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THERMOGRAPHIC ASSESSMENT OF HEAT GENERATION INDUCED BY DIFFERENT ENDODONTIC INSTRUMENTATION MOTIONS

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ABSTRACT

To evaluate the effect of different endodontic kinematic motions on heat generation during root canal preparation using real-time infrared thermography. Sixty standardized acrylic blocks with simulated curved canals were randomly allocated into three groups (n = 20) according to the kinematic motion used: continuous rotation, reciprocating motion, and Optimum Torque Reverse (OTR) adaptive motion. All canals were prepared using ProTaper Next X2 instruments (size 25/.06; M-Wire NiTi). Thermographic recordings were performed using a FLIR infrared thermal camera under controlled environmental conditions. Mean temperature, maximum temperature, minimum temperature, and thermal distribution patterns within a predefined region of interest were analyzed. Data interpretation focused on both numerical temperature values and dynamic thermal behavior. All kinematic motions produced detectable temperature changes during instrumentation. Continuous rotation demonstrated sustained heat accumulation with delayed thermal dissipation. Reciprocating motion produced moderate, intermittent temperature elevations. OTR motion exhibited the most stable thermal profile, with minimal temperature fluctuation and uniform heat distribution. Despite comparable mean temperatures among groups, distinct thermographic patterns were observed, indicating kinematic-dependent differences in heat behavior. Kinematic motion significantly influences thermal behavior during root canal preparation. Adaptive OTR motion demonstrated superior thermal control, whereas continuous rotation showed the least efficient heat dissipation. Infrared thermography is a reliable, non-contact method for assessing the thermal safety of endodontic instrumentation.

KEYWORDS: Thermography, Heat Generation, Root Canal Preparation, Kinematics, ProTaper Next, M-Wire, NiTi Instruments.

1. INTRODUCTION

Nickel–titanium (NiTi) rotary instrumentation has become a cornerstone of modern endodontic practice due to its enhanced flexibility, shaping efficiency, and ability to preserve canal anatomy (Peters, 2004; Elnaghy & Elsaka, 2014; Plotino et al., 2012). However, the mechanical interaction between rotating instruments and canal walls generates frictional forces that are inevitably converted into heat (Kim et al., 2010; Gambarini et al., 2015). Excessive heat transfer through dentin may adversely affect periodontal tissues, particularly when critical temperature thresholds are exceeded (Eriksson & Albrektsson, 1983; Saunders, 2009).

Experimental evidence has demonstrated that a temperature increases of approximately 10 °C on the external root surface may induce irreversible bone and periodontal ligament damage (Eriksson & Albrektsson, 1983). Consequently, controlling heat generation during canal preparation is of clinical importance, especially in curved canals and anatomically narrow roots (Martins et al., 2021; Peters, 2004).

Advances in endodontic motor technology have introduced various kinematic motions designed to reduce mechanical stress on instruments and dentin. These include continuous rotation, reciprocating motion, and adaptive torque-controlled motions such as Optimum Torque Reverse (OTR) (Gambarini et al., 2015; Grande et al., 2021; Plotino et al., 2022). While the mechanical performance and fatigue resistance of these kinematics have been extensively studied, their influence on heat generation remains insufficiently explored (Al-Rahabi et al., 2024; Galal et al., 2020).

Previous thermographic studies have often been confounded by differences in file design, taper, or alloy composition (Ye et al., 2016; Alves et al., 2023). Therefore, isolating the effect of kinematic motion alone is essential for valid thermal comparison. Infrared thermography offers a non-contact, real-time method for monitoring temperature changes without interfering with instrumentation (Zand et al., 2017; Keskin et al., 2020).

The aim of this study was to thermographically evaluate heat generation during root canal preparation using different kinematic motions while standardizing the instrument system by employing ProTaper Next (M-Wire) files in all experimental groups. The null hypothesis was that kinematic motion would not significantly influence thermal behavior during canal preparation (Peters, 2004; Plotino et al., 2012).

2. MATERIALS AND METHODS

2.1. Study Design

This experimental in vitro study evaluated the effect of different kinematic motions on heat generation during root canal instrumentation using a standardized (NiTi) rotary file system. To eliminate confounding variables related to instrument design, alloy, and taper, the same ProTaper Next X2 instrument (size 25, taper 0.06; Dentsply Sirona, Ballaigues, Switzerland), manufactured from M-Wire NiTi alloy, was used in all experimental groups. As this was an in vitro laboratory study using acrylic canal models, ethical approval was not required.

The temperature variation (°C) was recorded in real time using infrared thermal imaging camera during canal preparation. The maximum, minimum, and mean temperatures within a predefined region of interest (ROI) were also recorded.

2.2. Sample Size Determination

Sample size calculation was performed using G*Power software (version 3.1.9.7; Heinrich Heine University, Düsseldorf, Germany). Based on data from previous thermographic studies evaluating temperature changes during root canal instrumentation, Sample size was calculated assuming a medium effect size (f = 0.40), α = 0.05, and power = 0.90. The minimum required sample size was 18 specimens per group; therefore, 20 specimens were included in each group.

2.3. Canal Models

Standardized transparent acrylic resin blocks (Endo Training Blocks; Dentsply Sirona) were used to simulate curved root canals. Each block contained a single canal with the following specifications, canal length 16 mm, apical diameter 0.15 mm, canal curvature 30°, and radius of curvature 5 mm.

Acrylic blocks were selected to ensure uniform canal geometry, eliminate the anatomical variability, and optimize the visualization and standardized of the thermographic analysis. All blocks were stored at room temperature (23 ± 1 °C) for 24 h before experimentation to ensure thermal equilibrium.

2.4. Experimental Groups

Specimens were randomly allocated into three groups (n = 20 per group) according to the kinematic motion used:

Group I (Continuous Rotation) Instrumentation was performed using continuous clockwise rotation at Speed of 300 rpm and torque 2.5 N·cm according to manufacturer's instructions.

Group II (Reciprocating Motion) Instrumentation was performed using a reciprocating motion at Speed of 300 rpm and torque 2.5 N ·cm (counterclockwise 150° and clockwise 30°).

Group III (Optimum Torque Reverse - OTR Motion) Instrumentation was performed using OTR motion at Speed of 300 rpm and torque 2.5 N ·cm, in which the instrument rotates continuously in a clockwise direction until the preset torque limit is reached, after which a brief reverse rotation is activated before resuming clockwise motion.

2.5. Instrumentation Technique

All instrumentation procedures were performed by a single experienced operator to minimize inter-operator variability using ProTaper Next X2 instrument (size 25, taper 0.06; Dentsply Sirona, Ballaigues, Switzerland), manufactured from M-Wire NiTi alloy. Each instrument was used to prepare one canal only and then discarded to eliminate the effect of cumulative cyclic fatigue or plastic deformation on heat generation.

For all groups, canals were prepared according to the same standardized protocol: A glide path was established using a #10 K-file to full working length. Working length was set at 15 mm, and confirmed visually. The ProTaper Next X2 file was advanced using a gentle in-and-out pecking motion with an amplitude of approximately 2–3 mm using operated by Wismy Endo Motor (Black Edition; Bomedent, Changzhou, China). After three pecking motions, the file was withdrawn and cleaned. Instrumentation continued until the full working length was reached. The total active instrumentation time was standardized to 10 seconds per canal, measured using a digital stopwatch.

2.6. Irrigation Protocol

To isolate the effect of kinematic motion on heat generation, a minimal and standardized irrigation protocol was used using distilled water at 23 °C room temperature, 2 mL per canal, with a 30-gauge side-vented needle. Irrigation was performed before instrumentation only, and no irrigation was used during active instrumentation, allowing uninterrupted thermographic recording.

2.7. Thermographic Recording

Thermal Imaging Equipment Temperature changes were recorded using an infrared thermal imaging camera FLIR E6 (FLIR Systems, Wilsonville, OR, USA), with thermal sensitivity: ≤ 0.06 °C, accuracy: ± 2 °C, and frame rate: 9 Hz.

Experimental Setup and Image Acquisition The camera was positioned at a fixed distance of 30 cm from the specimen. To minimize angle of incidence errors and maintain a constant emissivity value across the field of view, the camera's optical axis was oriented perpendicular to the canal curvature region of the specimen. This positioning also helps ensure the region of interest fills the field of view adequately for accurate pixel coverage. The specimen was placed against a matte black, non-reflective background to eliminate stray thermal reflections and enhance contrast between the specimen and its surroundings, thereby improving the accuracy of temperature measurements. The thermal camera's internal parameters were configured, the emissivity value set to 0.95, as recommended for acrylic materials. All measurements were conducted in a temperature-controlled room (23 ± 1 °C) with no direct airflow or external heat sources.

Region of Interest (ROI) Definition A standardized rectangular region of interest (ROI) was selected at the level of maximum canal curvature, corresponding to the zone of highest instrument wall contact and stress concentration. The same ROI dimensions and position were applied to all specimens using the FLIR analysis software.

For each specimen, the following parameters were recorded within the ROI

- Mean temperature (°C)
- Maximum temperature (°C)
- Minimum temperature (°C)

Temperature values were continuously recorded from the start of instrumentation until 10 seconds after completion to assess heat dissipation behavior.

2.8. Data Processing

Thermal images were exported and analyzed using FLIR Tools software. Temperature-time curves were generated for each specimen. The highest temperature recorded during instrumentation was considered the peak temperature.

2.9. Statistical Analysis

Data were analyzed using SPSS software (version 26.0; IBM Corp., Armonk, NY, USA). The following parameters were recorded: Mean temperature, Maximum temperature, Minimum temperature, Thermal distribution pattern, Heat dissipation behavior after instrumentation

2.10. Results

The mean and standard deviation values were calculated for each group in each test. Data were explored for normality using Kolmogorov-Smirnov and Shapiro-Wilk tests, data showed parametric (normal) distribution. One-way ANOVA was used to compare between more than two groups in non-related samples. The significance level was set at P ≤ 0.05. Statistical analysis was performed with IBM® SPSS® Statistics Version 25 for Windows.

3. THERMOGRAPHIC FINDINGS

All kinematic motions resulted in measurable temperature changes during canal preparation. However, clear differences in thermal behavior were observed among groups. (Table1, Fig.1).

Table 1: Thermographic Measurements Recorded Within the Region of Interest (ROI).

Kinematic Motion	Mean Temp (°C)	Max Temp (°C)	Min Temp (°C)	Thermal Behavior
OTR	29.1	29.1	28.4	Stable, uniform, rapid dissipation
Reciprocation	29.1	29.1	28.6	Moderate, intermittent peaks
Continuous rotation	29.1	30.2	28.8	Sustained heat, delayed dissipation

Figure 1: Thermographic Image before Root Canal Instrumentation.

3.1. OTR Motion

OTR motion demonstrated the most stable thermal profile, characterized by minimal temperature fluctuation within the ROI. Mean and maximum temperatures were both 29.1 °C, with a narrow temperature range (<0.7 °C). Heat distribution was uniform, and rapid thermal dissipation was observed following instrumentation. Adaptive torque-controlled motion resulted in intermittent disengagement of the instrument from canal walls, effectively limiting friction-induced heat accumulation (Fig.2).

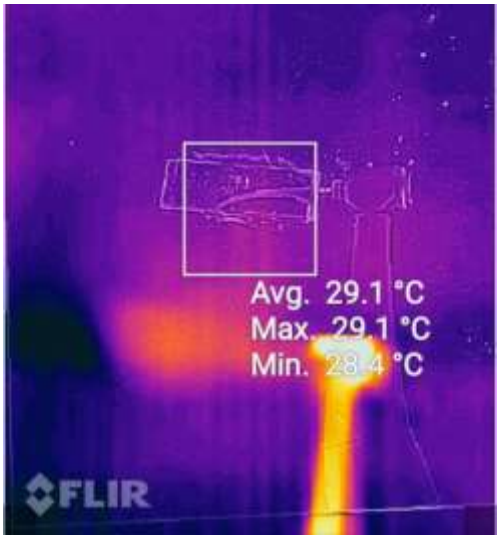

Figure 2: Thermographic Image during OTR Motion.

3.2. Reciprocating Motion

Reciprocating motion exhibited moderate thermal elevation, with intermittent temperature peaks. The mean temperature within the ROI was 29.1 °C, while the maximum temperature reached 29.1 °C. Heat accumulation was localized and less persistent than in continuous rotation motion. Compared with OTR motion, reciprocation demonstrated a wider thermal range and higher peak temperature values (Fig.3).

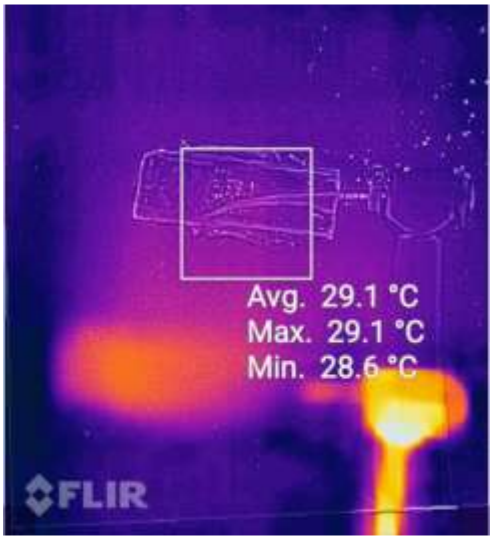

Figure 3: Thermographic Image during Reciprocation Motion.

3.3. Continuous Rotation

Continuous rotational motion showed sustained heat accumulation, particularly at the canal curvature region. Although mean temperatures were comparable to other groups, thermographic images revealed prolonged heat retention and reduced dissipation efficiency during and after instrumentation. (Fig.4).

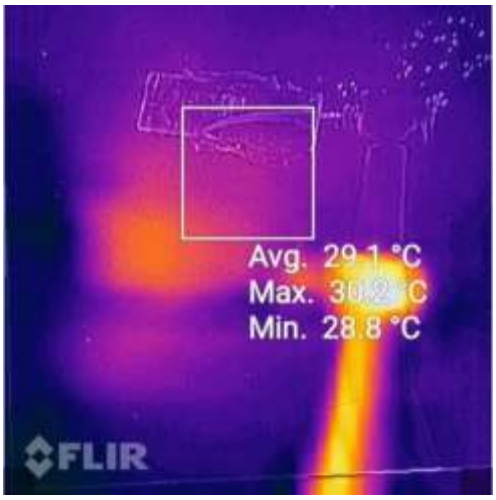

Figure. 4: Thermographic Image during Continuous Rotation Motion.

3.4. Comparative Interpretation

Despite similar mean temperature values across all groups, thermographic mapping revealed distinct kinematic-dependent thermal behaviors, with continuous rotation demonstrating the greatest thermal persistence, reciprocation showing intermediate behavior, and OTR motion exhibiting superior thermal control. (Table.2,3, Fig. 5)

There was a statistically significant difference between (OTR), (Reciprocation) and (Continuous) where ($p<0.001$). A statistically significant difference was found between (Continuous) and each of (OTR) and (Reciprocation) where ($p<0.001$). No statistically significant difference was found between (OTR) and (Reciprocation) where ($p=0.619$). The highest mean value was found in (Continuous), while the lowest mean value was found in (OTR).

Table 2: The Mean, Standard Deviation, and Std. Error Values of Thermal Fluctuations of Different Groups.

Variables	Thermal Fluctuation		
	Mean	**SD**	**Std. Error**
OTR	0.55 [b]	0.10	0.02
Reciprocation	0.60 [b]	0.07	0.01
continuous	1.32 [a]	0.22	0.05
p-value	**<0.001***		
Means with different letters in the same column indicate significant difference. *; significant ($p<0.05$)			

Table 3: Comparative Thermal Interpretation of Kinematic Motions.

Motion	Instrument-Wall Contact	Heat Accumulation	Dissipation Efficiency	Thermal Safety
OTR	Intermittent, stress-responsive	Minimal	High	Highest
Reciprocation	Alternating engagement	Moderate	Moderate	Intermediate
Continuous rotation	Continuous	Sustained	Low	Lowest

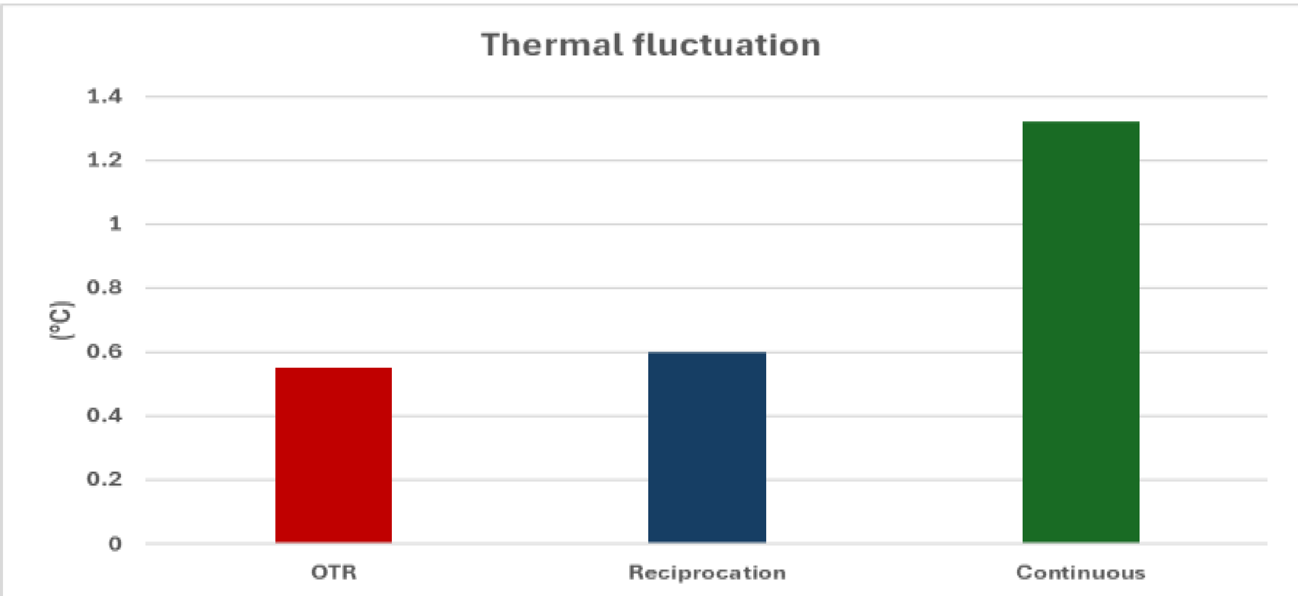

Figure 5: Bar Charts Representing Thermal Fluctuation of Different Groups.

4. DISCUSSION

The present study investigated the influence of different endodontic kinematic motions on heat generation during root canal preparation using real-time infrared thermography. By standardizing the instrument system across all experimental groups and employing ProTaper Next X2 files manufactured from M-Wire nickel–titanium alloy, the confounding effects of file design, taper, and metallurgy were eliminated, allowing the isolated assessment of kinematic motion on thermal behavior (Peters, 2004; Plotino et al., 2012; Ye et al., 2016). Consequently, the observed differences in heat generation can be attributed exclusively to the applied kinematics rather than instrument-related variables.

The use of acrylic canal blocks in the present study enabled strict standardization of canal geometry and improved internal validity by eliminating anatomical variability. Although acrylic resin exhibits different thermal conductivity compared with human dentin, previous studies have demonstrated that acrylic models remain suitable for comparative thermal assessments when experimental conditions are standardized (Zand et al., 2017; Alves et al., 2023). Furthermore, the use of infrared thermography allowed non-contact, real-time temperature monitoring without interfering with the instrumentation process, overcoming the spatial limitations associated with thermocouples (Keskin et al., 2020).

The findings demonstrated that kinematic motion significantly influences heat generation dynamics, with continuous rotation producing sustained thermal accumulation, reciprocating motion showing intermediate behavior, and Optimum Torque Reverse (OTR) motion exhibiting the most thermally controlled profile. These results support previous mechanical studies reporting increased frictional stress and torque generation during uninterrupted rotational motion, which directly contributes to friction-induced heat production (Kim et al., 2010; Gambarini et al., 2015).

Although mean surface temperatures were similar across all groups, thermographic mapping revealed distinct differences in thermal distribution, persistence, and dissipation. This observation highlights an important methodological consideration, reliance solely on mean or peak temperature values may underestimate the biological relevance of sustained heat accumulation (Eriksson & Albrektsson, 1983; Saunders, 2009). Continuous rotational motion demonstrated prolonged heat retention at the canal curvature region, reflecting uninterrupted instrument-wall contact and limited opportunities for thermal release (Schäfer et al., 2004).

In contrast, reciprocating motion resulted in moderate and intermittent thermal elevations. The alternating clockwise and counterclockwise movements intermittently disengage the instrument from the canal walls, reducing continuous frictional contact and partially limiting heat buildup (Yared, 2008; Grande et al., 2021). However, repeated re-engagement during cutting cycles likely accounts for the localized temperature peaks observed thermographically in the reciprocation group.

OTR motion exhibited the most favorable thermal behavior, characterized by minimal temperature fluctuation, homogeneous heat distribution, and rapid dissipation following instrumentation. This superior thermal control can be attributed to the stress-responsive nature of OTR kinematics, which allows continuous rotation under low resistance and initiates brief reverse rotation once a preset torque threshold is reached (Gambarini et al., 2015; Plotino et al., 2022). This adaptive disengagement mechanism reduces sustained instrument-canal wall contact, thereby limiting frictional energy conversion into heat. The present thermographic findings provide direct experimental confirmation of the mechanical advantages previously attributed to adaptive kinematic systems.

The results of this study are consistent with previous thermographic investigations reporting increased heat generation during continuous rotational instrumentation compared with interrupted kinematic motions (Zand et al., 2017; Keskin et al., 2020; Uslu et al., 2021). However, many earlier studies compared different file systems with varying geometries and alloys, which limited the ability to isolate the effect of kinematics.

Thermographic studies assessing different rotary systems have reported variable temperature rises depending on file design, taper, and alloy composition. However, many of these studies compared different instrument systems, limiting the ability to isolate the effect of kinematic motion. By using the same M-Wire instrument across all groups, the present study addresses this limitation and provides clearer evidence that kinematics alone plays a decisive role in thermal behavior during canal preparation (Alves et al., 2023; Dos Reis et al., 2025).

The lower heat generation observed with adaptive motion in this study corroborates reports suggesting improved safety margins with torque-controlled kinematics. However, the current study extends these observations by demonstrating not only reduced peak temperatures but also improved thermal dissipation dynamics, which are clinically relevant but often overlooked.

From a biological and clinical perspective, excessive heat transfer through root dentin may compromise periodontal tissues. Experimental studies have shown that temperature elevations of approximately 10 °C on the external root surface can result in irreversible damage to alveolar bone and periodontal ligament tissues (Eriksson & Albrektsson, 1983). Although the temperature increases observed in the present study did not approach this critical threshold, the sustained heat accumulation observed with continuous rotation may become clinically relevant in situations involving prolonged instrumentation time, curved canals, or roots with thin dentinal walls (Peters, 2004; Saunders, 2009).

The findings suggest that when using M-Wire rotary instruments such as ProTaper Next, adaptive torque-controlled kinematics may enhance thermal safety during canal preparation. This is particularly relevant in anatomically complex canals, where increased instrument-wall contact and stress concentration are expected (Kim et al., 2010; Plotino et al., 2022). Therefore, clinicians should consider the thermal behavior of kinematic systems in addition to shaping efficiency and fracture resistance when selecting instrumentation strategies.

Nevertheless, the present study has limitations. Acrylic blocks do not replicate the complex thermal and biological properties of natural teeth, and the absence of periodontal ligament and blood circulation restricts direct extrapolation to in vivo conditions (Saunders, 2009). In addition, distilled water was used as the irrigant to minimize confounding thermal effects, whereas clinical irrigants such as sodium hypochlorite may provide additional cooling (Uslu et al., 2021).

Future investigations should evaluate heat generation during root canal preparation in extracted human teeth and under dynamic irrigation conditions that more closely simulate the clinical environment. Combining thermographic analysis with torque and force measurements may further elucidate the relationship between mechanical stress and heat generation (Gambarini et al., 2015; Plotino et al., 2022).

Overall, the present study provides robust thermographic evidence that kinematic motion significantly influences heat generation during root canal preparation when file design and alloy are standardized. The demonstration that adaptive OTR motion offers superior thermal control compared with reciprocating and continuous rotational kinematics adds clinically relevant data to the ongoing optimization of endodontic instrumentation protocols.

5. CONCLUSION

Kinematic motion significantly affects thermal behavior during root canal preparation. Continuous rotation demonstrated sustained heat accumulation, reciprocating motion showed intermediate thermal behavior, and OTR motion exhibited superior thermal control. Infrared thermography provides a reliable and effective method for evaluating the thermal safety of endodontic instrumentation systems.

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