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Original Article

Influence of relative positions of the heat carrier and lateral canal opening on gutta-percha obturation of lateral canals in a three-dimensional-printed model

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KEYWORDS
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Abstract *Background/purpose:* Effective filling of the lateral canals is of great significance in successful root canal treatment, but it is generally being challenging. This study aimed to evaluate the influence of relative positions of the heat carrier and lateral canal opening on gutta-percha obturation of lateral canals in a three-dimensional (3D)-printed model.
Materials and methods: Thermal conductivity and real-time temperature transmission of gutta-percha were investigated using laser flash and thermal infrared analyses. 3D-printed root canal models with lateral canals at 1, 3, and 5 mm from the apex were fabricated, and different relative positions of the heat carrier were tested. The obturation process was recorded on video, and the obturation depth of the lateral canals was observed using X-ray micro-computed tomography.
Results: Gutta-percha showed low thermal conductivity of 1.07 W/(m·K), and heating increased the temperature of gutta-percha above 60 °C only within 1 mm beyond the heat carrier tip. For lateral canals at 1 and 3 mm from the apex, gutta-percha penetrated further with deeper penetration of the heat carrier ($P < 0.05$). For 5-mm lateral canals, the heat carrier was always at apical level and the gutta-percha obturation depth was more at 2 mm apically than at 3 or 4 mm ($P < 0.05$).

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Conclusion: Gutta-percha is a poor thermal conductor. The position of the heat carrier in relation to the lateral canal opening affects obturation depth. Only when the heat carrier reaches or passes the lateral canal opening can gutta-percha penetrate a lateral canal.

Introduction

The goal of root canal treatment is to disinfect and three-dimensionally obturate the root canal system, including the canal proper and associated irregularities. With the exception of the apical foramen, lateral canals may allow communication between the main root canal and the external root surface.[1] Inadequate disinfection and obturation of lateral canals may lead to root canal treatment failure.[2] Gutta-percha is one of the most widely-used endodontic obturation materials because of its good biocompatibility and dimensional stability.[3] Due to uncertain long-term dimensional stability and solubility of sealer,[4,5] gutta-percha is the material of choice for filling lateral canals instead of sealers during obturation.[6]

Commercial gutta-percha points are solid at room temperature and cannot flow into fine structures such as lateral canals. Gutta-percha polymer (trans-1, 4-polyisoprene), the major organic component of gutta-percha points, is a thermoplastic and viscoelastic material.[7] It becomes soft and plastic only at a certain temperature, changing from a crystalline phase to an amorphous phase.[8] The current warm vertical compaction technique for root canal obturation is based on the above-mentioned property of gutta-percha polymer. In addition to gutta-percha polymer, inorganic fillers (such as zinc oxide, barium sulfate) are also major components in commercial gutta-percha points. The inorganic fillers provide not only stiffness and radiopacity, but also thermal conductivity, so a gutta-percha point can be rapidly softened and deformed with heat in clinical use.

During warm vertical compaction, temperature and compaction force are two crucial factors influencing the rheological behavior and shape change of gutta-percha materials, and further affecting obturation of lateral canals. Heat is transmitted from the heat carrier to the gutta-percha material and spreads along the gutta-percha point. Only if the gutta-percha near the opening of the lateral canal is sufficiently heated and compacted with appropriate force, can the gutta-percha penetrate the lateral canal. It was reported that under the condition of 200 °C heating for 2 s, a mean heat conduction depth of ≥65 °C of 1.05 mm into the gutta-percha point was recorded.[9] Currently used commercial gutta-percha points vary slightly in composition, which may affect the rheological property and thermal conductivity of gutta-percha points.[10,11] Other factors are also involved in penetration of gutta-percha into lateral canals during warm vertical compaction, such as the pre-set temperature of the heat carrier and the relative position of the heat carrier and the lateral canal. However, the influence of these factors on the obturation depth of lateral canals at different locations inside the root canal is not clear.

In this study, one commercial brand of gutta-percha points with a higher proportion of gutta-percha polymer was selected, which means lower thermal conductivity.[12] We tested the thermal conductivity of the gutta-percha point, by designing and printing standardized root canal models with lateral canals at different levels. The effect of the relative positions of the lateral canal opening and the heat carrier on the obturation of the lateral canal was then analyzed. The null hypothesis tested was that the relative positions of the heat carrier and the lateral canal opening would not affect gutta-percha penetration of lateral canals.

Materials and methods

Thermal conductivity analysis of gutta-percha points

ProTaper Universal (PTU) gutta-percha points (Dentsply Maillefer, Ballaigues, Switzerland) were pressed with heat into square sheets (10 × 10 × 1 mm) and the thermal diffusivity of the gutta-percha material was measured using Laser Flash Analysis (LFA 467 HyperFlash®, Netzsch, Selb, Germany). The specific heat capacity of the gutta-percha material was measured using a differential scanning calorimeter (DSC 200 F3, Netzsch). The density of gutta-percha material was measured by the buoyancy method.

The thermal conductivity of the gutta-percha material was then calculated according to the equation:

$$k = \alpha \times Cp \times \rho.$$

where α is thermal diffusivity (m/s), k is thermal conductivity (W/m·K), ρ is density (kg/m^3) and Cp is specific heat capacity (J/kg·K). Measurements were performed three times, and mean values were calculated.

Thermal infrared analysis of heat transmission along gutta-percha points

In order to record temperature changes along the gutta-percha points during warm vertical compaction in real time, a split-root model was made.[9] A freshly-extracted lateral upper incisor was selected and the root canal (working length [WL] = 13 mm) was instrumented to F3 with PTU files (Dentsply Maillefer). A 4 mm tip of a PTU F3 gutta-percha point was placed into the split-root template (Fig. 1A). A heat carrier was preset to 200 °C and placed in contact with the cross-section of the gutta-percha point. The heat carrier was activated for 4 s without any compacting force. Then the activation was stopped and the

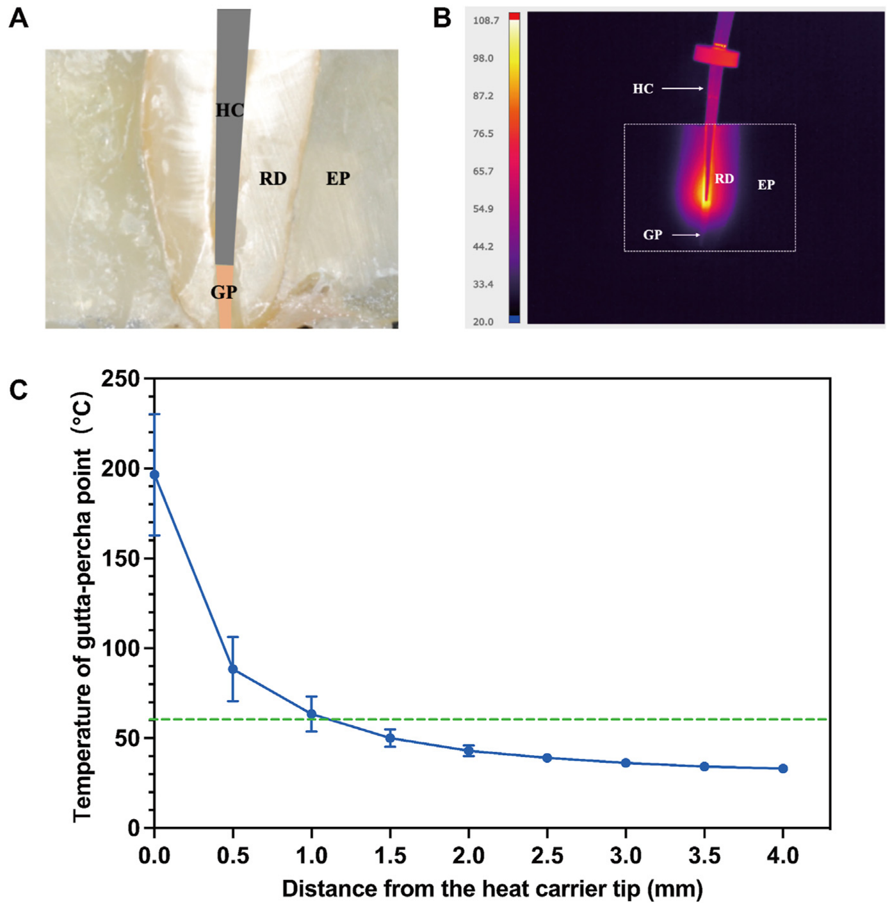

Figure 1 Infrared temperature measurement of gutta-percha points. (A) Longitudinal section of the experimental model. GP: gutta-percha point. HC: heat carrier. RD: dentin surface of the longitudinally-sectioned root canal. EP: epoxy resin block. (B) A thermal view of a specimen by infrared thermal imaging. (C) The temperature profile along the gutta-percha point with the heat carrier pre-set at 200 °C. The green dashed line indicates the melting temperature of the gutta-percha at 60 °C.

heat carrier was removed. Five repeated measurements were performed, each with a new gutta-percha point.

The temperature profiles of the gutta-percha points were graphically recorded over 14 s using an infrared thermal imager (TiX 660, Fluke, Everett, WA, USA) under controlled environmental conditions (temperature = 30 °C/± 0.5 °C, relative humidity = 50 ± 5%, air flow <0.5 m/s) (Fig. 1B). The temperature data for each gutta-percha point were gathered and calculated using SmartView 4.3.29.0 (Fluke). The highest temperature values at each level at intervals of 0.5 mm along the gutta-percha points were recorded.

Preparation of a three-dimensional-printed root canal model

The root canal models were fabricated with a three-dimensional (3D) printer (3D SYSTEMS S3600, 3D Systems, Rock Hill, SC, USA). A clear resin material (VisiJet® EX 200, VisiJet Crystal; 3D Systems) was adopted and the printing resolution was set at 16 μm. The model (4 × 2 × 10 mm) consisted of a primary canal (length 10 mm, taper 0.2 and 0.2 mm in apical diameter with open apex) and six lateral canals with a diameter of 0.15 mm. The lateral canals were located at 1, 3 or 5 mm away from the root apex, perpendicular to the long axis of the primary canal (Fig. 2A). The primary canal was instrumented to F3 with PTU in series. The oleophilic supporting materials were further removed using cleansing oil (DHC Corporation, Tokyo, Japan) in an ultrasonic device. Then the lateral canals were cleaned with a size 8 K-file (Dentsply Maillefer) from the external surface of the model and rinsed with distilled water, aiming at clearing the supporting materials in the lateral canals and simulating a clinical situation in which the lateral canal is completely unobstructed. Before root canal obturation, the models were observed under a light microscope to ensure that the lateral canal was patent and clean.

Root canal obturation

Sixty 3D-printed root canal models were obturated using the warm vertical compaction technique. Depending on level at which the lateral canals opened inside the canal and the relative positions of the lateral canal and the heat carrier, the models were assigned to one of three groups (n = 20/group) (Table 1). For the 1-mm lateral canals, the heat carrier was inserted either to the same horizontal position (Group L1-S) as the lateral canal opening, or to

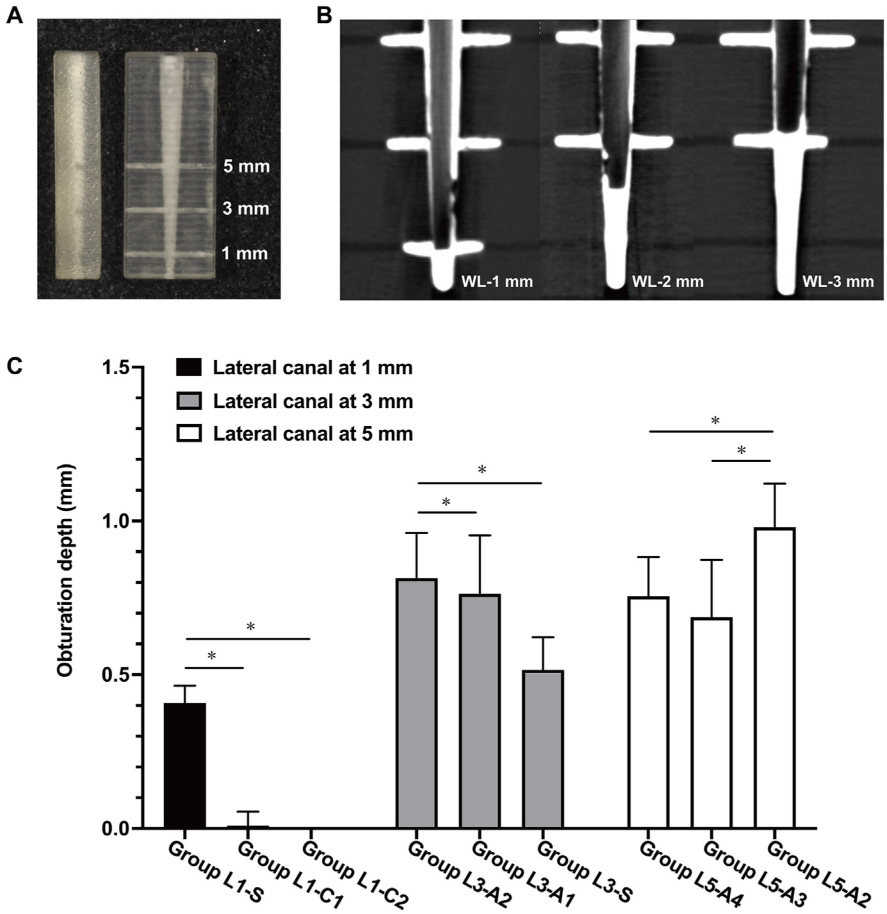

Figure 2 Obturation of lateral canals. (A) A three-dimensional-printed root canal model. (B) Representative micro-computed tomography images and measurement of obturation depth. WL: working length. (C) Bar graph of gutta-percha obturation depth in lateral canals in three locations. The bar graphs show the median and error bars represent the interquartile range. L1, L3, L5: lateral canal at 1 mm, 3 mm, 5 mm. S: The heat carrier was inserted to the same horizontal position as the lateral canal opening. C1, C2: The heat carrier was inserted to 1 mm, 2 mm coronally of the lateral canal opening. A1, A2, A3, A4: The heat carrier was inserted to 1 mm, 2 mm, 3 mm, 4 mm apically of the lateral canal opening. *: $P < 0.05$.

coronal 1 mm (Group L1-C1) or coronal 2 mm (Group L1-C2) positions of lateral canal opening. For the 3-mm lateral canals, the heat carrier was inserted to the same horizontal position (Group L3-S) as the lateral canal opening, or to 2 mm apically (Group L3-A2), or 1 mm apically (Group L3-A1) of the lateral canal opening. For the 5-mm lateral canals, the heat carrier was placed at the level of apical 2 mm (Group L5-A2), apical 3 mm (Group L5-A3), or apical 4 mm (Group L5-A4) of the lateral canal opening. Pre-fitted heat carriers (B&L Biotech, Ansan-si, Korea) and pluggers (B&L Biotech) were selected for each group: #3504 for WL-1 mm, #4504 for WL-2 mm, #5004 for WL-3 mm.

A F3 PTU gutta-percha point (Dentsply Maillefer) was placed to the WL, confirmed with tug-back sensation. No sealer was used in any group. The heat carrier was set at the designated temperature (200 °C), activated and inserted into the root canal to the preset depth for each group. The heat carrier was activated for 4 s, and a fixed pressure was maintained on the heat carrier for 10 s. A cold plugger was used to compact the softened gutta-percha material. Backfill of the root canal was not performed in the present study. All root canal obturations were carried out by one operator other than the examiner who read the micro-computed tomography (micro-CT) images later. The operator was trained to control the condensation pressure at 2.5—3.0 kg before the experiment began.

The obturation process was recorded using a video camera system through a microscope (magnification 3 ×, focal distance 250 mm). The frame rate was 30 frames per second and the effective display format was 1920 × 1080 pixels. The dynamic process of gutta-percha penetrating the lateral canal was observed.

The filled specimens were scanned with a micro-CT system (Inveon MM CT, Siemens AG, Munich, Germany) at a voxel size of 8.9 μm. Images were reconstructed with 3D visualization software (Inveon Research Workplace, Siemens AG) and analyzed using a voxel size of 17.9 μm. The obturation depth of gutta-percha material into lateral canals was measured on the images (Fig. 2B).

Statistical analysis

Statistical analysis was performed using IBM SPSS Statistics V22.0 software (IBM SPSS Statistics for Windows, Armonk, NY,

Table 1 Groups determined by the relative position of the heat carrier and lateral canal, and the median (the first quartile, the third quartile) of gutta-percha obturation depth in lateral canals in each group.

Lateral canal opening	Depth of heat carrier	Group name	Filling depth of lateral canal (mm)
Lateral canal at 1 mm	WL-1 mm	Group L1-S	0.41 (0.32, 0.46)
	WL-2 mm	Group L1-C1	0.01 (0.00, 0.05)
	WL-3 mm	Group L1-C2	0.00 (0.00, 0.00)
Lateral canal at 3 mm	WL-1 mm	Group L3-A2	0.81 (0.73, 0.96)
	WL-2 mm	Group L3-A1	0.76 (0.64, 0.91)
	WL-3 mm	Group L3-S	0.52 (0.41, 0.62)
Lateral canal at 5 mm	WL-1mm	Group L5-A4	0.76 (0.69, 0.88)
	WL-2 mm	Group L5-A3	0.69 (0.62, 0.86)
	WL-3 mm	Group L5-A2	0.98 (0.89, 1.12)

WL: working length.
L1, L3, L5: lateral canal at 1 mm, 3 mm, 5 mm.
C1, C2: The heat carrier was inserted to 1 mm, 2 mm coronally of the lateral canal opening.
A1, A2, A3, A4: The heat carrier was inserted to 1 mm, 2 mm, 3 mm, 4 mm apically of the lateral canal opening.
S: The heat carrier was inserted to the same horizontal position as the lateral canal opening.

USA) and the nonparametric Kruskal-Wallis test was employed. Post-hoc pairwise comparisons were conducted using Dunn's multiple comparisons test for statistical analysis. Statistical significance level was pre-set at $\alpha = 0.05$.

Results

The gutta-percha material used in this study had a low thermal conductivity, which was only 1.07 W/(m·K). The gutta-percha in contact with the heat carrier showed a temperature close to the setting temperature (Fig. 1C), but the temperature of the gutta-percha point dropped with distance from the heat carrier tip. The temperature of gutta-percha 1 mm away from the heat carrier tip was above 60 °C (the melting temperature of the gutta-percha material), but the temperature 3 mm away from the heat carrier tip was close to room temperature.

Representative micro-CT images and a bar graph of lateral canal obturation depths are shown in Fig. 2B and C. The median (the first quartile, the third quartile) of gutta-percha obturation depth in lateral canal in each group is shown in Table 1. The results showed that the lateral canal obturation depths were affected by the relative positions of the heat carrier and the lateral canal opening. For the 1-mm lateral canals, the obturation depths with gutta-percha were much greater in Group L1-S than in Group L1-C1 or Group L1-C2 ($P < 0.05$). For 3-mm lateral canals, the obturation depths were much greater in Group L3-A2 than in Group L3-A1 or Group L3-S ($P < 0.05$). For 5-mm lateral canals, the obturation depth was much greater in Group L5-A2 than in Group L5-A3 or Group L5-A4 ($P < 0.05$).

A representative screenshot from the video recording of the obturation process is shown in Fig. 3. When the heat carrier was inserted into the main root canal, the gutta-percha close to the heat carrier tip melted. When the heat carrier reached and passed a 5-mm lateral canal opening, the melted gutta-percha material was compacted into the 5-mm lateral canals. When the heat carrier reached and passed a 3-mm lateral canal opening, the obturation depth of the 5-mm lateral canal deepened, and the gutta-percha material began to penetrate the 3-mm lateral canal, but no deformation of gutta-percha in the 1-mm lateral canal was observed. When the heat-carrier approached the 1-mm lateral canal opening, gutta-percha material melted and entered the 1-mm lateral canal. The obturation depth of the 3-mm lateral canal increased, and there was also a small increase in obturation depth of the 5-mm lateral canal.

Discussion

Lateral canals are difficult to clean and obturate during root canal treatment. In the present study, as the heat carrier penetrated deeper into the root canal and closer to the lateral canal opening, the gutta-percha material penetrated further into the lateral canal. Our hypothesis was rejected because the relative position between lateral canal opening and heat carrier affected the obturation depths of gutta-percha.

Due to the temperature-dependent thermoplasticity of gutta-percha polymer,[7] one condition has to be satisfied to press gutta-percha into a lateral canal: the gutta-percha at the lateral canal opening should be sufficiently heated. A study has shown that the temperature of a PTU gutta-percha point transforming from the α phase to the amorphous phase is around 53-60 °C (melting temperature).[10] From the thermal infrared observation results, it could be seen that the temperature of the gutta-percha point in contact with the heat carrier was far above the melting point. Direct contact with the heat carrier tip induced rapid melting of the gutta-percha material. Therefore, as long as the heat carrier passed the lateral canal opening, the gutta-percha could be softened and squeezed into the lateral canal. Heating of the gutta-percha material which is not in direct contact with the heat carrier depends on thermal conduction, which is affected by the thermal conductivity of the material. Since the gutta-percha material is a poor conductor of heat, only the gutta-percha within 1 mm of the heat carrier tip was heated to at least 60 °C, as shown by thermal infrared imaging. This suggests that the heat carrier should be inserted to a depth no more than 1 mm away from the lateral canal opening to obturate

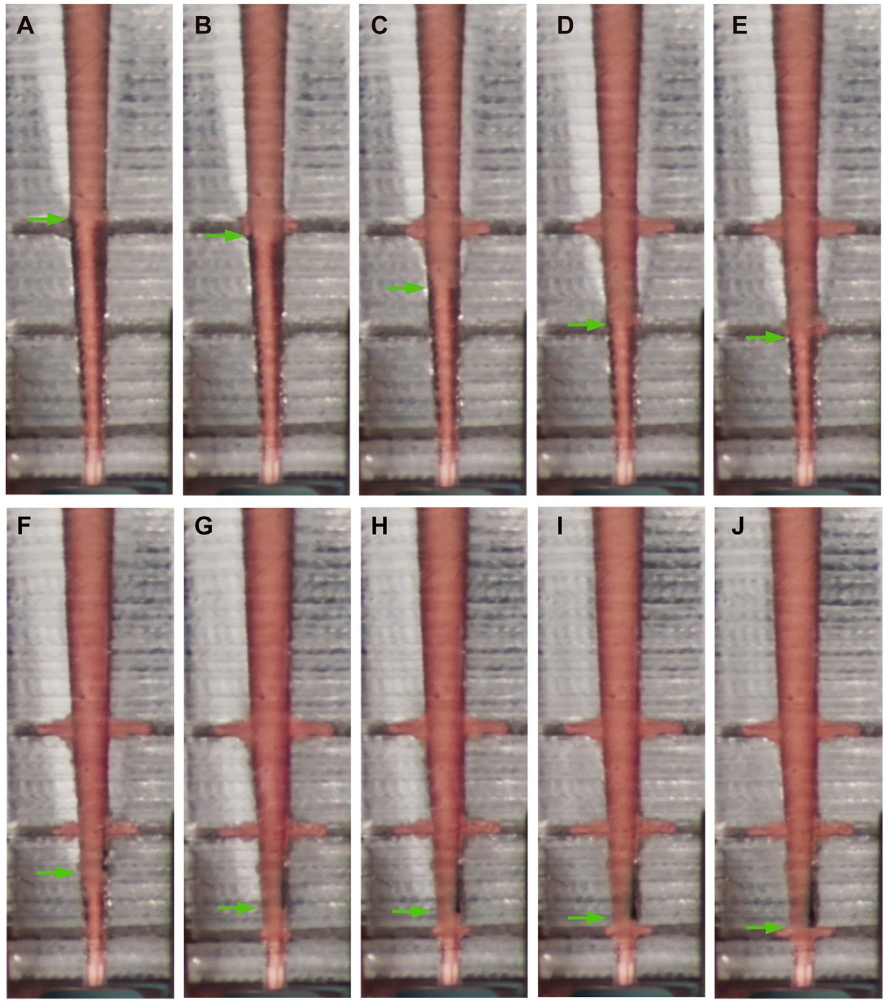

Figure 3 Screenshots from a video of the obturation process when the heat carrier was inserted to the same position as the lateral canal opening at the 1 mm level. The arrow indicates where the heat carrier has reached.

a lateral canal with gutta-percha. This explains why the gutta-percha material only slightly deformed and could not sufficiently enter a lateral canal at 1 mm above the apex when the heat carrier was inserted to WL-2 mm. From the observation of the dynamic obturation process, we can also see that when the heat carrier was within 1 mm of the 1-mm lateral canal opening and extended further down, the gutta-percha could be gradually plasticized and enter the 1-mm lateral canal. In addition, it was worth noting that regarding the 5-mm lateral canal, the difference among groups may be due to the use of heat carriers of different sizes.[13] The diameter of the heat carrier used in Group L5-A2 was a better match with the root canal at the 5-mm level. That allowed less room for gutta-percha to flow backward when heated and softened.

The results showed that the gutta-percha could be easily pressed into the lateral canals at 3 mm and 5 mm, but could not enter a lateral canal at 1 mm when the heat carrier was inserted to WL-3 mm, which is the recommended penetration depth of heat carrier for warm vertical compaction.[14] In the clinic, if the lateral canal appears in the apical part, it may be difficult to insert the heat carrier to the depth within 1 mm of the lateral canal opening, because of the risk of overfilling and the limitation of root canal curvature. In these circumstances, the obturation effect could be improved by using gutta-percha with higher thermal conductivity, or relying on sealer to fill the lateral canal as much as possible.[15] However, the long-term stability of sealer when used to seal a canal space is not clear and the performance of sealer in lateral canal obturation also needs further investigation. Although deeper depths of heat carrier were included in this study, the purpose was to observe the filling capacity of gutta-percha for lateral canals at the 1-mm level during continuous wave of condensation, and such deep depth of heat carrier should be avoided in clinical practice. From a technical obturation point of view, increasing the heating temperature, extending the heating time, and increasing the compacting force may be helpful for lateral canal obturation. However excessive heat may increase the temperature of the external root surface and cause thermal damage to surrounding tissue,[16,17] while excessive force may increase the risk of vertical root fractures and overfilling.[18]

The thermal conductivity of a polymer such as gutta-percha is mainly due to phonons. Because the molecular chain structure and molecular chain vibration cause the phonons to scatter, the thermal conductivity of the polymer is generally low.[19—21] Adding thermal conductive filler to a polymer matrix is a common method to improve the thermal conductivity of polymer composite materials.[22] The thermal conductivity of conventional gutta-percha materials is enhanced by the addition of zinc oxide.[23] The thermal conductivity of zinc oxide is approximately 20—30 W/(m·K).[24] Zinc oxide has been found to cause a very limited increase in thermal conductivity of polymer composites.[10,25—27] A previous study also revealed that the thermal conductivities of six brands of gutta-percha materials were all lower than 1 W/(m·K).[10] In this study, the laser flash method was used to measure the transient thermal conductivity of the gutta-percha point used, which was found to be only 1.07 W/(m·K). Based on this, the poor thermal conductivity of conventional gutta-percha materials may not be conducive to the full potential of the warm vertical compaction technique. By adjusting the type, particle shape, and size of the filler, or by mixed application of multiple fillers, the thermal conductivity of gutta-percha material may be further improved.[25] This needs to be investigated in future research.

Previous studies have used demineralized teeth[28] and split-tooth models[14] with lateral canals. However, it is difficult to ensure the consistency of lateral canals on demineralized roots. Reassembly of split tooth-halves invariably results in expression of thermoplastic gutta-percha between the two halves which adversely affects the accuracy of the results. The use of 3D-printed models ensures the consistency and integrity of the root canal system. A root canal system with natural morphology[29,30] can also be created by using 3D printing technology combined with micro-CT data. The limitations of the standard lateral canal model are obvious since it cannot simulate a natural lateral canal with complex and varied shape.[31] However, it is easier to remove the supporting material and provide a more direct measurement of obturation depth.[15] The surface of the root canal wall in a plastic model is also different from the real dentin surface. Therefore, the clinical situation can never be completely simulated. Moreover, during CWC, the gutta-percha was heated and compacted continuously to complete the apical filling in a single down-pack motion, which simplifying traditional vertical compaction.[32] But in actual clinical practice, gutta-percha point is usually heated several times in down-pack motion. It was reported that 2-mm incremental down-pack in combination with incremental backfill obtained better adaption of gutta-percha to the root canal wall in the apical part when compared with continuous down-pack with incremental backfill.[33] Different down-pack procedure may affect the generation of heat and the heat conduction of gutta-percha point, thus affecting the obturation depth in the lateral canal, which needs further research.

In conclusion, the relative positions of the lateral canal opening and heat carrier influence the obturation of a lateral canal with gutta-percha material alone. Due to the low thermal conductivity of gutta-percha points, it is suggested that the heat carrier should be inserted to a level at or lower than the lateral canal opening, then the gutta-percha could be pressed into the lateral canal by heat and pressure. Further research should be directed towards modifying the thermal conductivity of gutta-percha materials or improving the performance of sealers in obturation of apical lateral canals.

Declaration of competing interest

The authors have no conflicts of interest relevant to this article.

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