1997; Singh et al., 2015) and only three studies (Hanning and Bott, 1999; Michalakakis et al., 2006; Seelbach et al., 2010) used water baths or chambers to simulate intraoral body temperature conditions. Only one study attempted a model to simulate the complex intrapulpal fluid flow (Daronch et al., 2007). Moreover, whilst heat flow has been well-documented in the literature, no study reported any value for heat flow through the layer of residual dentine. Since heat transfer and reducing the damage to pulp tissue is of primary concern to researchers, it will be beneficial to evaluate heat transfer across the residual dentine layer as a possible risk to the dental pulp to understand the thermal behaviour of different temporary crown systems.

Therefore, the aim of this study was to measure and analyse the change in temperature that takes place at different sites of prepared teeth and with different types of teeth (Incisors, premolars and molars) during the direct fabrication of two different crown systems, such as a conventional direct fabricated and a preformed thermoplastic resin system.

## 2. Materials and methods

Ethical approval (Reference H18/039) was obtained from the Human Ethics Committee, University of Otago to collect a total of six human teeth, after obtaining informed consent from the teeth donors. Teeth were collected at the time of extraction and conserved in 10% formalin solution. Inclusion criteria included teeth without any visual evidence of carious lesions or cracks. In total, two central incisors, two premolars, and two molars were selected and respectively assigned to test groups to be used (one tooth per material group; Figure 1). Custom box-shaped jigs



**Figure 1.** A diagram showing testing groups (WT: Testing with water bath; pulpal simulation and RT: Testing done without water bath; room temperature).

with lids were 3D-printed (Form 2, Formlabs, Massachusetts, USA). Teeth were then secured to 3D-printed lids in a vertical position (Figure 2) using pattern resin (Patern Resin, GC, Japan). After being secured to the lid, an impression (Coltene, Whaudent AG, Altstätten, Switzerland) was made of the tooth using a 3D-printed custom tray (Form 2, Formlabs, Massachusetts, USA).

All teeth were then prepared for a full-coverage ceramic restoration with a 360-degree shoulder finish line, with the axial wall and occlusal reduction of 1.0 mm each. The root portion was sectioned below the cemento-enamel junction (CEJ) perpendicular to the long axis of the tooth using a diamond disk. A wider access was made from the radicular portion of the tooth into the pulp chamber with a rose head tungsten carbide bur for the insertion of a thermocouple. The pulp chamber was cleaned of residual pulp tissue with endodontic K-files (ReadySteel, Maillefer Instruments, Ballaigues, Switzerland) and a thermocouple (K-type thermocouple; Omega, USA) was placed inside the pulp chamber.

The positional endpoint of the thermocouple was confirmed by radiography (Sirona Xios XG; Dentsply, USA) and the pulp cavity was subsequently filled with a syringable thermal compound (Arctic Silver 5, Arctic Silver Incorporated, Visalia, USA). This thermal compound injected into the pulp facilitated the transfer of heat from the occlusal and axial walls to the thermocouple wire, thus allowing for accurate reading to be recorded from all directions within the pulp chamber. An additional thermocouple was secured to the occlusal surface of the prepared tooth to record change in temperature at the cut dentine surface directly exposed to the temporary crown material (Figure 2).

Pin-sized holes were created in the impression matrix to allow the placement of a thermocouple on the inner occlusal surface of the temporary crown. The placement of a thermocouple inside the matrix was to

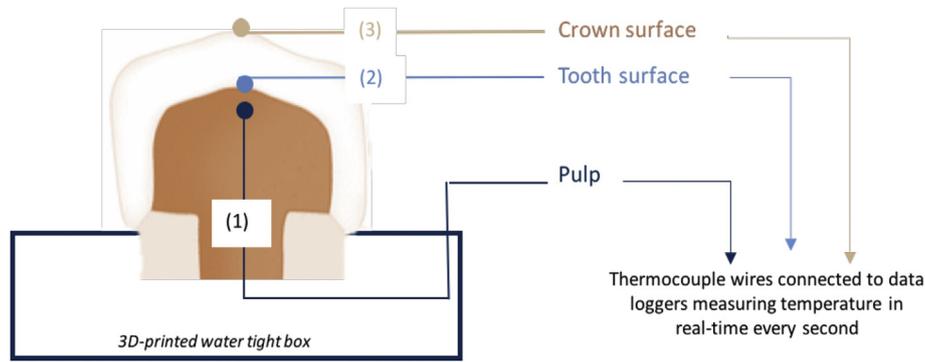


Figure 2. Schematic diagram of the test assembly.

record the temperature change within the temporary crown material. The matrix was kept in place during the curing process of the temporary crown materials. In total there were three thermocouples used per temporary crown specimen assembly and connected to individual digital data loggers (Figure 2). Each thermocouple recorded temperature change at different sites (the pulp chamber (P), surface of tooth preparation (S), and occlusal surface of the temporary crown materials (C)) during procedural moulding of the temporary crowns by the direct method. Prior to placement of the temporary crowns, the specimens were kept in a water bath and conditioned to  $37.5 \text{ }^\circ\text{C} \pm 0.9 \text{ }^\circ\text{C}$ . Thus, the pulp (filled with thermal compound) was exposed to the warm water underneath and intrapulpal temperature raised and stabilised at  $37.5 \text{ }^\circ\text{C}$  (WT group). The entire process are repeated with the teeth at room temperature with no water bath (RT group) in order to evaluate the influence of pulpal simulation ( $37 \text{ }^\circ\text{C}$ ) to the temperature profiles and to make comparisons with previous published studies (Figure 2).

The first group of specimens were tested using autopolymerising resin temporary material (Luxatemp, DMG, Germany). The Luxatemp was dispensed using the manufacturer's auto-mixing dispensers. Material was loaded into the preformed matrix containing the thermocouple and was moulded on the tooth preparation which had been coated with a thin, brushed-on layer of petrolatum jelly to facilitate post-setting removal of the temporary crown. After insertion of the resin-filled matrix, and following the manufacturer's recommended times, the tooth-crown preparation assembly was kept undisturbed while the temperature changes were recorded. The second group of specimens received thermoplastic provisional crowns (Hi-tempo, HiTem Corp, Korea). A thin spot application of varnish (Hicoat, HiTem Corp, Korea) was used and then light cured to secure the third thermocouple to the external occlusal surface of these preformed crowns. The medium-sized full-contour preformed temporary crowns were softened for 4 s in  $70 \text{ }^\circ\text{C}$  water as per manufacturer's instructions and then adapted onto the tooth preparation. The total time required was 3 min from softening to crown removal. The experiment was repeated for 10 crowns for both directed (Luxatemp) and thermoplastic temporary crowns (Hi-tempo) and for both WT and RT conditions (Figure 1).

Temperature changes at three different sites: the pulp chamber, occlusal surface of tooth preparation, and occlusal surface of temporary crown materials were recorded as a function of time. There was continuous recording of temperature across these three established sites throughout the direct fabrication process of the temporary crown. The individual temperature profile for each site was registered every 2 s by the thermocouple connected to a digital thermocouple data logger (GFX Data Logger Series and EL-USB-TC, Lascar Electronics Inc, Erie, PA, USA). Recorded data were retrieved using EasyLog Software (Lascar Electronics Inc, Erie, PA, USA). Temperature profile curves were plotted and peak temperature determined from the temperature versus time plot.

To calculate heat flow, all tooth preparations used were CAD-scanned (Ceramill Map400, AmannGirrbach, Austria) and STL files were used to calculate the surface area ( $\text{mm}^2$ ) required to calculate heat flow. After

completion of the temperature recording phase of the study, the last specimens (temporary crown on tooth preparation with thermocouples in place) were embedded in EpoFix Resin (Struers, Ohio, USA). A diamond cut-off wheel (MOD 13, Struers, Denmark) fitted to a precision cut-off saw (Accutom-50, Struers, Denmark) was used to section the specimens along the coronal plane in a buccal/lingual direction to produce two halves. Residual dentine thickness was measured under a light microscope (Nikon, SMZ800, USA) from the cross-section of each tooth preparation design (Figure 3). Five measurements were taken from the cross-section of the tooth surfaces, including the buccal and lingual axial walls and occlusal surface and the average of these was used for calculating heat flow. The formula used to calculate the flow of heat (Equation 1) was (Tjan et al., 1989):

$$H = \frac{KA(t_2 - t_1)}{D} \quad (1)$$

where

- $H$  is heat flow through dentine per unit time ( $\text{J}\cdot\text{s}^{-1}$ )
- $K$  is the thermal conductivity of dentine ( $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ )
- $A$  is the surface area exposed to the heat stimulus ( $\text{mm}^2$ )
- $D$  is the thickness of the residual dentine layer (mm)
- $t_2 - t_1$  is the temperature difference ( $^\circ\text{C}$ )

Statistical analysis were performed using one-way ANOVA by the SPSS (Ver 24, IBM Corp) software.

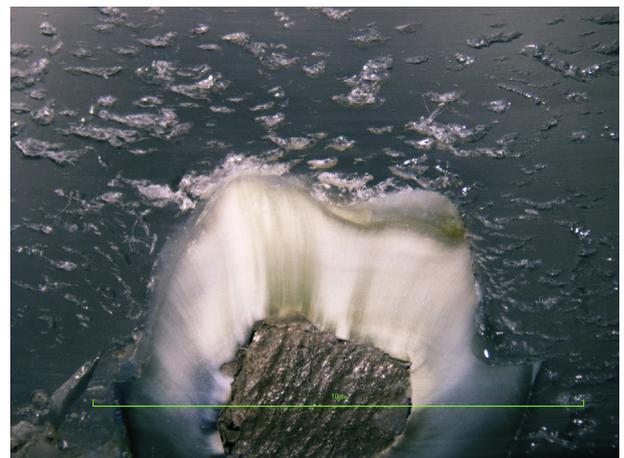


Figure 3. Example of cross-sectioned tooth preparation used to measure residual dentine thickness under a light microscope.

### 3. Results

This study has provided data that report on the thermal influence of two temporary crown materials (Luxatemp and Hi-tempo) during the temporalisation process of tooth preparations in prosthodontic treatment. The findings are grouped into three categories; (i) the recorded temperature difference across different tooth sites, (ii) the influence of an intrapulpal baseline temperature and (iii) the calculated heat flow through the residual dentine layer.

The mean of pulp chamber temperatures recorded for the Luxatemp and Hi-tempo groups are reported in Tables 1a, 1b, 2a and 2b respectively. All the mean starting temperature values for Luxatemp® group showed similar temperature across all three types of teeth with incisors = 37.3 °C, premolars = 37.8 °C, and molars = 37.5 °C with a statistical difference ( $p < 0.01$ ). The rise in temperature recorded was 0.1 °C for the incisor and molar groups, whereas no rise in temperature was observed for the premolar group (Tables 1a and 1b). When comparing the temperature change in the RT group tested without the 37 °C water (simulated pulp temperature), they showed markedly lower temperature ranging from 23.8 - 24.9 °C for starting temperature and 26.2–28 °C for peak temperature, compared to 37.4–37.8 °C. The temperature curves for each groups are depicted in Figure 4. A distinctive difference in temperature curves is shown between the two groups (RT and WT), when testing was done with and without 37 °C water to simulate pulpal temperature. Under the RT testing condition, all the Luxatemp samples showed recorded mean pulp chamber temperature changes of +2.4 °C for incisors, +3.1 °C for premolars and +0.1 °C for molars. For the RT group, temperatures logged from different sites of the tooth including the pulp chamber, surface of the tooth preparation and the temporary crown increased, without a big peak or a drop. Whereas under the WT testing condition, all the Luxatemp samples showed recorded mean pulp chamber temperature changes of +0.1 °C for incisors, and +0.1 °C for molars with no mean change in temperature for the premolar samples.

For the Hi-tempo groups, the increase in temperature recorded within the pulp chamber were +6.6 °C for the incisor group, +7.5 °C for the premolar group, and +6.7 °C for the molar group (Tables 2a and 2b). The mean peak pulp chamber temperatures recorded for the Hi-tempo groups were incisors = 43.9 °C, premolars = 45.1 °C and molars = 43.8 °C with a statistical difference between three groups ( $p = 0.016$ ). Temperature curves for Hi-tempo crown groups are depicted in Figure 5. In contrast to the Luxatemp groups, temperature profiles observed for both RT and WT Hi-tempo groups showed a similar pattern of temperature change during crown fabrication and adaptation to the tooth preparation. The results from the Hi-tempo crown materials were all statistically significantly different across all test conditions ( $p < 0.01$ ).

Table 3 provides an overview of heat flow calculations for the dimensions established from the sectioned temporary crown/prepared teeth. When analysing each tooth preparation design and crown material assembly, the group with the highest calculated heat flow value also produced the highest change in intrapulpal temperature within that group's test conditions.

**Table 1a.** Change in pulpal temperature with Luxatemp crowns.

	Tooth	Mean starting temp (SD) °C	Mean peak temp (SD) °C	Temperature difference °C
WT	Incisor	37.3 (±0.4)	37.4 (±0.4)	+0.1
	Premolar	37.8 (±0.4)	37.8 (±0.4)	0
	Molar	37.5 (±0.4)	37.6 (±0.4)	+0.1
RT	Incisor	23.8 (±2.9)	26.2 (±3.3)	+2.4
	Premolar	24.9 (±1.5)	28.0 (±1.0)	+3.1
	Molar	23.7 (±3.0)	26.9 (±3.3)	+3.2

**Table 1b.** Overall mean temperature within the crown and on the surface of the tooth with Luxatemp crowns.

	Site	Mean Temp (±SD) °C	P value
WT	Crown	23.8 (±6.0)	<0.01
	Tooth surface	29.2 (±10.1)	
	Pulp chamber	31.7 (±8.8)	
RT	Crown	23.5 (±6.2)	0.091
	Tooth surface	25.8 (±7.6)	
	Pulp chamber	24.7 (±8.2)	

**Table 2a.** Change in pulpal temperature with Hi-tempo crowns.

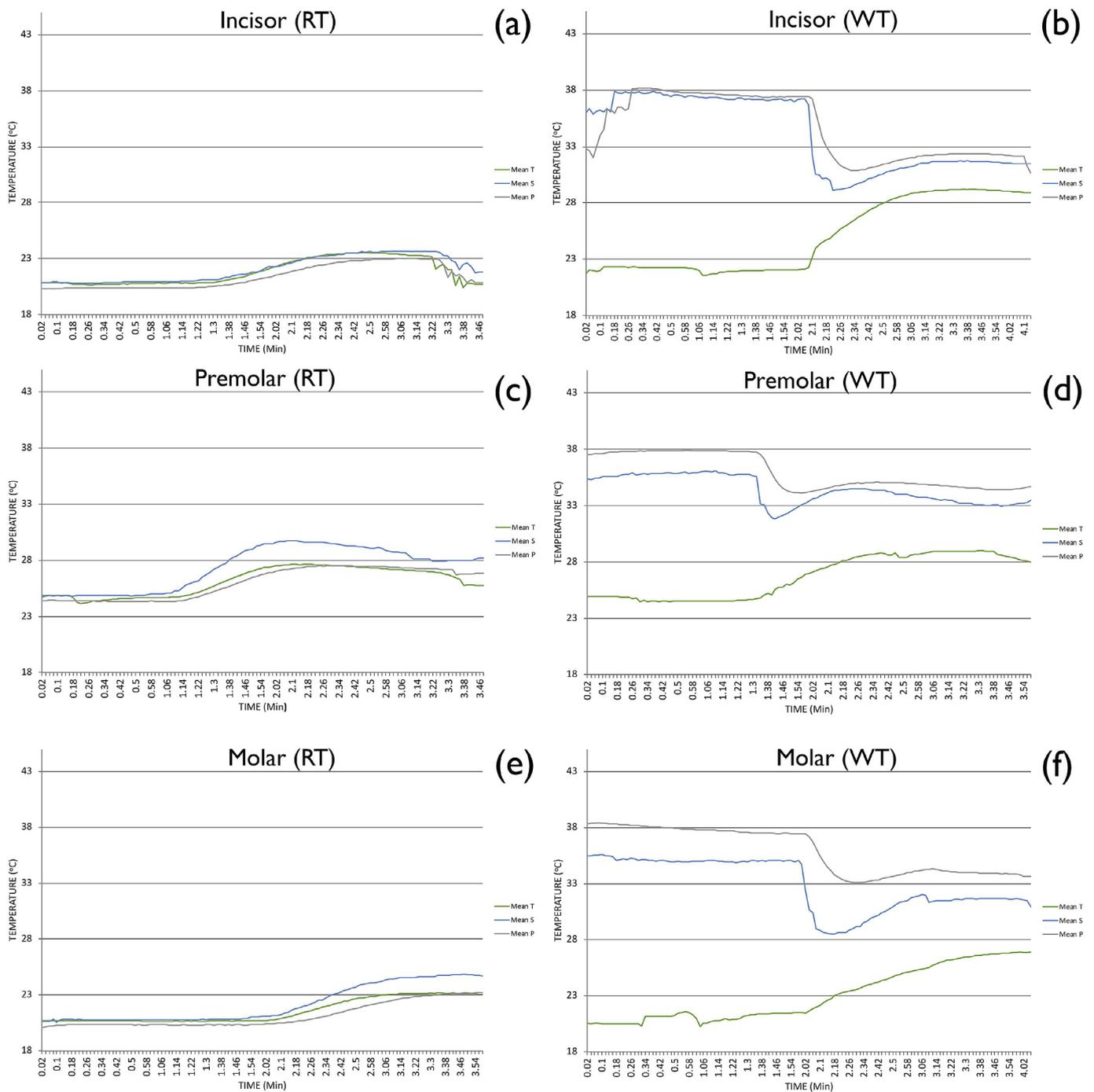
	Tooth	Mean starting temp (±SD) °C	Mean peak temp (±SD) °C	Temperature change °C
WT	Incisor	37.3 (±0.5)	43.9 (±2.7)	+6.6
	Premolar	37.6 (±0.7)	45.1 (±2.4)	+7.5
	Molar	37.1 (±0.6)	43.8 (±1.5)	+6.7
RT	Incisor	18.7 (±1.2)	31.6 (±2.8)	+12.9
	Premolar	19.9 (±2.8)	32.2 (±2.3)	+12.3
	Molar	21.2 (±1.4)	31.3 (±2.0)	+10.1

**Table 2b.** Overall mean temperature within the crown and on the surface of the tooth with Hi-tempo crowns.

	Site	Mean Temp (±SD) °C	P value
WT	Crown	33.3 (±9.3)	<0.01
	Tooth surface	38.7 (±4.9)	
	Pulp chamber	39.2 (±2.5)	
RT	Crown	26.9 (±9.6)	<0.01
	Tooth surface	26.7 (±8.6)	
	Pulp chamber	23.6 (±6.6)	

### 4. Discussion

The purpose of the current study was to measure and analyse the change in temperature that takes place at different sites of prepared teeth during the direct fabrication of two different crown systems. Simulating the intraoral environment in an *in vitro* setting is a challenge. Despite this limitation, the current study attempted to obtain values for temperature change which could be translated into a clinical setting. This was the purpose of recording temperature changes in a water-bath environment maintained at 37.5 ± 0.9 °C. Literature suggests that an increase in pulpal temperature of 5.6 °C is able to cause irreversible pulp damage in 15% of the cases (Tjan et al., 1989; Michalakis et al., 2006; Daronch et al., 2007). Pulp blood flow rate is also reported to increase significantly when pulp temperature rises above 42 °C (Lin et al., 2010). The mean temperature recorded was higher on all thermocouple sites across both temporary crown material groups when tests were performed under WT conditions (with pulpal temperature simulation). Moreover, the highest change in mean temperature for both temporary materials came from the RT condition, while the lowest change in mean temperature was reported from the WT condition. This finding highlights a clear trend of higher mean temperature but lower temperatures changes logged from different sites of a tooth when testing was performed under WT conditions rather than RT conditions. This questions the reliability of the data obtained by previous *in vitro* studies conducted without pulpal temperature simulation. Kim and Watts (2004) investigated Luxatemp crown materials thermal behaviour during polymerisation at room temperature and reported that the change in baseline and peak temperature was 6.9 °C (Kim and Watts, 2004). Since disc shaped specimens were used in Kim and Watts (2004)'s study, the results are rather difficult to compare however,



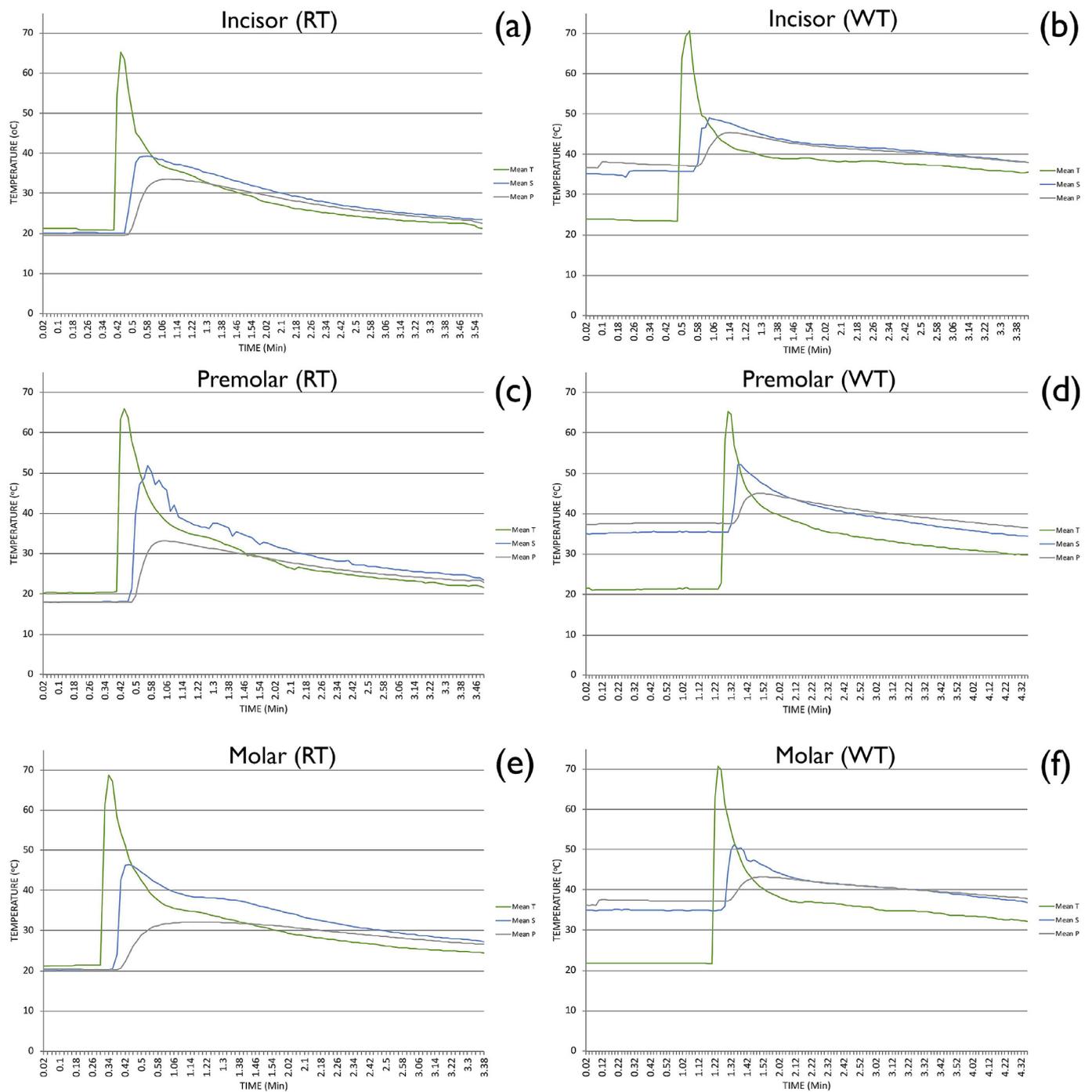
**Figure 4.** Temperature profiles for Luxatemp temporary crowns made for an incisor, premolar and molar. Note the differences in temperature curves between RT (a,c,e) and WT groups (b,d,f); Green line = Temporary crown (T), Blue line = surface of tooth preparation (S), Grey line = Pulp temperature (P).

the temperature change observed of 6.9 °C was twice as high than the temperature change of Luxatemp investigated in the current study under room temperature and 69 times higher than the change observed with pulpal temperature simulation. This emphasises the importance of simulating pulpal temperature in an *in vitro* study since it may produce a very different temperature profile and has more clinical significance, as observed in Figures 4 and 5.

When considering only the tooth structure, namely, the thermocouple on the cut dentine surface and the intrapulpal thermocouple, the highest mean temperature observed in the pulp chamber was 45.1 ± 2.4 °C on the premolar samples from the Hi-tempo crown under WT condition. On the other hand, the highest peak temperature on the tooth surface (32.2

± 2.3 °C) was also reported on a premolar tooth from the Hi-tempo group but under the RT condition. These results suggest that though the WT condition demonstrated a trend of increasing the mean temperature, the actual mean change in temperature decreases under the WT conditions for the key areas of concern, at the cut dentine surface and the pulp cavity.

When it came to comparing the two crown systems, Hi-tempo temporary crown system showed a 6.9 °C increase in the mean pulp chamber temperature, peaking at 45.1 ± 2.4 °C. Luxatemp temporary material reported negligible change in mean pulp temperature with the highest change of 0.1 °C reported at a peak mean temperature of 37.8 ± 0.4 °C. This is probably due to the different processes by which these materials



**Figure 5.** Temperature profiles for Hi-tempo temporary crowns made for an incisor, premolar and molar. Note the differences in temperature curves between RT (a,c,e) and WT groups (b,d,f); Green line = Temporary crown (T), Blue line = surface of tooth preparation (S), Grey line = Pulp temperature (P).

**Table 3.** Heat flow through dentine.

Specimen		Pulp temperature (°C)			Thermal conductivity (W.m <sup>-1</sup> .K <sup>-1</sup> )	Surface area (mm <sup>2</sup> )	Dentine thickness (mm)	Heat flow (J.s <sup>-1</sup> )
		Lowest	Highest	Difference				
Incisor	Luxatemp	37.45	38.18	+0.73	0.58	9.01	2.03	20.65
	Hi-tempo	37.26	45.40	+8.14				
Premolar	Luxatemp	37.79	37.90	+0.11	0.58	85.76	2.18	2.51
	Hi-tempo	37.63	45.03	+7.40				
Molar	Luxatemp	37.44	38.41	+0.97	0.58	111.22	2.38	26.29
	Hi-tempo	37.17	43.24	+6.07				

are shaped intraorally into the desired crown form. In case of Luxatemp it is the exothermic reaction which generates the heat. Whereas, in case of Hi-tempo it would be the 70 °C water bath which transfers the heat to the crown material which in turn transfers the heat to the tooth preparation and the pulp chamber respectively.

In the Hi-tempo temporary crown system, the crowns made from thermoplastic are available from the outset in the shape of a preformed crown. This is then thermally activated in a warm water bath (70 °C) and adapted onto the prepared tooth surface intraorally until it hardens and stabilizes. The heat transferred from the material to the tooth in this case is from the initial external heat applied to the Hi-tempo crown in order to activate its plastic mouldable phase. Luxatemp on the other hand is available as a paste which is mixed and dispensed into a tooth shaped mould which is then inverted onto the prepared tooth surface intraorally. This mould is kept in place until the setting time of Luxatemp has elapsed and then taken out of the oral cavity. During this setting phase, Luxatemp which consists of bis-acrylic undergoes a chemical self-polymerization, originating from an exothermic chemical reaction (Tjan et al., 1997; Singh et al., 2015; Abdullah et al., 2016). This difference in origin of the heat energy from these materials is probably the explanation for the different results (Tjan et al., 1997; Kim and Watts, 2004; Singh et al., 2015; Abdullah et al., 2016). One of the possible reasons for the comparatively lesser rise in temperature in the Luxatemp crowns could be the influence of the silicon mould which was used to fabricate mould matrix. The concept of silicon mould materials acting as a heat sinks has been well-reported; the bulk of these materials helps to dissipate heat away from the tooth and the amount of cooling is strongly dependent on the type and volume of mould material (Tjan et al., 1989; Castelnovo and Tjan 1997; Michalakis et al., 2006).

When assessing different teeth such as incisors, premolars and molars, the data revealed that the highest change was at the pulpal level of an incisor at 6.5 °C increase, with a peak temperature of  $43.9 \pm 2.7$  °C while fabricating the Hi-tempo crown. Whereas for Luxatemp the highest increase in pulpal temperature was seen on a molar specimen at a 3.2 °C increase, with a peak temperature of  $26.9 \pm 3.3$  °C. The type of tooth appears to have a direct impact on the difference in temperature increase in the pulp chamber. The transmission of heat through the dentine appears to be different, which is shown in the difference in heat flow values across all three tooth types tested (Table 3). This was true individually for both temporary crown materials tested. Hi-tempo groups showed a drop in temperature from crown zone to the pulpal zone, which was probably due to the fact they are made out of thermoplastic materials which are softened by heat. If there was a drop in temperature from the crown level to the pulp level, it would be due to the distribution and dispersion of heat to the surroundings. On the other hand, Luxatemp groups showed negligible difference in temperature between crown and pulp. This may be due to the silicon mould heat sinks take away some of the generated exothermic heat, which means that less heat is transferred towards the pulp chamber. Further studies investigating various measures to decrease the initial heat propagation in the Hi-tempo system would be helpful.

This study also set out with the aim of investigating heat flow through the residual dentine layer as there appears to be no reported values on this in the literature. The intrapulpal temperatures observed in the data correlated to heat flow values for the tested teeth specimens. When analysing each tooth preparation design and crown material assembly, the group with the highest calculated heat flow value also produced the highest change in intrapulpal temperature within that group's test conditions. It suggests that heat flow can be affected by the physical properties of the tooth preparation design such as residual dentine thickness and surface area. The temperature changes observed in the current study for Luxatemp crown material was in agreement with the result reported by Seelbach et al. (2010). They investigated how different thicknesses of residual dentine affect the temperature rise in temporary crown materials and reported that for Luxatemp, when the residual dentine was 2mm thick and the crown material was 1–2 mm, the temperature change in pulp chamber ranged from 37.0 - 36.3 °C, which was also observed in our

study. Seelbach et al.'s (2010) study used pulpal temperature simulation (37 °C water) and the correlation of our data with theirs confirms the validity of our experimental design of adopting the actual human tooth with a clinically relevant tooth preparation and incorporating pulpal simulation.

To the best of our knowledge, the heat flow data results from our study have not previously been described elsewhere. A question that remains unanswered is how to accurately quantify the residual dentine thickness across the entire surface area exposed to the heat source, such as the temporary crown material, rather than measuring the mean thickness after sectioning the specimens. While the present study was also able to reasonably simulate an intraoral environment, a major limitation remains to be overcome, that of the pulpal blood flow, intraoral temperature and humidity so that intrapulpal temperature rise can be more accurately reported in future investigations.

## 5. Conclusion

Within the limitations of this study, the following conclusion can be drawn:

- 1) A distinctively different pattern was found in temperature profiles between direct and preformed temporary crown systems, with the preformed crown system showing statistically higher temperature peaks ( $p < 0.01$ ).
- 2) The mean pulp temperature difference found for crowns made for incisors, premolars and molars showed a statistical significant difference, as well as between the sites measured for each tooth.

## Declarations

### Author contribution statement

Maykon Dias: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Joanne Jung Eun Choi: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Caira Ellyse Uy: Performed the experiments; Contributed reagents, materials, analysis tools or data.

Rishi Sanjay Ramani, Ritu Ganjigatti: Analyzed and interpreted the data; Wrote the paper.

John Neil Waddell: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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The authors declare no conflict of interest.

### Additional information

No additional information is available for this paper.

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