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Comparative Analysis of Temperature Variation with Three Continuous Wave Obturation Systems in Endodontics: An In Vitro Study

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Abstract: The aim of this study was to assess temperature changes with different continuous wave obturation systems when downpacking to 2 mm and 4 mm from the apical foramen in an open system not simulating the surrounding biological structures at body temperature. Sixty single-rooted teeth were divided into three groups: (A) Dia-Duo® (DiaDent Group International, Cheongju-si, Korea), (B) Elements Free® (Kerr Corporation, Orange, CA, USA) and (C) Calamus® (Dentsply Sirona, Ballaigues, Switzerland). The root canals were instrumented with Protaper Gold (Dentsply Sirona, Ballaigues, Switzerland) to size F2 (25.08). The root canals were filled by a continuous wave using an AH Plus® sealer (Dentsply Sirona). Temperatures during the obturation procedure were measured by a thermal imaging camera (Testo 875-1®) perpendicular to a vice where the teeth were held at −2 mm and −4 mm from the apical foramen. Comparisons were made by applying Student's *t*-test and ANOVA ($p = 0.05$). The continuous wave technique at −2 mm with the Dia-Duo system® emitted average temperatures of 37.3 °C, Elements Free® emitted 39.85 °C and Calamus® emitted 40.16 °C. At −4 mm, the Dia-Duo system® emitted average temperatures of 34.81 °C, Elements Free® emitted 33.73 °C and Calamus® emitted 32.91 °C. There were significant differences between continuous waves at −2 mm and at −4 mm ($p < 0.05$). Dia-Duo® was the only system that did not present significant differences between the two lengths ($p = 0.197$). Regarding the heat emitted, the best system was Elements Free®, since, at −2 mm, it emitted the highest temperature without going above 47 °C. The Dia-Duo® system had lower temperatures. It could be concluded that not all systems transmit the same temperature to the apex and, therefore, to the periapical tissues. The surrounding conditions, such as temperature and humidity, have not been considered in this study.

Keywords: continuous wave technique; endodontic treatment; gutta-percha; heat packing; root canal obturation; temperature

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1. Introduction

The main purpose of root canal treatment is a good intracanal preparation followed by adequate filling. According to Schilder [1], the final objective of obturation should be the complete and three-dimensional filling of the root canal, achieving a hermetic seal [2–7]. Up to 60% of endodontic failures can be attributed to the inadequate filling of the root canal, which is a very important field to study in order to obtain new materials and methods for filling in endodontics [2].

Long-term sealing plays an important role in supporting healing of the periapical tissue and prevents intracanal contamination after treatment [8]. Different thermoplastic obturation systems aim to completely seal both the apical and coronal pathways from a possible leak and maintain the state of disinfection achieved to prevent reinfection [9]. Full root space debridement, the development of a fluid-tight seal of the apical foramen and total canal obliteration must be accomplished to ensure the long-term success of the treatment [8–10]. There are several methods of root canal filling, but none are perfect, and we can always expect complications. Therefore, choosing the most precise and safest root canal filling device is still a challenge for practitioners.

The thermal environment of teeth caused by eating or drinking hot or cold food and beverages or simply breathing cold air varies over a wide range of temperatures. Different studies have been carried out to address this challenge [11,12]. Jacobs et al. reported that thermal stresses induced by repetitive temperature cycling can lead to cracks in the teeth [11]. The structural changes that teeth undergo when subjected to heat will depend on the temperature and the exposure time, but also on the way in which these high temperatures are produced or applied [12]. When one tooth is suddenly subjected to a change in temperature, the surface does not change immediately; it takes time for heat transfer to occur, eventually resulting in the increased thermal energy of the tooth [11,12].

According to some authors, the maximum temperature increase tolerated by the external surface of the root without causing damage to the supporting tissues is 10 °C [3]. In this sense, exceeding this limit could cause bone resorption, ankylosis of the tooth, or postoperative pain. In addition, the resorption of alveolar bone tissue was observed without evidence of regeneration after an increase of 10 °C for 5 min and of 13 °C for 1 min [4]. The thickness of dentin walls is another factor, because the thinner the walls, the greater the damage to surrounding tissues [13–15].

Enamel and dentin have different thermal and mechanical properties. The differences in these properties can lead to thermal stresses and cracking within the tooth when subjected to thermal stimuli [16]. The thermal denaturation of dentin collagen often occurs in endodontic treatments, during which root canal dentin may be exposed to a temperature of ∼300 °C. The denaturation temperatures of the demineralised dentin matrix have been reported to be 65.6 °C, 148.5 °C and 166.8–172.7 °C for demineralised dentin saturated with water; dentin saturated with methanol, ethanol or acetone; and dentin bonded with resin, respectively [16,17].

Periapical disease is an inflammatory response around the root canal endings due to intracanal bacterial infection. The dental pulp and periodontium have different communication pathways such as the apical root canal, accessory (or lateral) canals and dentinal tubules [18]. Pathological communication between these structures includes the migration of microorganisms and inflammatory mediators between the root canal and the periodontium [18,19].

Although root canal sealers are very important in obturation, the amount used should be minimal. To achieve a high amount of gutta-percha, filling techniques have been developed to achieve this purpose. When the apical part of the canal is filled with the Buchanan continuous wave technique at −4 mm, the gutta-percha is not thermoplasticised in the last few millimetres, since the gutta-percha is a very poor conductor of heat [20–22]. For that reason, in this study, canals have been filled to different depths with three different systems, and the emitted heat has been observed. In a study performed by Lipski and Woźniak in 2003, the temperatures recorded at the tips of a continuous wave plugger varied with their taper and were lower than the temperature set on the System B LCD display [23]. There are other studies that have measured the real intracanal temperature during different obturation techniques [18,24] and studies that compare the same technique with different devices [25], but the temperature transmitted by new devices is not known. Furthermore, the actual temperature changes in periapical tissues are currently unknown.

The aim of this study was to calculate the heat emitted when downpacking at −2 mm and −4 mm with three different continuous wave obturation systems.

2. Materials and Methods

A randomized experimental in vitro trial was carried out conducted in accordance with the principles defined in the statement of the German Ethics Committee for the use of organic tissues in medical research (Zentrale Ethikkommission, 2003), and was approved by the University Ethics Committee (Process No. 07/2020). All patients who were asked to transfer teeth agreed and signed an informed consent document before entering the study. The sample size of the study was calculated on the basis of the EPIDAT 4.2 program (Dirección Xéral de Saude Pública, Galicia, Spain) and the article by Lipski and Woźniak [23] with statistical significance (p-value < 0.05). The randomization of the study sample was carried out with the EPIDAT 4.2 statistical package, which was used to generate a table of random numbers in three groups. Sixty single-rooted first upper premolar teeth extracted for orthodontic or periodontal reasons were selected at random in this study. The inclusion criteria consisted of patients 15–65 years of age, the absence of caries, cervical abfraction or root fracture, a curvature of less than 5° according to Schneider's technique [22], a root length of 14 ± 1 mm and rather similar mesiodistal and buccolingual dimensions (±10%). Furthermore, the teeth were submitted to a radiographic exam to analyse the number of root canals, and the absence of previous endodontic treatment, restorations and root resorption. The teeth were divided into 3 groups: Group A made with Dia-Duo® (DiaDent Group International, Cheongju-si, Korea), Group B with Elements Free® (Kerr Corporation, Orange, CA, USA) and Group C with Calamus® (Dentsply Sirona, Ballaigues, Switzerland). Each filling system had two groups of 10 teeth each. One group was performed at −2 mm and the other at −4 mm of the apical foramen.

The distance from the apex to the cementoenamel junction (CEJ) as well as the diameters in the oral–buccal and mesial–distal directions at the CEJ were measured. The teeth were randomized into 6 groups (n = 10) according to the distance from the apex to the CEJ (p = 0.999) and the ratio of the diameters in the oral–buccal and mesial–distal directions at the CEJ (p = 0.824). The homogeneity of the 6 groups with respect to the aforementioned parameters was assessed using analysis of variance and the post hoc Student–Newman–Keuls test.

The roots were cleaned with ultrasound to remove the plaque and adhering tissues. Teeth were then cut to 16 mm by means of a calliper and a disk bur.

Once the canals had been opened, they were permeabilized with #10 k-file (Dentsply Sirona, Ballaigues, Switzerland) and instrumented with Protaper Gold® (Dentsply Sirona, Ballaigues, Switzerland), up to the F2 file (25.08). The canals were irrigated with 5.25% hypochlorite after each instrument in 2 mL syringes. Canals were filled according to the Buchanan technique. The continuous wave of condensation obturation technique was applied to simplify warm gutta-percha downpacking of Schilder's warm vertical condensation; the continuous wave of condensation is an obturation technique that applies a heated "plugger" into a single custom fit master gutta-percha cone with a greater taper. The heat plugger is placed through the master cone to within 3–5 mm of the predetermined working length. Gutta-percha cones from Protaper Gold® F2 (25.08) (Dentsply Sirona, Ballaigues, Switzerland) were used. First, AH Plus cement® (Dentsply Sirona, Ballaigues, Switzerland) was introduced with a paper point and then the gutta-percha F2 (25.08) cone up to the working length.

All systems were adjusted to 200 °C and the downpacking was activated for 3 s, based on the article by Zhou et al. [24] in which they concluded that the plugger should not be activated at 200 °C for more than 3 s inside the tooth since it can reach temperatures higher than 47 °C, which is harmful to the tissues adjacent to the teeth.

Once the gutta-percha cone had been inserted into the tooth, the plugger was activated to cut away the excess gutta-percha and was left at the level of the canal entrance. Next, the plugger was activated, softening the gutta-percha until it reached the predetermined length (−2 mm or −4 mm from the apical foramen) at 3 s. The pluggers of three systems were different: #40.04 (Dia-Duo), #40.06 (System B) and #40.03 (Calamus).

When the working length had been reached, the apical pressure was maintained for 10 s, which allowed the gutta-percha to cool, then pressed for 1 s, and the plugger was extracted.

When it came to filling the canals and measuring temperatures, a vice was used so that the last 5 mm of the root was in the air. The temperatures were collected from the mesial face of the teeth using a thermographic camera (model Testo 875-1®, Testo SE & Co. KGaA, Titisee-Neustadt, Germany).

Measuring a temperature gradient across a boundary layer requires high accuracy. Typical values for the convective heat transfer coefficients for air and water are shown in Table 1.

Table 1. Typical values for the convective heat transfer coefficient in water and in air.

System	Heat Transfer Coefficient h (W/m^2 K)
Air (natural convection)	5−25
Water (forced convection)	300–600

The camera was mounted perpendicular to the tooth surface at about 11 cm. The experiment was carried out at a room temperature of 23.9 °C (Figure 1).

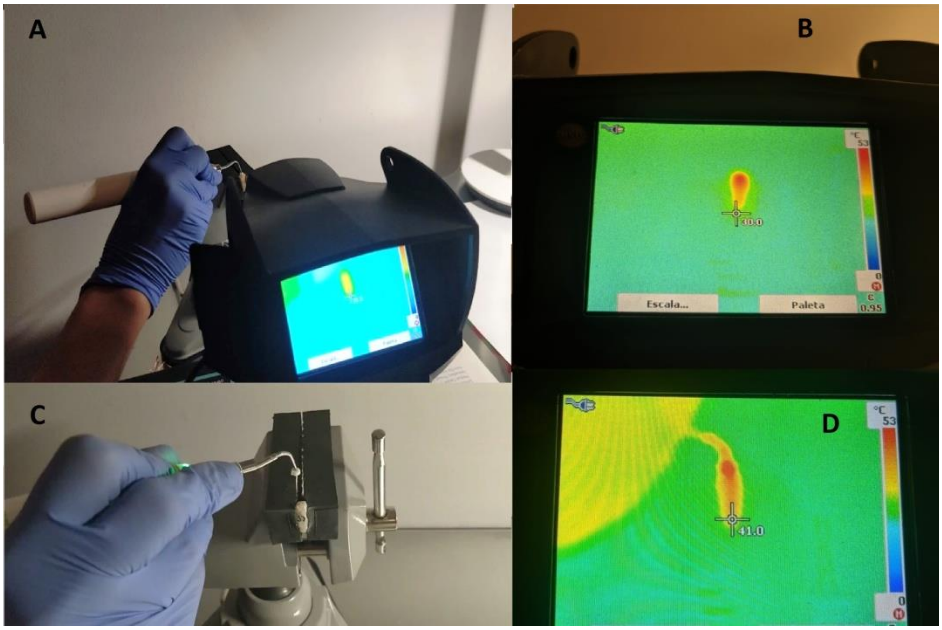

Figure 1. Experimental set up. (**A**,**C**) Positioning of the tooth with respect to the camera and location of the vice. (**B**,**D**) Images of the thermographic camera.

Descriptive statistics were obtained for each study variable with the corresponding normality tests. The statistical analysis was performed using Student's *t*-test and ANOVA to compare the three systems used, always assuming a confidence level for our study of 95%. When the data did not follow normality, the Mann–Whitney U test was carried out (in this case, when the plugger length of the systems was analysed).

3. Results

The results obtained are shown in Table 2. The mean temperature when the teeth were filled at −2 mm was higher with Calamus® than with the other systems (40.16 °C vs. 39.85 °C and 37.3 °C) while at −4 mm, the highest temperature was found with Dia-Duo® (34.81 °C) followed by Elements Free® (33.73 °C) and Calamus® (32.91 °C). The Calamus® system presented higher temperatures at −2 mm.

When we compared the different systems, there was no statistically significant difference between filling at −4 mm and −2 mm in the Dia-Duo System® (p = 0.213) (Figure 2). There were statistically significant differences between filling at −4 mm and −2 mm for the Elements Free System® (p = 0.001) (Figure 3) and the Calamus System® (p = 0.002) (Figure 4).

Table 2. System averages based on their sealing depth and minimum and maximum temperature values.

System	Length	Mean	>Temperature	<Temperature
Dia-Duo	−2 mm	37.3	42.4	33.4
	−4 mm	34.81	45.1	27.8
Elements Free	−2 mm	39.85	45.2	34.2
	−4 mm	33.73	40.3	29.8
Calamus	−2 mm	40.16	51.4	35
	−4 mm	32.91	42.1	29.8

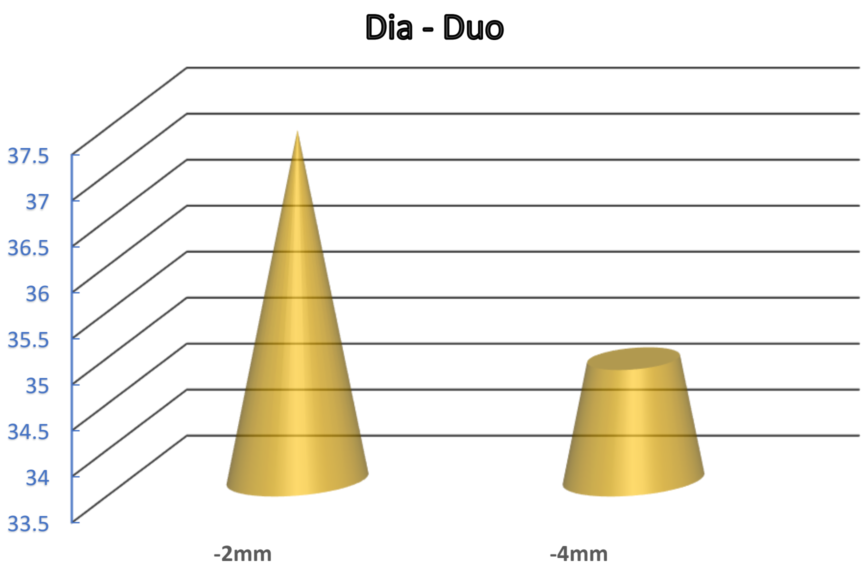

Figure 2. Graph of temperatures at −2 mm and −4 mm with Dia-Duo® (p = 0.213).

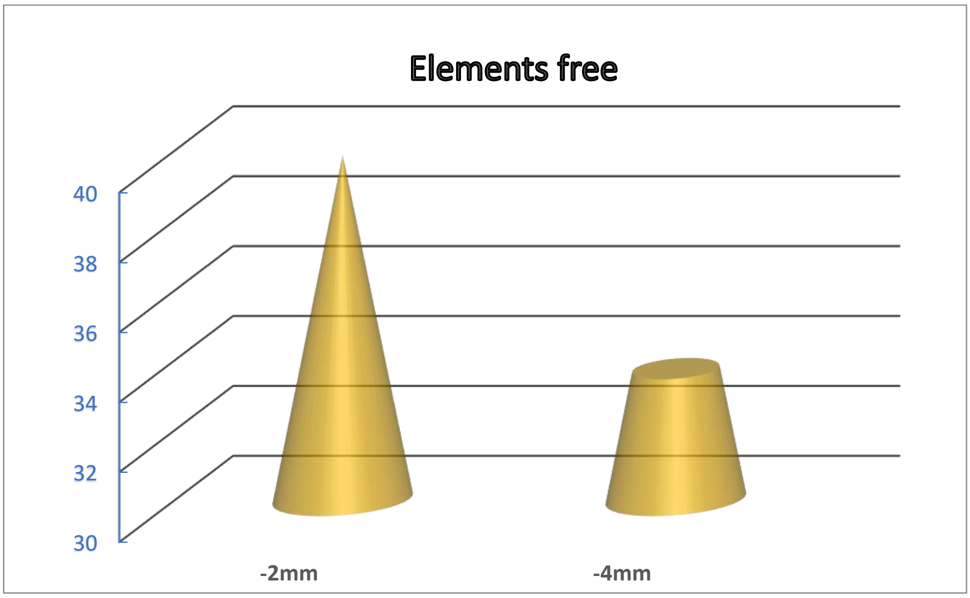

Figure 3. Average temperatures at −2 mm and −4 mm with Elements Free® (p = 0.01).

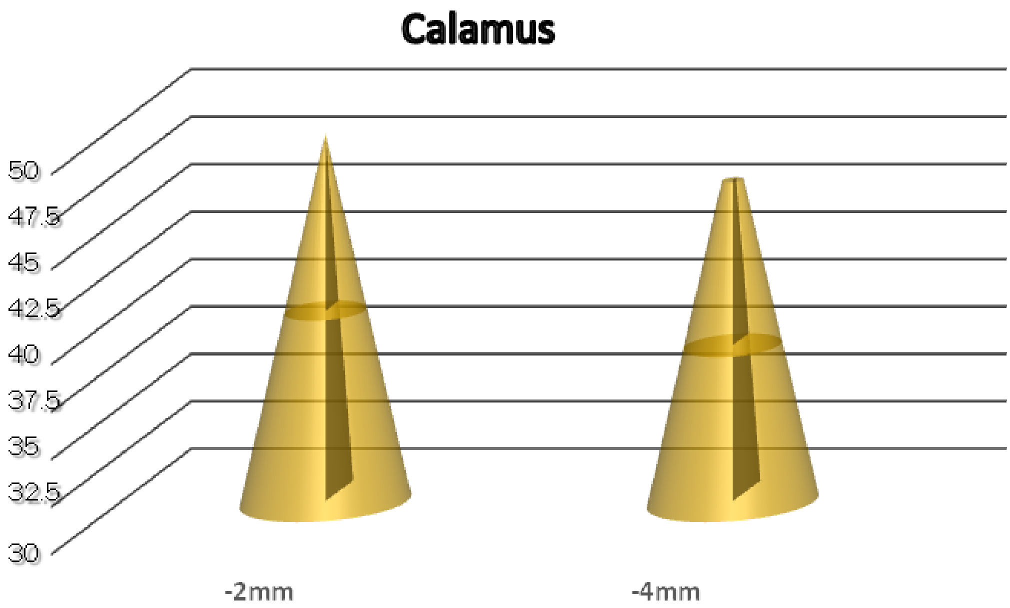

Figure 4. Average temperatures at −2 mm and −4 mm with Calamus® (p = 0.002).

If the different systems were compared according to the sealing depth, no statistically significant differences were found between the different systems at −2 mm (p = 0.197) (Figure 5) or −4 mm (p = 0.620) (Figure 6).

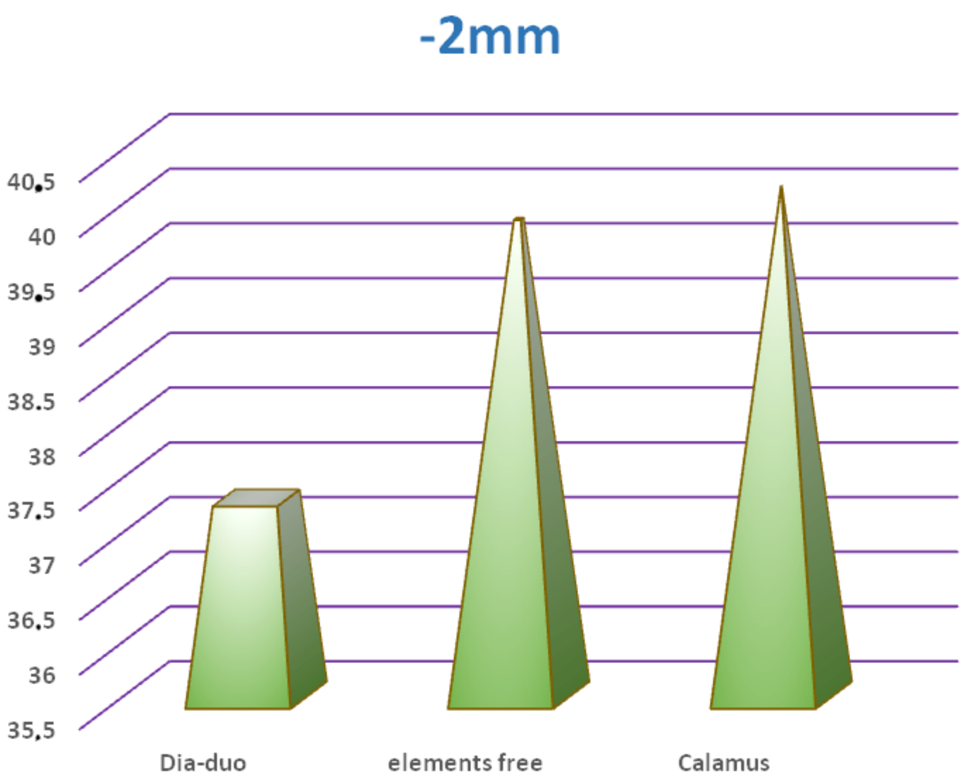

Figure 5. Average temperatures at −2 mm of the three systems compared. The data show no statistically significant differences (p = 0.197).

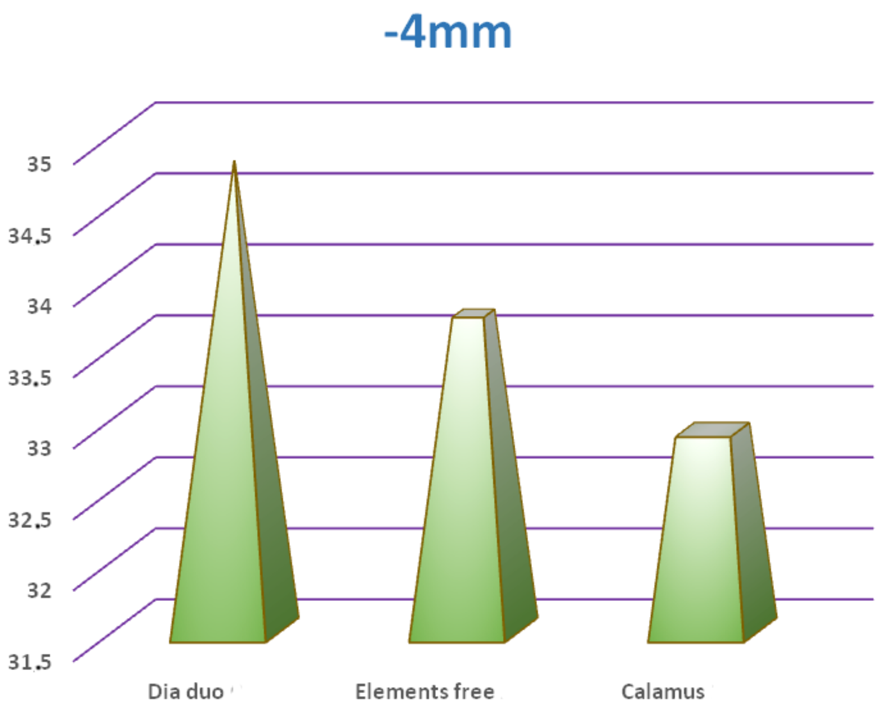

Figure 6. Average temperatures at −4 mm of the three systems compared. The data show no statistically significant differences (p = 0.620).

Finally, all systems were examined according to the depth of obturation, and a statistically significant difference was observed in the obturation at −2 mm and −4 mm (p = 0.000). A temperature difference of about 5 °C was also found between the obturation at −2 mm and −4 mm (Figure 7).

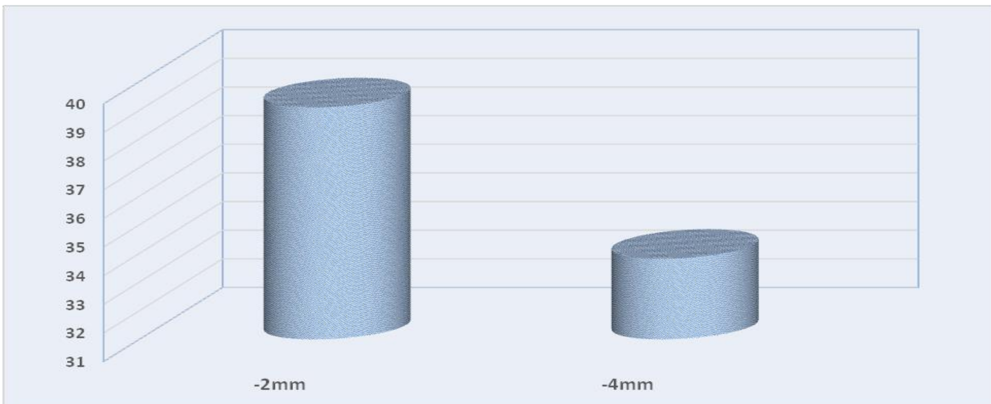

Figure 7. Comparison of mean values of temperature between all systems at −2 and −4 mm. There were significant statistical differences (p = 0.000).

4. Discussion

In this in vitro study, the temperature of the outer root surface was measured during root canal filling using the continuous heat wave technique. It has been suggested that an increase in temperature greater than 10 °C at the external root surface could be responsible for damage to the cementum, the periodontal ligament and the alveolar bone that may trigger resorption or ankylosis [26,27]. With the experimental technique applied in this study, the rise in temperature of the single-rooted teeth never exceeded 10 °C except in one sample (maximum temperature recorded: 51.4 °C).

The current findings contrast with the study by Romero et al. [26], which reported that the elevation of the root surface temperature during the continuous heat wave technique did not exceed 1−2 °C. In the abovementioned study, the extracted teeth (maxillary canines and mesial roots of mandibular molars) were imbibed in a water-containing medium (alginate), similar to the periodontal ligament. When selecting the present in vitro study model, the possibility of simulating the periodontal ligament and bone, similar to Romero et al. [26], was considered; however, it was decided not to include the samples in any medium but to keep the external conditions constant in all measurements. In addition, the aim was to know the increase in the external temperature, and this was not influenced by the environmental conditions, since the amount of bone, periodontal ligament or bone conditions that exist in the maxilla and mandible cannot be accurately reproduced in an in vitro study.

Venturi et al. [28] revealed that a negligible temperature rise (0.5–0.9 °C) was induced in the apical gutta-percha by the System B® obturation technique. These data indicated that the apical gutta-percha was often compacted at body temperature when using the continuous heat wave condensation technique, as described by Buchanan. In the present study, the heat of the plugger tip was not measured, but the increase in the external temperature was dissipated, meaning that it was actually transmitted to the patient, who sometimes feels that heat. Similar to the study of Venturi et al. [28], the measurements were performed in the air, unlike Dimopoulos et al. [21], who used a polytetrafluoroethylene (PTFE) cylinder. According to Nikolaev et al. [29], the current devices used to perform the continuous heat wave technique are completely safe and effective. In their study, they used GuttaEst® at −5 mm and observed a temperature difference of +3.8 ± 0.6 °C. Nevertheless, Lipski [30] examined the heat emitted by sealing with System B® on the maxillary and mandibular central incisors and maxillary canines; on mandibular incisors, they observed a temperature increase of more than 10 °C. McCullagh et al. [31] reported a temperature increase of 13.9 °C by measuring the heat with a thermoelectric couple and 28.4 °C with a thermographic camera, so their results were also higher than 10 °C.

Lipski and Woźniak [23], in another study, re-treated teeth obturated with Thermafil® and used the B-System® to seal the canals for 5 and 8 s, and observed that the temperatures ranged from 26.7 °C to 46.0 °C, with possible damage to the periodontal tissues. It is known that if heat is applied for more than 3 s, temperatures above 10 °C can be reached; therefore, all manufacturers recommend not applying heat for more than 3 s.

Romero et al. [26], Venturi et al. [28] and Nikolaev et al. [29] reported that with the continuous heat wave technique, there was almost no rise in temperature. The present study agrees with these authors, since we found an increase in temperature that exceeded 3.8 °C with the three systems used; nevertheless, no statistically significant differences were found. On the other hand, Lipski [30] and McCullagh et al. [31] explained that when the technique was applied to mandibular central incisors, temperatures exceeded 10 °C using System B®. In the present study, only one sample exceeded 10 °C. Lipski and Woźniak [23] reported an increase of more than 10 °C with the use of System B® as a shutter system, but their time of application was 5 s and 8 s. Zhou et al. [24] conducted a study on mandibular molars filled with System B® for 3 s and 4 s. They reported that when obturating for 3 s, the temperature of the periodontal ligament was 46,914 °C and when obturating for 4 s, the temperature increased by more than 10 °C; in conclusion, one should be careful not to extend the activation time beyond 3 s. In the present study, the plugger in all systems was set to 3 s.

Eriksson et al. [27] observed that bone resorption occurs when temperatures of 47 °C and above are reached during bone drilling. In a study on the temperature threshold for heat-induced bone tissue injury in rabbits, it was found that a temperature of 47 °C maintained for 1 min could cause microscopic evidence of bone remodelling and adipose tissue necrosis. Molyvdas et al. [15] showed a periapical inflammatory histological reaction in beagle dogs after an injection of thermoplasticized gutta-percha at a high temperature (160 °C) into the root canal. However, the tissue destruction was localized in the area around the apical foramen, while the periodontal ligament of the root surfaces remained normal. Saunders [32] performed a study on canine teeth filled with thermomechanical compacted gutta-percha in 17 ferrets, in which a histological evaluation of the root cementum, adjacent periodontal membrane and alveolar bone was performed at time intervals of 24 h, 20 days and 40 days. At 24 h, there was no inflammatory response and no evidence of hyperaemia. At 20 days, 20% of the teeth showed resorption of the cementum surface in the central section of the root. This resorption was not of an inflammatory nature, unlike resorptions due to trauma. All control teeth and their supporting tissues appeared normal. However, 40 days after thermomechanical compaction, 28% of the experimental teeth were affected by surface resorption; of these, 22% showed ankylosis of the alveolar bone. Therefore, these authors concluded that the heat generated by thermomechanical compaction stimulates surface resorption and long-term ankylosis.

Eriksson et al. [27], Molyvdas et al. [15] and Saunders et al. [32] observed alterations such as necrosis, destruction around the foramen and ankylosis in their studies. In all of these studies, temperatures above 47 °C or a time longer than 3 s were harmful to teeth. From these studies, it can be concluded that caution is necessary to avoid excessive heat when performing techniques with thermoplastic gutta-percha.

Cen et al. [33] conducted a study of a 3D-printed mandibular molar sealed by a computer system with System B® and Obtura II®. They made two models: one simulating blood flow and one without blood flow. The study concluded that in the model without blood flow, the temperature in the periodontal ligament was 50 °C along the distal canal and 52.5 °C in the mesiolingual canal. However, in the model simulating the blood flow in the periodontal ligament, the peak temperature was 47 °C. The conclusion of the study is that the blood flow of the periodontal ligament is one of the factors to be taken into account when investigating the heat emitted during thermoplastic filling.

Cumbo et al. [34] studied three obturation systems used for different times, namely 10, 15, 20 and 25 s, and the different systems used were System B®, Endo-Twin® and E-Fill®. The results obtained showed that System B® reached temperatures of 86.85 °C after 10 s, 94.9 °C after 15 s, 100.4 °C after 20 s and 104.5 °C after 25 s; with Endo-Twin®, similar results to System B® were observed but E-Fill® had temperatures lower than 69.9 °C. The study concluded that with System B® and Endo-Twin®, the temperatures reached at 25 s were sufficient for correct gutta-percha adaptation in the canals. This study did not take into account the possible damage to surrounding tissues that could occur at these temperatures.

In the studies by Zhou et al. [24] and Cumbo et al. [34], a temperature increase of more than 10 °C was observed if the heat application time with the plugger was longer than 3 s, but the temperatures still did not exceed 10 °C.

One limitation of this study was that only one heat carrier was assigned per manufacturer. Therefore, the quality of the heat carriers used for this study could have affected the results. Furthermore, not having included the samples in some medium that simulated the periodontal ligament could have affected the temperature measurements. Measurement with a thermographic camera instead of a thermocouple could also have yielded different results. In the future, finite element analysis (FEA) may use these data to reveal the actual effect of these temperature levels on the periodontal membrane and alveolar bone.

From a clinical point of view, this in vitro study presented the difficulties associated with all the clinically relevant factors, so the question of the possible implications of temperature increases in the periodontal tissues remains unsolved. However, knowing which system transfers the temperature most effectively allows better use of the technology.

5. Conclusions

The results of this study showed that Dia-Duo® was the only system in which there were no statistical differences between the two filling lengths (−2 mm and −4 mm). Regarding heat emission, the best system was Elements Free®, as at −2 mm, it emitted the highest temperature without exceeding 47 °C. It can be concluded that not all systems transmit the same temperature to the apex and, therefore, to the periapical tissues.

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References

1. Schilder, H.; Hargreaves, K.M. Filling root canals in three dimensions. *J. Endod.* **2006**, *32*, 281–290. [CrossRef] [PubMed]
2. Kulkarni, G.; Balakrishnan, R.; Shetty, H.H.K.; Praveena, G. A Quantitative Evaluation of the Sealing Ability of Three Different Obturation Techniques Using the Glucose Leakage Test: An In Vitro Study. *J. Int. Oral Health* **2016**, *8*, 787–794.
3. Pommel, L.; Camps, J. In Vitro Apical Leakage of System B Compared with Other Filling Techniques. *J. Endod.* **2001**, *27*, 449–451. [CrossRef] [PubMed]
4. Kandemir Demirci, G.; Çalışkan, M.K. A Prospective Randomized Comparative Study of Cold Lateral Condensation Versus Core/Gutta-percha in Teeth with Periapical Lesions. *J. Endod.* **2016**, *42*, 206–210. [CrossRef]
5. Schäfer, E.; Nelius, B.; Bürklein, S. A comparative evaluation of gutta-percha filled areas in curved root canals obturated with different techniques. *Clin. Oral Investig.* **2012**, *16*, 225–230. [CrossRef]
6. Kontakiotis, E.; Chaniotis, A.; Georgopoulou, M. Fluid filtration evaluation of 3 obturation techniques. *Quintessence Int.* **2007**, *38*, e410–e416.
7. Jindal, D.; Sharma, M.; Raisingani, D.; Swarnkar, A.; Pant, M.; Mathur, R. Volumetric analysis of root filling with cold lateral compaction, Obtura II, Thermafil, and Calamus using spiral computerized tomography: An in vitro Study. *Indian J. Dent. Res.* **2017**, *28*, 175–180.
8. Kumar, V.; Ludlow, J.B.; Mol, A.; Cevidanes, L. Comparison of conventional and cone beam CT synthesized cephalograms. *Dentomaxillofac. Radiol.* **2007**, *36*, 263–269. [CrossRef]
9. Ulbricht, R.D.; Marretta, S.M.; Baker, G.J.; Siegel, A.M.; Klippert, L.S. Comparison of two heated gutta-percha obturation techniques of the mandibular first molar in the dog. *J. Vet. Dent.* **2002**, *19*, 63–70. [CrossRef]
10. Shetty, K.P.; Satish, S.V.; Luke, A.M.; Badade, A.R.; Kilaru, K.R. In vitro Interrelationship between Apical Fill and Apical Leakage Using Three Different Obturation Techniques. *J. Int. Soc. Prev. Community Dent.* **2018**, *8*, 503–507. [CrossRef]
11. Jacobs, H.R.; Thompson, R.E.; Brown, W.S. Heat Transfer in Teeth. *J. Dent. Res.* **1973**, *52*, 248–252. [CrossRef] [PubMed]
12. Spierings, T.A.M.; Peters, M.C.R.B.; Bosman, F.; Plasschaert, A.J.M. Verification of Theoretical Modeling of Heat Transmission in Teeth by in vivo Experiments. *J. Dent. Res.* **1987**, *66*, 1336–1339. [CrossRef] [PubMed]
13. Roti, J.L. Cellular responses to hyperthermia (40–46 °C): Cell killing and molecular events. *Int. J. Hyperth.* **2008**, *24*, 3–15. [CrossRef] [PubMed]
14. Zhang, L.; Zhou, X.; Wang, Q.; Wang, Y.; Tang, L.; Huang, D. Effect of heat stress on the expression levels of receptor activator of NF-κB ligand and osteoprotegerin in human periodontal ligament cells. *Int. Endod. J.* **2012**, *45*, 68–75. [CrossRef]
15. Molyvdas, I.; Zervas, P.; Lambrianidis, T.; Veis, A. Periodontal tissue reactions following root canal obturation with an injection thermoplasticized gutta-percha technique. *Dent. Traumatol.* **1989**, *5*, 32–37. [CrossRef]
16. Lin, M.; Xu, F.; Lu, T.J.; Bai, B.F. A review of heat transfer in human tooth-Experimental characterization and mathematical modeling. *Dent. Mater.* **2010**, *26*, 501–513. [CrossRef]
17. Baldissara, P.; Catapano, S.; Scotti, R. Clinical and histological evaluation of thermal injury thresholds in human teeth: A preliminary study. *J. Oral Rehabil.* **1997**, *24*, 791–801. [CrossRef]
18. Seltzer, S.; Bender, I.B.; Ziontz, M. The interrelationship of pulp and periodontal disease. *Oral Surg. Oral Med. Oral Pathol.* **1963**, *16*, 1474–1490. [CrossRef]
19. Zuza, E.P.C.A.; Lia, R.C.; Pires, J.R.; de Toledo, B.E. Histopathological features of dental pulp in teeth with different levels of chronic periodontitis severity. *ISRN Dent.* **2012**, *2012*, 271350. [CrossRef]
20. Peng, L.; Ye, L.; Tan, H.; Zhou, X. Outcome of root canal obturation by warm gutta-percha versus cold lateral condensation: A meta-analysis. *J. Endod.* **2007**, *33*, 106–109. [CrossRef]
21. Dimopoulos, F.; Dervenis, K.; Gogos, C.; Lambrianidis, T. Temperature Rise on the Plugger Surface of 2 Commercially Available Gutta-percha Heating Devices. *J. Endod.* **2017**, *43*, 1885–1887. [CrossRef] [PubMed]

22. Chang, H.S.; Park, S.H.; Cho, K.M.; Kim, J.W. Plugger temperature of cordless heat carriers according to the time elapsed. *Restor. Dent. Endod.* **2018**, *43*, e12. [CrossRef] [PubMed]
23. Lipski, M.; Woźniak, K. In vitro infrared thermographic assessment of root surface temperature rises during thermafil retreatment using system B. *J. Endod.* **2003**, *29*, 413–415. [CrossRef] [PubMed]
24. Zhou, X.; Chen, Y.; Wei, X.; Liu, L.; Zhang, F.; Shi, Y.; Wu, W. Heat transfers to periodontal tissues and gutta-percha during thermoplasticized root canal obturation in a finite element analysis model. *Oral Surg. Oral Med. Oral Pathol. Oral Radiol. Endod.* **2010**, *110*, 257–263. [CrossRef]
25. Diegritz, C.; Gerlitzki, O.; Fotiadou, C.; Folwaczny, M. Temperature changes on the root surface during application of warm vertical compaction using three different obturation units. *Odontology* **2020**, *108*, 358–365. [CrossRef]
26. Romero, A.D.; Green, D.B.; Wucherpfennig, A.L. Heat transfer to the periodontal ligament during root obturation procedures using an in vitro model. *J. Endod.* **2000**, *26*, 85–87. [CrossRef]
27. Eriksson, A.R.; Albrektsson, T. Temperature threshold levels for heat-induced bone tissue injury: A vital-microscopic study in the rabbit. *J. Prosthet. Dent.* **1983**, *50*, 101–107. [CrossRef]
28. Venturi, M.; Pasquantonio, G.; Falconi, M.; Breschi, L. Temperature change within gutta-percha induced by the System-B Heat Source. *Int. Endod. J.* **2002**, *35*, 740–746. [CrossRef]
29. Nikolaev, A.; Nikolaeva, E.A.; Ginali, A.N. Continuous wave technique: Temperature changes in different parts of the tooth root. *Guident* **2015**, *8*, 38–43.
30. Lipski, M. Root surface temperature rises during root canal obturation, in vitro, by the continuous wave of condensation technique using System B HeatSource. *Oral Surg. Oral Med. Oral Pathol. Oral Radiol. Endod.* **2005**, *99*, 505–510. [CrossRef]
31. Mc Cullagh, J.J.P.; Setchell, D.J.; Gulabivala, K.; Hussey, D.L.; Biagioni, P.; Lamey, P.J.; Bailey, G. A comparison of thermocouple and infrared thermographic analysis of temperature rise on the root surface during the continuous wave of condensation technique. *Int. Endod. J.* **2000**, *33*, 326–332. [CrossRef]
32. Saunders, E.M. In vivo findings associated with heat generation during thermomechanical compaction of gutta-percha. Part, I.I. Histological response to temperature elevation on the external surface of the root. *Int. Endod. J.* **1990**, *23*, 268–274. [CrossRef]
33. Cen, R.; Wang, R.; Cheung, G.S.P. Periodontal Blood Flow Protects the Alveolar Bone from Thermal Injury during Thermoplasticized Obturation: A Finite Element Analysis Study. *J. Endod.* **2018**, *44*, 139–144. [CrossRef]
34. Cumbo, E.; Russo, R.; Gallina, G. System, B. Endo-Twinn and E-Fill. True temperatures inside the canal. *J. Conserv. Dent.* **2012**, *15*, 342–345. [CrossRef]