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Research Article

FINITE ELEMENT ANALYSIS OF 3D TRANSIENT LINEAR TEMPERATURE CHANGES IN THE PERIODONTAL LIGAMENT DURING THERMOPLASTICIZED GUTTA-PERCHA OBTURATION TECHNIQUES

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ABSTRACT

Objective: This study used finite element analysis to evaluate temperature changes in the periodontal ligament due to various thermoplasticized gutta-percha obturation techniques.

Materials and Methods: Mandibular premolar models were created in SolidWorks software, simulating carrier-based obturation (CBO) and continuous wave of condensation with backfill obturation (CWC+BFO).

Results: Upon analyzing seven models, the study revealed that the CWC+BFO models with the highest temperature settings (Models 4 and 7) recorded the highest maximum temperatures, nearing 127°C. In contrast, the CBO model (Model 1) exhibited the lowest maximum temperature at 47.835°C. These temperatures were primarily measured at the apical region. The duration exceeding 10°C above body temperature was highest in Models 4 and 7. CBO caused a brief 10.835°C rise for 0.43 s, deemed safe, while all CWC+BFO techniques exceeded 10°C above body temperature, lasting up to 14.40 s. Lower temperature settings, particularly during CWC, are recommended for safer CWC+BFO application.

Conclusion: The CBO technique caused minimal temperature increase and appears safe. However, the CWC technique with BFO resulted in significantly higher temperatures, potentially harming the periodontal ligament. The authors recommend using lower temperatures with both techniques, especially with the CWC technique, and applying the BFO technique in multiple layers to minimize risks.

Keywords: Backfill obturation, carrier-based obturation, continuous wave of condensation, periodontal ligament, Ttemperature rise

INTRODUCTION

Thermoplasticized filling techniques employ heat to plasticize the gutta-percha, achieving greater homogeneity and enhanced canal adaptation (1). However, warm gutta-percha obturation techniques have the disadvantage of causing high temperatures on the external root surface (2). Dental treatments that raise the temperature of the outer root surface beyond the established critical threshold of 10°C have the potential to cause damage to the periodontal tissues, as demonstrated in a classic study of implant dentistry conducted by Eriksson and Albrektsson. Their research, involving rabbit tibia exposed to temperatures exceeding 47°C, revealed fat cell replacement and irreversible bone resorption (3,4). According to another source, the upper limit of acceptable temperature is suggested to be 53°C (16°C increase) and surpassing this limit has been proposed to lead to bone necrosis potentially (5,6). Some previous studies mentioned that an increase of 10°C above body temperature for 1 minute is considered the safety threshold for periodontal tissues (7–9). It is widely accepted that limiting any temperature increase on the root surface to within 10°C is essential to prevent periodontal ligament and bone injury (4).

Carrier-based obturation (CBO) aims to reduce working time and ensure predictable thermoplasticization and gutta-percha flow using a specialized oven with precise temperature control. CBO simplifies the procedure by eliminating the need for instruments like spreaders, pluggers, heaters, and compactors in complex root canals (10). In the continuous wave of condensation (CWC) technique, a single master cone and a heat source are used to obturate the root canal by applying pressure from a heated plugger (11). When the CWC method is chosen as a canal filling technique, the limitations of the technique are usually overcome by using the backfill obturation (BFO) technique.

Various precise methodologies, including thermistor (12), infrared cameras (13), finite element analysis (FEA) (4,14,15), and thermocouples (13,16), have been used to quantify the heat produced within the root canal and its dispersion to the periodontium and bone. In the present investigation, FEA has been utilized to evaluate the alterations in temperature on the external root surface. FEA is a well-established technique for evaluating stress and temperature distribution in teeth under in vitro conditions (4,15). It is a faster and more reliable alternative to physical measurement devices for measuring temperature (14). The finite element method offers significant advantages, as complex structures that are either difficult or costly to investigate experimentally can be readily modeled (15).

To the best of our knowledge, although there are a few studies in the existing literature (4,14,15) that evaluate the effect of warm gutta-percha obturation techniques on the tooth and surrounding tissues using finite element analysis, there is currently no study that compares CBO and CWC+BFO techniques using FEA. Therefore, this FEA study aimed to assess the temperature increases in the PDL generated by two different thermoplasticized gutta-percha obturation techniques (CBO and CWC+BFO) on a simulated mandibular premolar tooth model.

MATERIALS AND METHODS

Creation of the FEA models

A mandibular second premolar tooth with supporting tissues was created, and the geometric and anatomical dimensions of the models were established based on the existing literature (17). The surrounding tissues and bones were also included, and the enamel, dentin, periodontal ligament (PDL), cancellous bone, and cortical bone regions were identified. The assumed width of the periodontal ligament was 0.3 mm, while the alveolar bone was created 2 mm below the cemento-enamel junction. The thin cementum layer was neglected, and the hard tissue of the roots was assumed to be dentin only. The root canal's working length was supposed to be 12 mm. It had undergone root canal instrumentation before the filling procedure (taper: 6%, master apical file size: 40). All the mentioned processes and thermoplasticized gutta-percha (GP) canal fillings were performed using the SolidWorks software program (SolidWorks Corp, Waltham, MA, USA). The heating process applied to the GP layers was performed using ANSYS software (version 18.1; ANSYS, Canonsburg, PA).

Thermoplasticized GP techniques

Carrier-based obturation (CBO) technique (soft-core)

In this technique, it was assumed that a well-fitted Soft-Core (Kerr, Romulus, MI, USA) carrier-based gutta-percha obturator (Size #40) was heated in a Soft-Core oven (Kerr Endodontics) to a temperature of 110°C (18). The obturator cone was inserted into the root canal with apical pressure until reaching the apical stop, and this insertion process took one second. When the obturator cone had cooled, it was assumed that the handle and insertion pin were removed, and the gutta-percha was compacted vertically by hand plugger (Figure 1).

Continuous wave of condensation (CWC) technique followed by backfill obturation (BFO) (elements IC) technique (CWC+BFO)

In this study, the CWC technique is evaluated with two different BFO layering approaches, each with three different temperature settings. First, it was assumed that a well-fitted master gutta-percha cone (size: #40, taper: 6%) was placed into the root canal at the working length, and a heat plugger was advanced towards the apex by approximately 4 mm with CWC technique at 140°C, 200°C or 400°C using down pack unit of the Elements IC device (Kerr, Culver City, CA, USA), according to the description by Buchanan (11). It was assumed that this process took 3 seconds. Subsequently, the heat was turned off, and a 10-second wait was allowed for cooling. After this waiting period, an additional 1 second of heat was applied to the heating plugger to retrieve the cooled gutta-percha (at the temperature at which the down pack procedure was performed). The time elapsed while removing the heat plugger from the canal (1 second) and the condensation of apical GP into the canal using the appropriate Buchanan's hand plugger (5 seconds) was considered a total of 6 seconds. Then, the BFO procedure was initiated.

The first approach performed BFO in a single layer (SL). For this purpose, the remaining 8 mm portion of the canal was filled with flowable GP using the backfill unit of the Elements IC Device (Kerr) at 100°C, 170°C, or 230°C, and it was assumed that this process took 3 seconds. BFO was performed in two layers (TL) in the second approach. The 4 mm portion in the middle third of the canal was filled with flowable GP (1.5 seconds)

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at 100°C, 170°C or 230°C. It was assumed that 4 seconds were required for condensing GP into the canal using hand pluggers. Subsequently, the 4 mm portion in the coronal third of the canal was filled with flowable GP (1.5 seconds) (at the temperature at which the first layer of BFO was performed) (Figure 1).

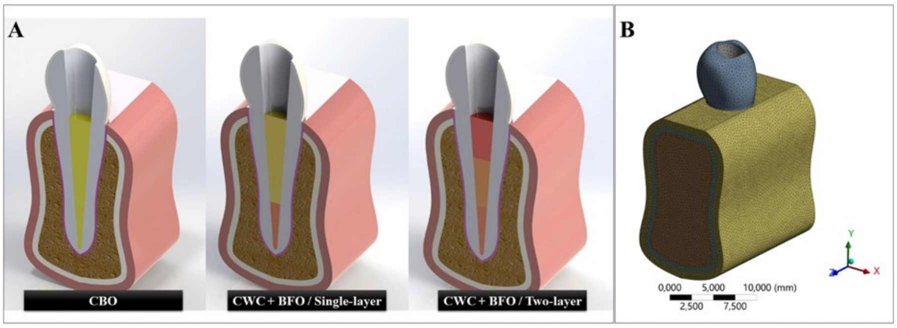

Figure 1. A) Finite element models of carrier-based obturation (CBO) and continuous wave of condensation technique followed by backfill obturation (CWC + BFO) techniques. **B)** A meshed model containing elements and nodes.

The preferred temperature settings were determined considering the default temperature setting (DefTS) (200°C/170°C) provided by the Elements IC device (Kerr) and the minimum and maximum down pack and backfill temperature settings (MinTS and MaxTS) (140°C/100°C, 400°C/230°C) that the device can offer (19).

Consequently, a total of seven models were assessed in this study:

Model 1 (M1): CBO at 110°C.
Model 2 (M2): CWC followed by single-layer BFO with minimum temperature settings (140°C-100°C).
Model 3 (M3): CWC followed by single-layer BFO with default temperature settings (200°C-170°C).
Model 4 (M4): CWC followed by single-layer BFO with maximum temperature settings (400°C-230°C).
Model 5 (M5): CWC followed by two-layer BFO with minimum temperature settings (140°C-100°C-100°C).
Model 6 (M6): CWC followed by two-layer BFO with default temperature settings (200°C-170°C-170°C).
Model 7 (M7): CWC followed by two-layer BFO with maximum temperature settings (400°C-230°C-230°C).

Root canal sealer was not used for obturation due to its negligible thickness and to minimize the number of variables, as in the study by Zhou et al (14). In all FEA models, temperature changes were monitored from the start of heat application until 13 seconds after the procedures were completed.

Geometric models were meshed with 10-node tetrahedral elements with quadratic displacement shape functions and 3 degrees of freedom per node, with an average size of 0.2 mm (Figure 1). The preferred modeling type between different tissues/materials was the "bonded" interface. Additionally, the accuracy of the FEA models was validated through a convergence test. The CBO, CWC+BFO/SL, and CWC+BFO/TL finite element models were created using nodes and tetrahedral solid elements, with approximately 429,226 nodes and 242,906 elements, 455,795 nodes, and 247,999 elements, and 454,051 nodes and 247,406 elements, respectively. It was assumed that the materials under consideration were homogeneous and isotropic.

Table 1. The thermal properties of dental materials.

	Specific heat [J / (g . °C)]	**Thermal Conductivity [J/(mm . s . °C)]**	**Density [g/mm³]**
Enamel	0.75366	9.2114E-04	2.9E-03
Dentin	1.17236	6.2805E-04	4E-03
Cancellous bone	1.84228	5.8618E-04	1.3E-03
Cortical bone	1.84228	5.8618E-04	1.3E-03
Periodontal ligament	4.817	5.8618E-04	1E-03
Gutta-percha	1.828	1.53E-04	0.97E-03

The thermal properties of the elements utilized in FEA were sourced from the existing literature (Table 1) (14,20,21). All dental components within the tooth model were assumed to have a standard body temperature of 37°C and the ambient air was set at a constant 22°C (14). Additionally, the process assumed transient heat conduction throughout the tooth elements. Furthermore, free heat convection from the tooth crown to the surrounding ambient air occurred during the process. For this purpose, a heat convection coefficient of h = 6E - 06 [J/(mm². s. °C)] was used (22). Temperature measurements started at the moment of applying the heat source. The temperature changes in the dentine and surrounding tissues were analyzed and recorded using ANSYS v.18.1 software (Canonsburg, PA, USA).

RESULTS

The durations from the initiation of root canal obturation to the onset of post-procedural cooling were 14, 37, and 41 seconds for the CBO, CWC+BFO/SL, and CWC+BFO/TL techniques, respectively. The time-dependent temperature changes in all tested FEA models are illustrated in Figure 2.

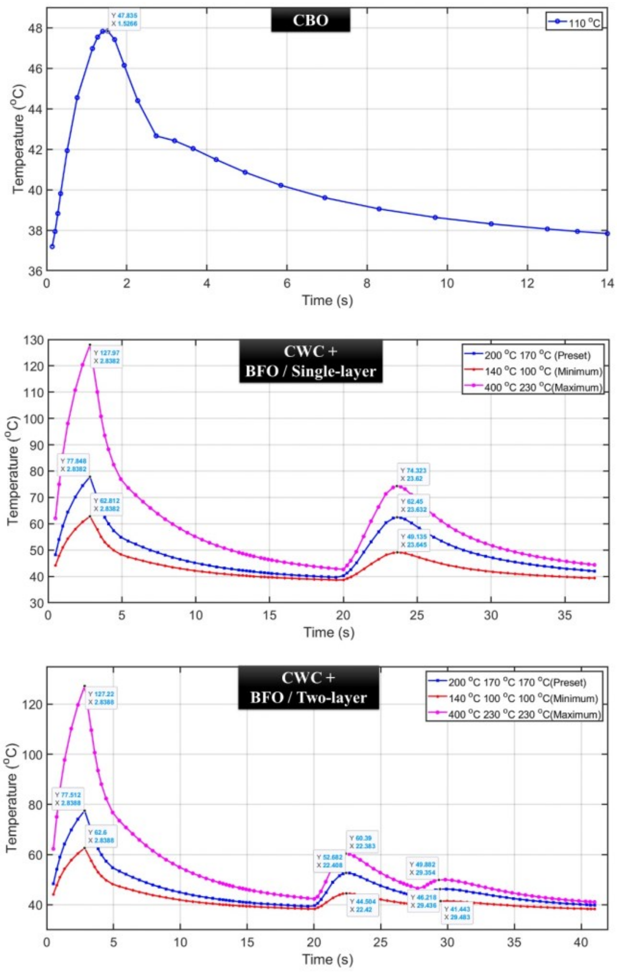

Figure 2. Time-dependent temperature changes in periodontal ligament tissue in each FEA model. The initial peaks in temperature represent the application of CWC and CBO techniques, while the second and third peaks indicate the application of the BFO technique for CWC + BFO models, respectively.

During the CWC technique (down pack), the highest maximum temperatures in the PDL were recorded in the apical regions of the M4 and M7 models (~127°C). For approximately 14 seconds, the temperature levels remained above 10°C higher than the body temperature. The M1 model exhibited the lowest maximum temperature of 47.835°C in the apical region of the PDL, surpassing a 10°C difference from the body temperature in less than 1 second (0.43 seconds). In the BFO application, the highest PDL temperature was observed in the M4 model (74.323°C), lasting 12.24 seconds, while the lowest maximum temperature was detected in the M5 model (44.504°C), which never exceeded 10°C above the body temperature; and these changes were observed in the middle thirds of the roots. The distributions of maximum temperatures induced by various stages of the tested warm gutta-percha obturation techniques in the PDL are illustrated in Figures 3 and 4.

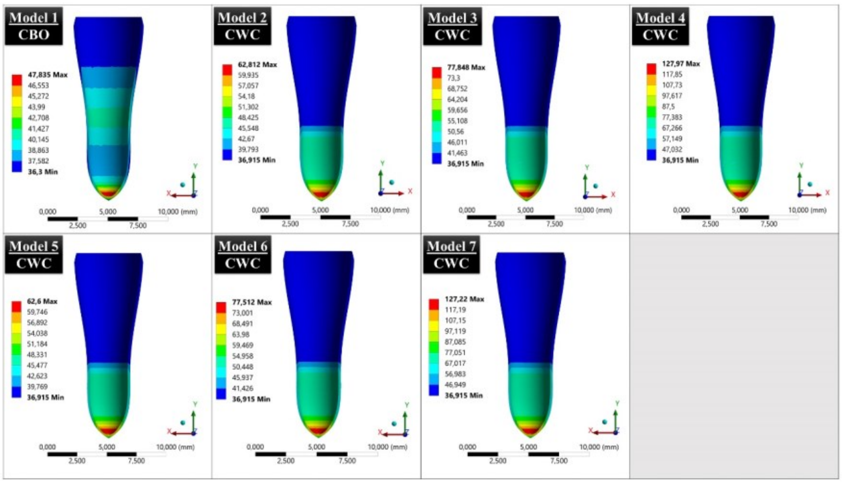

Figure 3. The maximum temperatures observed in periodontal ligament tissue in the FEA models.

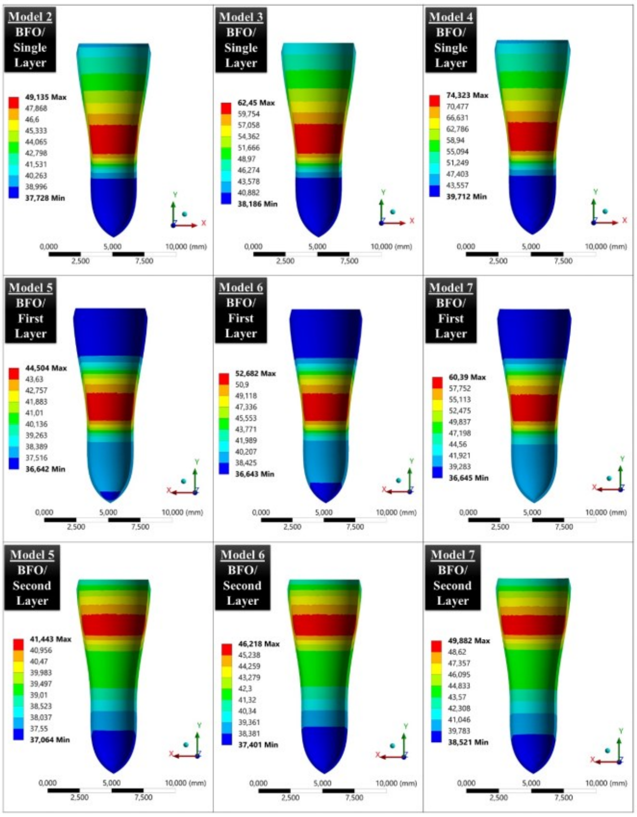

Figure 4. Maximum temperatures observed in BFO applications in the FEA models from Model 2 to Model 7.

In addition, temperature distributions 13 seconds after the completion of the obturation process in all models are shown in Figure 5.

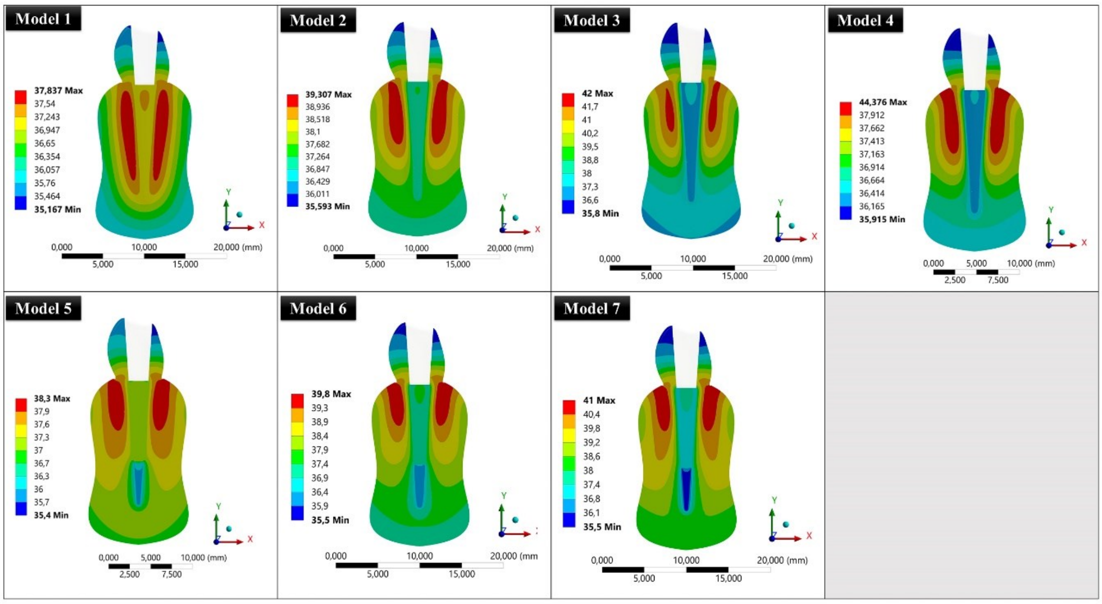

Figure 5. The maximum temperatures detected 13 s after the completion of thermoplasticized gutta-percha obturation procedures in the FEA models.

After a cooling period of 13 seconds, no temperature levels capable of causing damage to the PDL were observed in any model. Data regarding temperature changes and time parameters for all experimental models are provided in Tables 2 and 3.

Table 2. The maximum temperatures detected in the periodontal ligament, the maximum temperature increase in the periodontal ligament relative to body temperature, and the maximum temperature after cooling for 13 s in the tested FEA models.

	Maximum temperatures (°C)	**Maximum temperature increase according to body temperature (°C)**	**Maximum temperatures after cooling (°C)**
Model 1	47.835	10.835	37.837
Model 2	62.812	25.812	39.307
Model 3	77.79	40.79	42
Model 4	127.97	90.97	44.376
Model 5	62.6	25.6	38.3
Model 6	77.512	40.512	39.8
Model 7	127.22	90.22	41

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Table 3. The durations (seconds) above the increase of 10°C.

	Obturation Phase			
	Carrier-Based Obturation (s)	**Continuous wave of Condensation (s)**	**Backfill Obturation (First Layer) (s)**	**Backfill Obturation (Second Layer) (s)**
Model 1	0.43	-	-	-
Model 2	-	4.68	2.24	-
Model 3	-	8.43	8.74	-
Model 4	-	14.40	12.24	-
Model 5	-	4.68	_	-
Model 6	-	8.44	3.58	-
Model 7	-	13.94	6.37	4.80

DISCUSSION

Premolars were selected to ensure compatibility with other studies in the literature, facilitating result comparison (2). Additionally, mandibular premolars offer several advantages, such as a more rounded root morphology, consistent dentin thickness throughout most of the root, and generally curvature-free roots. In our study, the Soft-Core (Kerr) system was used as a reference to replicate the CBO technique. Following the manufacturer's instructions, the Soft-Core (Kerr) system operates at 110°C (18), thus, our simulation for this model was conducted at 110°C. For the CWC+BFO technique, the wireless Elements IC device (Kerr), currently widely used in clinical practice, was chosen as a reference. This device is being evaluated because it allows a broad range of temperature adjustments in the CWC and BFO stages. In this regard, the minimum temperatures provided by the device (140°C for CWC, 100°C for BFO), the preset temperatures that come with the device (200°C for CWC, 170°C for BFO), and the maximum temperatures it can achieve (400°C for CWC, 230°C for BFO) were included in this study. Notably, the maximum temperatures offered by this device align with a temperature range that has not been previously explored in the literature.

According to the findings of our study, the highest temperatures in the PDL were detected at the apical third of the roots in all tested models (Figure 3). As the distance from the apex of the root to the coronal third of the root increased, the maximum temperatures in the PDL decreased gradually (Figure 4). One of the reasons for this is that the root narrows. The remaining dentin thickness decreases as the apex of the root is approached (23). Thus, the applied heat can more readily be emitted to the PDL, inducing undesirable temperature increases in these regions. Lipski et al. reported that the temperature rise on the root surface depends on the remaining radicular dentin, and they mentioned that the temperature elevation was three times higher on mandibular incisors with thin root walls compared to maxillary incisors (24). McCullagh et al. stated that the most elevated temperatures recorded on the external root surface are associated with the final position reached by the tip of the heat carrier in the root canal (13). The findings of these studies are consistent with our findings. In accordance with the laws of thermodynamics, all systems in nature strive to reach equilibrium, leading to the occurrence of heat transfer (25). When there is a temperature difference, heat transfer takes place from the warmer environment to the cooler one to achieve thermal equilibrium. In this study, based on these laws, cooling begins from the outermost layer and progresses toward the warmer environment.

When Figure 3 is examined, the most noticeable observation is that CWC application causes higher temperature increases in the PDL than CBO and BFO applications. Among the CWC applications, the most elevated maximum temperatures were observed in models M4 (127.97°C) and M7 (127.22°C), while the lowest maximum temperatures were obtained in models M2 (62.812°C) and M5 (62.6°C). The default settings determined by the device manufacturer resulted in a temperature increase between the temperature increases caused by these minimum and maximum temperature settings (77.79°C for M3, 77.512°C for M6). Consequently, the heat intensity applied during the CWC phase appears to be a determining factor in the temperature increase in the PDL. The CBO technique, on the other hand, caused a maximum temperature of 47.835°C, which is approximately at the threshold of potential harm to the PDL. The reason CBO causes lower temperature increases than CWC applications may be due to the lower applied temperature (110°C) and the shorter application time (1 second) compared to the 3-second application time of CWC. Ulusoy et al. examined temperature changes during root canal filling, comparing techniques with and without simulated internal resorption. They assessed injectable gutta-percha (Obtura II, 160°C), carrier-based (Soft-Core, 110°C), and continuous wave of condensation (System B, 200°C). High-temperature methods (System B and Obtura II) exceeded the critical 10°C threshold with internal resorption, while the carrier-based (Soft-Core) technique remained within safe limits regardless of resorption (2). Our study findings were also consistent with their study.

When reviewing relevant literature, Venturi et al. used thermocouples to examine temperature variations within gutta-percha during vertical compaction using a System-B Heat Source heated to 250°C. Their findings indicated that the System-B Heat Source could be safely employed for vertical compaction, as it did not substantially elevate gutta-percha temperature and posed no risk to periradicular tissues (16). However, in our study, particularly in CWC techniques with higher temperature settings, we observed potentially harmful temperature increases in the periodontal ligament. These discrepancies may be attributed to differences in experimental conditions, such as the types of teeth used, dentin thickness, and methodological variations. Er et al. assessed the temperature variations in a maxillary canine using finite element analysis on the adjacent periodontal tissues and bones during the continuous wave of condensation technique (System-B). The maximum temperature observed in the periodontal ligament was 43.5°C. The continuous wave of condensation technique did not generate temperature levels considered potentially harmful (15). While our study identified higher temperatures, especially in the apical region, when the CWC+BFO technique was used. These discrepancies may result from differences in tooth morphology and the thermal properties of tissues modeled in the studies. On the other hand, McCullagh et al. discovered an average temperature increase of 13.9°C on the root surface when employing the continuous wave of condensation technique with the System-B heat carrier system for root canal obturation (13). Which is consistent with our findings of elevated temperatures in the CWC models. Using finite element analysis, Cen et al. compared two dental filling techniques (System-B and Obtura II). They found that without blood flow, both techniques could reach potentially elevated temperatures (50-52°C) in a molar tooth. However, with simulated blood flow, peak temperatures dropped below 47°C, suggesting blood effectively cools the tooth during both procedures (4). While our study did not simulate blood flow, the observed temperature increases align with their findings.

BFO applications also led to harmful temperature levels (up to 74.323°C), mainly when used at higher temperatures. The difference of BFO applications from CBO and CWC applications lies in their impact on the middle and coronal thirds of the root rather than the apical third. Before initiating the BFO application, there is some cooling opportunity for the apical PDL, and the newly applied backfill layers mainly affect the PDL, corresponding to the regions where they are used. All CWC+BFO/SL models exhibited temperatures higher than the maximum observed in CBO during the BFO phases. In the two-layer backfill models, relatively lower maximum temperatures were observed in both backfill layers of CWC+BFO/TL MinTS and the second backfill layer of CWC+BFO/TL DefTS compared to those detected in CBO. Our findings regarding the BFO technique are consistent with the results reported by Ulusoy et al., who compared the injectable Obtura II system with Soft-Core and System-B and said that this system could lead to elevated temperatures in the PDL (2).

Additionally, it is observed that the maximum temperature values in models with a two-layer backfill are lower than those in models with a single-layer. The reason for this could be the application of hot GP for shorter durations and smaller masses, allowing for a cooling period by being exposed to room temperature between the two layers. Zhou et al. used finite element analysis to measure temperature increases in the periodontal ligament and apical gutta-percha in a mandibular molar tooth model. The apical thirds of the canals were filled using a continuous wave of condensation. The remainder was backfilled with injected gutta-percha in 2 segments (using Obtura II), and during the obturation procedure using Obtura II, the temperature at the periodontal ligament remained below 47°C (14). Another aspect related to BFO is the observation of maximum temperatures being lower in BFO applications in each model compared to CWC. Possible reasons for this situation include the application of less heat in BFO than in CWC and a thicker dentin layer in the teeth's middle and coronal root thirds compared to the apical third.

The carrier-based obturation technique caused a maximum temperature rise (10.835°C) near the threshold of potential harm for 0.43 seconds. Additionally, all CWC applications resulted in excessive temperature increases (up to 90.97°C), surpassing 10°C above body temperature, lasting up to 14.40 seconds. Among the BFO applications, the CWC+BFO/SL MaxTS model caused a temperature rise of 37.323°C above body temperature, lasting 12.24 seconds. In the CWC+BFO/TL MinTS model, hazardous temperatures were never reached during the BFO stage. In all other CWC+BFO models except the CWC+BFO/TL MaxTS model, dangerous temperatures did not occur during the second layer backfill process. It is essential to avoid prolonged exposure to temperatures above 47°C, which can harm teeth. Previous studies have suggested that an increase of 10°C above body temperature for 1 minute is considered the safety threshold for periodontal tissues (7–9). In light of these data, among all tested models, only the M1 model (CBO) appears to have the potential to be safe for the periodontal ligament (PDL), as it marginally and briefly exceeded the harmful temperature limit. This finding is per the study of Ulusoy et al., further supporting the safety profile of the carrier-based obturation technique (2).

In thermoplasticized obturation techniques, as the duration of heat application increases, the temperature also rises in the root and surrounding tissues. Lipski and Wozniak used the thermoplasticized core techniques (Thermafil system) for root canal obturation and employed the continuous wave of condensation with System B heat source for 5- and 8-seconds during retreatment procedures. They observed temperatures ranging from 26.7°C to 46.0°C, potentially causing harm to the periodontal tissues (26). Zhou et al. investigated continuous wave of condensation filling in mandibular molars for 3 and 4 seconds. They found that, when filling for 3 seconds, the periodontal ligament temperature reached 46.9°C, and extending the activation time to 4 seconds caused a temperature increase of more than 10°C. In conclusion, they advised against exceeding the 3-second activation time (14). Therefore, the duration of heat application did not exceed 3 seconds in this study.

A monitoring period of 13 seconds was established following the completion of root canal filling procedures in the tested finite element models, as the models exhibited a trend of returning to non-harmful temperatures after 10 seconds. Temperature changes in the models were tracked until the end of this monitoring period. After this cooling period, maximum temperatures in the PDL were measured, and no destructive elevated temperatures were observed in the PDL and bone in any of the models (Figure 5).

Finally, the maximum temperature values observed in our study are generally higher than other studies in the literature (4,14,15). This may be attributed to methodological differences such as the teeth used in the studies, differences in dentin thickness, and variations in operator application.

One of the limitations of this study is the standardization of the working length of the teeth to 12 mm for the finite element analysis (FEA). This was done to ensure consistency across the models and to minimize variability in temperature distribution due to root length differences. However, in clinical practice, root lengths vary, and this variation may influence the heat transmission to the periodontal ligament (PDL) and surrounding tissues. In teeth with shorter roots, the proximity of the heat source to the apical region and surrounding tissues may lead to faster heat transmission, potentially increasing the risk of thermal injury. Conversely, in teeth with longer roots, the greater distance between the heat source and the PDL may act as an insulator, reducing the amount of heat transmitted to the surrounding tissues. These factors could impact the safety thresholds of the tested thermoplasticized obturation techniques. Future studies should consider evaluating the effects of these techniques on teeth with varying root lengths to provide a more comprehensive understanding of temperature dynamics in clinical conditions.

The cementum layer was omitted in our study to simplify the model and reduce computational complexity, focusing primarily on the heat transfer within the root and surrounding tissues. Given the thinness and low thermal conductivity of the cementum, we believed its impact on temperature distribution in the periodontal ligament (PDL) would be minimal. Cement layer had not been modeled in previous studies in the literature (4,14,27). However, we recognize that in clinical settings, the cementum may act as an insulator, slightly affecting heat dissipation.

CONCLUSION

This study compared two warm gutta-percha obturation techniques using FEA method. The CBO technique remained within safe temperature limits, with only a brief and minimal temperature rise of 10.835°C above body temperature, making it a safer option. In the CWC+BFO technique, models with higher temperature settings (200°C-400°C for CWC and 170°C-230°C for BFO) exceeded the critical 10°C temperature rise, lasting up to 14.40 seconds, which could pose a risk to the PDL. The two-layer backfill (TL) approach at minimum temperature settings (140°C/100°C for CWC+BFO) was found to be the safest variant of the CWC+BFO technique, with temperatures staying within safer limits. The authors recommend using lower temperatures with both techniques, especially with the continuous wave technique, and applying the backfilling technique in multiple layers to minimize risks.

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Authorship contributions

Conceptualization: Özgür Er; Tuğrul Aslan; Methodology: Tuğrul Aslan, Emir Esim; Validation: Emir Esim; Formal analysis: Emir Esim; Data curation: Emir Esim; Writing—original draft preparation: Tuğrul Aslan; Ayşe Tuğba Eminsoy Avcı; Yakup Üstün Writing—review and editing: Tuğrul Aslan; Yakup Üstün; Ayşe Tuğba Eminsoy Avcı

Declaration of competing interest

The authors declare no competing interests.

Data availability statement

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Ethics

This finite element analysis study did not involve the use of human or animal subjects. Therefore, no ethical approval was required

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