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Influence of heat-treated Ni-Ti rotary files and irrigant type on the accuracy of integrated apex locators: An in vitro study

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Purpose: This study investigated the effect of different nickel–titanium file systems and irrigation protocols on the accuracy of working length measurements during root canal preparation.

Methods: A total of 72 extracted mandibular central incisors were decoronated at 18 mm. Actual lengths (AL) were determined using a hand file and digital caliper under a microscope. Teeth were divided into four main groups based on irrigation solution, and then into two subgroups by file system: 2.5% or 5% NaOCl with/without 9% HEDP, combined with either WaveOne Gold(WOG) or WaveOne(WO). Root canals were shaped using WOG or WO files with a VDW Gold Reciproc motor in an alginate model simulating the oral environment, following the respective irrigation protocol. Electronic lengths (EL) were determined using an integrated electronic apex locator. EL–AL differences were calculated and analyzed using Kruskal-Wallis and Mann-Whitney U tests ($p<0.05$).

Results: No significant differences in EL–AL values were observed among the main irrigation solution groups or between files with different heat treatments ($p>0.05$). All tested conditions showed clinically acceptable accuracy.

Conclusion: These findings suggest that the type of file system and irrigation solution, including continuous chelation, do not compromise the reliability of EL determination during endodontic treatment.

Keywords: Chelating agents; endodontics; nickel-titanium; root canal preparation; sodium hypochlorite.

Introduction

One of the most critical steps for performing a successful root canal treatment is to accurately determine the working length. The apical constriction, also known as the minor foramen, serves as a key anatomical reference point for effective treatment (1). The studies that examined periapical tissues following root canal therapy have consistently demonstrated that the best clinical outcomes are achieved when treatment is terminated at the apical constriction level. Working length can be determined by using tactile sensation, radiographic evaluation, checking for the presence of moisture on paper points, having root canal morphology knowledge, and so on. The most commonly used

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method is the combination of periapical radiographs and electronic apex locators (EALs) (2).

The fundamental operating principle of EALs is based on the assumption that human tissues possess specific electrical properties. EALs determine the apical foramen location by measuring the changes in the resistance or impedance of dental tissues (3). To ensure rapid and efficient root canal preparation, manufacturers have integrated EALs into endodontic motors, allowing working length control during instrumentation (4). These hybrid devices not only regulate torque and speed but also enable the real-time monitoring of the apical limit while mechanically shaping the root canals using nickel-titanium (Ni-Ti) files. This is paramount for preventing over- or under-instrumentation during root canal treatment. Under-instrumentation can result in the retention of microorganisms and pulp remnants in the uninstrumented areas of the root canal system, which compromises the success of endodontic treatment (5). Conversely, over-instrumentation may lead to the extrusion of instruments, irrigants, pulp debris, microorganisms, and their toxins beyond the apical foramen, causing acute periapical irritation. If not corrected, over-instrumentation may further result in overfilling, leading to treatment failure (6).

The measurement accuracy of EALs depends on various factors, such as the type and size of the instrument used and the irrigation solutions applied (7). Ni-Ti files, frequently used in endodontic treatment because of their superelasticity and flexibility, undergo different heat treatments to improve their mechanical properties and enhance their fracture resistance. Owing to these favourable characteristics, heat-treated Ni-Ti rotary file systems are widely utilised in endodontic practice (8,9). However, the studies that evaluated EALs' accuracy when used in conjunction with heat-treated Ni-Ti files are limited (7,10).

During the mechanical instrumentation of root canals, a smear layer is formed on the radicular dentin surface. This layer may harbour bacteria and can hinder the penetration of antimicrobial agents and root canal filling materials into the dentinal tubules (11). Alternating irrigation with ethylenediaminetetraacetic acid (EDTA) and sodium hypochlorite (NaOCl) is recommended for effectively removing the layer. NaOCl, commonly used at concentrations ranging between 0.5% and 6%, is a non-specific proteolytic agent with notable tissue-dissolving capability and pronounced antimicrobial and anti-biofilm properties. However, NaOCl alone cannot completely eliminate the smear layer or prevent hard tissue debris accumulation. Such debris may act as a physical barrier, impeding NaOCl's access to the root canal system's anatomical intricacies and thereby reducing its antimicrobial efficacy (12). To overcome this limitation and facilitate inorganic debris removal, a chelating agent such as EDTA, typically used at concentrations ranging between 15% and 17%, is applied after NaOCl irrigation for one to two minutes. While EDTA is widely used in daily clinical practice, it has several drawbacks, including cytotoxicity, reduced bonding strength of resin-based filling materials, limited effectiveness in removing the smear layer from the apical third, depletion of free chlorine when mixed with NaOCl, and precipitate formation when combined with chlorhexidine (13).

Recently, the Dual Rinse irrigating solution (Medcem, Weinfelden, Switzerland) was introduced to the market, which combines NaOCl with etidronic acid (1- hydroxyethane-1, 1-diphosphonic acid; HEDP). It simultaneously provides chelating and disinfecting actions. The term "continuous chelation" does not refer to the removal of an already formed smear layer but rather to the prevention of its formation during instrumentation by the continuous use of the Dual Rinse irrigating solution. The HEDP–NaOCl combination offers clinical advantages by maintaining the solution's tissue-dissolving ability without increasing NaOCl's cytotoxicity (14). Moreover, the electrochemical properties and conductivity of irrigation solutions influence impedance measurements in electronic apex locators, which may lead to deviations in working length measurements depending on the irrigant used during root canal preparation (15).

The irrigation solutions used in the cleaning and shaping phases of endodontic treatment play a critical role in effectively disinfecting the root canal system. The electrolytes present in root canals are considered one of the primary factors that influence the accuracy of certain EALs' working length measurements (16). In this context, understanding the effects of the various irrigants used in root canal treatment on EAL accuracy is quite significant. In addition to irrigation solution type, the mechanical properties of Ni-Ti file systems used during root canal instrumentation may also influence the accuracy of integrated apex locators (IALs). Heat-treated NiTi files such as WaveOne Gold demonstrate superior flexibility and greater resistance to cyclic fatigue compared to conventional NiTi instruments due to their proprietary thermal processing (17). In contrast, WaveOne files, manufactured from M-Wire NiTi alloy, show reduced flexibility and shape memory, resulting in different behavior during canal preparation (17). Numerous studies have investigated the impact of different irrigation solutions on EAL accuracy, but no comprehensive study, to the best of our knowledge, has evaluated the effect of heat-treated Ni-Ti rotary file systems, in combination with various concentrations of

NaOCl and continuous chelation, on the measurement accuracy of IALs. This study evaluated the effect of using two heat-treated Ni-Ti files, in combination with varying concentrations of NaOCl and continuous chelation, on the accuracy of IALs during root canal preparation performed with an integrated endomotor. The following null hypothesis was tested: The combined use of NaOCl at different concentrations and continuous chelation, together with heat-treated Ni-Ti files, has no statistically significant effect on the measurement accuracy of IALs.

Materials and Methods

Sample size calculation and inclusion/exclusion criteria

This in vitro study received ethical approval from the Kütahya university ethics committee (Reference No: 2024/10-11, Date: 12/08/2024) and the study is conducted according to Declaration of Helsinki. Sample size estimation using G*Power (version 3.1.9.7) revealed that allocating nine samples to each group would provide 80% statistical power at a 0.05 significance level with an effect size of 0.5. The manuscript of this laboratory study has been written according to Preferred Reporting Items for Laboratory studies in Endodontology (PRILE) 2021 guidelines.

A total of 72 extracted human mandibular central incisors with approximately similar root dimensions were selected for this study. The inclusion criteria were: single straight root canal, fully developed apex, intact root structure, and root canal curvature less than 10°, measured according to Schneider's method (18). The exclusion criteria were: previously root canal–treated teeth, primary teeth, teeth with caries, restorations, internal or external root resorption, root fractures or cracks, calcified canals, or open apices. Clinical examination confirmed that the selected teeth were free of caries, restorations, and signs of resorption. Standardized periapical radiographs were taken from the buccal, lingual, mesial, and distal aspects to confirm canal morphology and exclude anatomical variations. The specimens were also examined under a dental operating microscope to detect any cracks or structural defects. All teeth were obtained with informed consent and ethical approval from the Department of Oral and Maxillofacial Surgery, Kütahya Health Sciences University, and were extracted for orthodontic or periodontal reasons. Immediately after extraction, the teeth were rinsed with phosphate-buffered saline, and the periodontal tissues were removed from the root surfaces using a curette.The specimens were stored in saline solution at 4°C until use.

Experimental design

For standardization, all the teeth were decoronated to a working length of 18 mm, which was done by marking the root surface with an acetate pencil and a digital caliper and creating a flat reference surface at 18 mm with a diamond fissure bur. A #10 K-file (Dentsply Maillefer, Ballaigues, Switzerland) was used to verify the apical patency, and the teeth in which a #20 K-file (Dentsply Maillefer, Ballaigues, Switzerland) fit snugly at the apex were included. During initial canal patency verification, teeth in which a #20 K-file (Dentsply Maillefer, Ballaigues, Switzerland) did not passively reach the apical foramen were excluded and replaced with new specimens meeting the inclusion criteria; therefore, the total sample size was maintained (n=72).

Before the experimental measurements, the digital caliper (Hogetex, Germany; 0.01 mm precision) was verified using a 10 mm gauge block to ensure measurement accuracy. The actual length (AL) was determined when the tip of a #15 K-file (Dentsply Maillefer, Ballaigues, Switzerland) became visible at the apical foramen under ×19.4 magnification using a dental operating microscope (OMS 2350, Zumax Company, China). A reference point was marked on the coronal surface of each tooth to ensure consistent positioning during all measurements. The distance between the rubber stopper and the file tip was then measured using a digital caliper under microscopic magnification, and this value was recorded as the AL. For each tooth, the measurement was repeated three times consecutively by a single operator, and the mean value was calculated. To ensure standardization, the electronic length (EL) was subsequently measured 0.5 mm short of the AL for all specimens. To minimize potential bias, all recorded working lengths were documented according to the assigned specimen numbers by another researcher (A.K.M.) who was not involved in the measurement procedures.

Experimental groups

The teeth were randomly divided into eight experimental groups according to the type of irrigation solution and the Ni-Ti alloy of the rotary instruments used during root canal preparation (n=9), using a computer-generated random number sequence at randomizer.org. (n=9). (Table 1)

Freshly prepared alginate (Tropicalgin, Zhermack Spa, Badia Polesine, Italy) was placed into plastic containers. The root specimens prepared up to the cementoenamel junction (CEJ), along with the labial clip of the EAL integrated into the VDW Gold Reciproc (VDW GmbH, Munich, Germany) device, were embedded in the unset alginate. To maintain proper conductivity and moisture levels, all the measurements were completed within 30 minutes after the alginate moulds were prepared. The EAL function of the VDW Gold Reciproc endomotor was operated under software version 1.0. The VDW Gold Reciproc endomo-

Table 1. Group classification according to the type of irrigating solution and Ni-Ti file system

Groups	İrrigation Solution	Ni-Ti File
Group 1a	2.5% NaOCl	WOG #25.07
Group 1b	2.5% NaOCl	WO #25.08
Group 2a	5.25% NaOCl	WOG #25.07
Group 2b	5.25% NaOCl	WO #25.08
Group 3a	2.5% NaOCl +9% HEDP	WOG #25.07
Group 3b	2.5% NaOCl +9% HEDP	WO #25.08
Group 4a	5.25% NaOCl +9% HEDP	WOG #25.07
Group 4b	5.25% NaOCl +9% HEDP	WO #25.08

Ni-Ti: Nickel Titanium; WOG: WaveOne Gold; WO: WaveOne; NaOCl: Sodium hypochlorite; HEDP: Etidronic acid.

tor (VDW, Munich, Germany) was then calibrated, and its integrated EAL function and "auto-apex-stop" function were activated.

To determine the electronic length (EL), irrigation was performed according to the experimental groups. In Groups 1 and 2, 0.5 mL of 5.25% NaOCl (Wizard, Rehber Chemistry, Istanbul, Turkey) was used. In Groups 3 and 4, a Dual Rinse solution was prepared by dissolving 0.9 g of Dual Rinse® HEDP powder (Medcem, Weinfelden, Switzerland) in 10 mL of 5.25% NaOCl, following the manufacturer's instructions. Then, 0.5 mL of the prepared NaOCl/Dual Rinse solution was used to irrigate the root canals of the teeth embedded in the alginate model. The excess irrigant from the coronal area was removed using a cotton sponge. In groups 1a, 2a, 3a, and 4a, the ELs were determined using the 25/07 WaveOne Gold file system (Dentsply Maillefer, Ballaigues, Switzerland), which operates in reciprocating motion and is manufactured with a gold heat-treated Ni-Ti alloy. In groups 1b, 2b, 3b, and 4b, the ELs were determined using the 25/08 WaveOne file system (Dentsply Maillefer, Ballaigues, Switzerland), which also operates in reciprocating motion. For both file systems, the VDW Gold Reciproc endomotor (VDW GmbH, Munich, Germany) was operated in the preset "Reciproc All" mode, which provides a manufacturer-controlled reciprocating motion equivalent to approximately 300 rpm. In this mode, torque is automatically regulated by the motor according to canal resistance, and the numeric settings are not user-modifiable. According to Fidler et al. (19), the Reciproc All mode involves an engaging (CCW) angle of 186.34°±1.02, a disengaging (CW) angle of 65.07°±0.93, an engaging speed of 428.32±7.61 rpm, and a disengaging speed of 261.06±7.72 rpm, confirming an asymmetric reciprocation corresponding to a mean dynamic equivalent of approximately 300 rpm.

During instrumentation with the WaveOne Gold and WaveOne files, the file was removed after every three pecking motions to clean the debris with a moist sponge. The root canals were then irrigated with 1 mL of the corresponding solution: NaOCl (groups 1 and 2) or Dual Rinse (groups 3 and 4). Irrigation was performed using a 30-gauge side-vented needle (NaviTip, Ultradent, South Jordan, UT, USA) inserted 2 mm short of the working length. All irrigants were used at room temperature (approximately 23 °C) and left in the canal for about 1 min before aspiration. Recapitulation was performed with a #15 K-type file (Dentsply Maillefer). These steps were repeated until the file stopped automatically via the "auto-apex-stop" function. Following this, the operator aligned the rubber stopper with the coronal reference point of the tooth, withdrew the instrument from the root canal, and determined the length indicated by the integrated EAL using a digital caliper. Each EL was measured and recorded separately for every specimen. All the procedures were conducted by a single experienced operator familiar with the VDW Gold Reciproc endomotor system's built-in EAL functionality. The measurements were obtained using a digital caliper (Hogetex, Germany) with 0.01 mm precision under a dental operating microscope (×19.4) (Fig. 1).

To evaluate the measurement discrepancies, ALs were subtracted from the ELs. A positive result (+) indicated that the EL exceeded the AL, whereas a negative value (–) indicated a shorter EL. A difference of 0 signified complete agreement between the two values. Measurements within ±0.5 mm of the AL were considered clinically acceptable.

Statistical analysis

The data distribution's normality was assessed using the Shapiro–Wilk test. The data did not follow a normal distribution, and the Kruskal–Wallis test was used for intergroup comparisons. When significant differences were found,



Fig. 1. Experimental setup displaying the specimen model and device adjustment prior to testing.

pairwise comparisons were performed using the Mann–Whitney U test. All the statistical analyses were conducted using SPSS software (IBM SPSS Statistics for Windows, ver.26; IBM Corp., Armonk, NY, USA), and the significance level was set at $p<0.05$.

Results

The Shapiro–Wilk test revealed that the data was not normally distributed. Non-parametric statistical methods were thus employed ($p<0.05$).

The differences in deviation values, calculated based on the difference between EL and AL, were compared across the eight groups using the Kruskal–Wallis test. A statistically significant level was set at $p<0.05$. Table 2 presents the mean differences and standard deviations between the ELs and ALs obtained using various irrigation solutions and heat-treated Ni-Ti files. Table 3 provides a detailed overview of the EL–AL difference distribution across different reference intervals.

No statistically significant differences were observed in the deviations between EL and AL among the groups using different irrigating solutions ($p>0.05$). Similarly, there were no significant differences in the EL–AL values between file systems with different heat treatments ($p>0.05$). These findings indicate that neither the type of irrigating solution nor the file system had a statistically significant effect on the accuracy of the electronic working length measurements.

The Bland–Altman analysis showed a mean bias of 0.03 mm with 95% limits of agreement between –0.79 mm and +0.86 mm. A total of 73.6% of all measurements were within the clinically acceptable ±0.5 mm range, indicating good agreement between EL and AL measurements (Fig. 2).

Discussion

This study aimed to evaluate the influence of two nickel-titanium (Ni-Ti) file systems differing in heat treatment

Table 2. Mean value and standard deviation (SD) of the EL-AL difference for varying irrigation solutions and heat treatment Ni-Ti file

Groups	Overall Accuracy (a)	WaveOne Gold (b)	WaveOne	p1
	Mean ± SD	Mean ± SD	Mean ± SD	
EL – AL (mm)				
Group 1 (2.5% NaOCl)	0.41±0.304	0.371±0.208	0.451±0.387	0.965
Group 2 (5.25% NaOCl)	0.296±0.192	0.312±0.189	0.280±0.205	0.565
Group 3 (2.5% NaOCl + 9%HEDP)	0.327±0.223	0.404±0.234	0.251±0.193	0.112
Group 4 (5.25% NaOCl + 9%HEDP)	0.305±0.291	0.252±0.250	0.358±0.334	0.401
p2	0.522			

EL: Electronic length; AL: Actual length; Ni-Ti: Nickel Titanium; WOG: WaveOne Gold; WO: WaveOne; NaOCl: Sodium hypochlorite; HEDP: Etidronic acid.
p1 represents the statistical significance of differences in EU-AL values among different heat treatment file types. p2 indicates the statistical significance of differences in EL-AL values across varying irrigation solutions.

Table 3. Distribution of the EL-AL difference across groups defined by varying reference intervals

EL - AL (mm)	Group 1 (2.5% NaOCl)		Group 2 (5% NaOCl)		Group 3 (2,5% NaOCl+9% HEDP)	
	WOG	WO	WOG	WO	WOG	WO
	n (%)	n (%)	n (%)	n (%)	n (%)	n (%)
<-0.50	1 (11.1)	3 (33.3)	0 (0)	0 (0)	1 (11.1)	0 (0)
-0.5 to -0.01	1 (11.1)	4 (44.4)	1 (11.1)	2 (22.2)	2 (22.2)	6 (66.6)
0.00	0 (0)	0 (0)	0 (0)	0 (0)	1 (11.1)	0 (0)
0.01 to 0.50	6 (66.6)	1 (11.1)	6 (66.6)	6 (66.6)	3 (33.3)	2 (22.2)
>0.50	1 (11.1)	1 (11.1)	2 (22.2)	1 (11.1)	2 (22.2)	1 (11.1)

EL: Electronic length; AL: Actual length; WaveOne Gold: WOG; WaveOne: WO; HEDP: Etidronic acid; NaOCl: Sodium hypochlorite. Negative values represent a file position coronal to the perforation, while positive values indicate an apical file position.

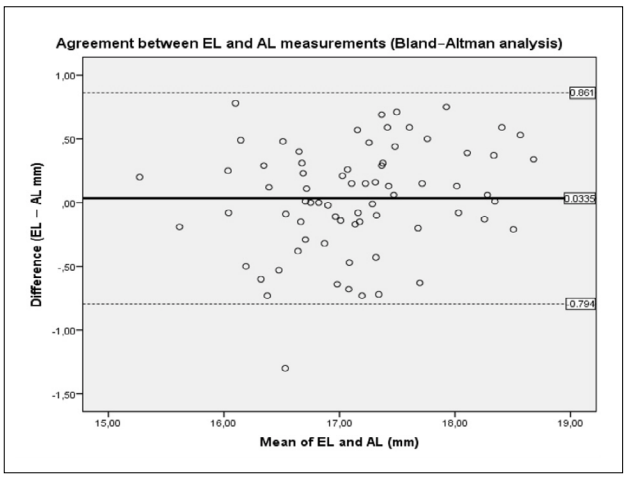


Fig. 2. Bland–Altman plot showing agreement between electronic (EL) and actual (AL) working length measurements. The solid line represents the mean bias (0.03 mm), and the dashed lines represent the 95% limits of agreement (–0.79 mm and +0.86 mm).

status, applied together with various irrigation protocols involving different concentrations of NaOCl, with or without continuous chelation, on the accuracy of EALs integrated into an endodontic motor during root canal preparation. Neither the thermal characteristics of the file systems nor the type and concentration of the irrigants were found to produce a statistically significant effect on the electronic working length measurements. The null hypothesis was thus accepted.

The accuracy of working length determination in endodontic procedures has improved with the introduction of EALs, which enable reliable measurements without necessitating a completely dry canal environment. These devices function by completing an electrical circuit through the patient's body and measuring impedance at the file tip using multiple frequencies to identify the apical constriction (20). Moreover, the integration of EALs into endodontic motors has enhanced both the efficiency and precision of root canal treatments by allowing continuous monitoring of the apical limit throughout instrumentation. One such motor, the Gold Reciproc motor, integrates an EAL, enables real-time working length control with both reciprocating and rotary file systems, and offers independent length measurements. According to the manufacturer, its LED display offers a real-time visualisation of the file tip's location in distinct canal zones. In a previous study, the Gold Reciproc motor was found to offer accurate working length determination, which confirms its reliability and effectiveness as an integrated endodontic device. We thus selected the Gold Reciproc motor with a reciprocating file system for our study (4).

Various electroconductive media, including saline, gelatine, agar-agar, and alginate, were employed in previous in vitro studies to assess the effectiveness of EALs (21,22). Among these, alginate has been frequently identified as the most dependable medium for assessing EAL measurement accuracy, a conclusion supported by numerous investigations (23,24). In a comparative study by Duran-Sindreu et al. (25), no statistically significant differences were observed between the results obtained from in vivo conditions and those using alginate-based in vitro models, thus reinforcing its validity. Because of its favourable properties—high elasticity, suitable viscosity, effective electrical conductivity, and ease of manipulation—we chose alginate as the embedding medium. These characteristics enable it to closely conform to the root surface and offer a realistic simulation of periodontal tissue (26).

EALs' accuracy has been widely investigated in relation to various instrumentation sizes (27), irrigating solutions (1), and file systems with differing heat treatments (7). However, limited data exist concerning the performance of integrated EALs when used with Ni-Ti rotary systems that differ in thermal treatment alongside varying concentrations of NaOCl and continuous chelation protocols. Our study was designed to address this research gap, and our findings offer valuable contributions to the literature.

Nickel-titanium (Ni-Ti) instruments are widely employed in root canal preparation due to their unique properties of super elasticity and shape memory (8). These characteristics are derived from the alloy's ability to exist in two distinct crystallographic phases: austenite and martensite. The martensitic phase is known to be more ductile and flexible, exhibiting higher resistance to cyclic fatigue compared to the austenitic phase. The phase state is temperature-dependent: When the temperature exceeds the austenitic finish (Af) point, the alloy assumes an austenitic structure. Conversely, at temperatures below the martensitic finish (Mf), the material enters the martensitic phase (9). In certain Ni-Ti instruments, heat treatment is applied to increase the Af temperature, enabling the instrument to retain the martensitic phase at room temperature. This thermal modification enhances mechanical performance, providing increased flexibility and improved resistance to fracture compared to conventional Ni-Ti files (9). However, a notable difference in electrical resistivity between the austenitic and martensitic phases has been reported, raising questions regarding the influence of these structural changes on the accuracy of EALs, which rely on electrical conductivity for working length determination (28). However, the research on the effect of heat-treated Ni-Ti files on EAL performance is limited. Sarıyılmaz et al. (10) evaluated the impact of reciprocating Ni-Ti files, including WaveOne Gold and WaveOne, on the accuracy of apex lo-

cator-integrated endomotors. Their findings indicated no statistically significant differences between the file types, concluding that heat treatment did not negatively affect the reliability of working length measurements. Similarly, Heo et al. (7) assessed the accuracy of two different EALs using heat-treated Ni-Ti glide path files (ProGlider and HyFlex EDM) and found no significant deviations in measurement accuracy, supporting the conclusion that heat treatment does not impair EAL function. Consistent with these findings, our study demonstrated that heat-treated Ni-Ti files do not adversely affect the accuracy of EALs. Our finding aligns well with that of the aforementioned studies, reinforcing the notion that thermally modified instruments can be reliably used in electronic working length determination.

A material's electrical resistance is primarily determined by three fundamental factors: resistivity, length, and cross-sectional area (3). In this study, the length of the instruments was kept constant across all groups as part of the experimental design. However, minor variations in taper and cross-sectional geometry were present among the tested files. Additionally, there were significant differences in the electrical resistivity between the austenitic and martensitic phases of Ni-Ti alloys (28). Due to these structural and material-related differences, it was reasonable to expect some variation in electrical resistance among the instruments. However, Sarıyılmaz et al. (10) reported identical electrical resistance values of WO and WOG files. In this study, the EAL-integrated endodontic motor produced similar accuracy with both WO and WOG files, suggesting that minor changes in resistance—potentially resulting from thermal processing or manufacturing differences—may not have a clinically significant impact on the measurement accuracy of EAL-integrated endodontic motors during working length determination between these files, and the similar results observed between the WO and WOG files in our study may be attributed to these factors. Nevertheless, further comprehensive studies are required to validate these findings.

Root canal treatment aims to remove pulp tissue and reduce bacterial load to levels compatible with periapical health, which remains difficult due to the anatomical complexity of the root canal system (29). Despite different instrumentation techniques, studies have shown poor debridement and insufficient disinfection. Recent research has thus focused on irrigants with strong antibacterial and tissue-dissolving capabilities to support mechanical cleaning (30). The NaOCl–EDTA combination is considered the gold standard for dissolving necrotic tissue, removing the smear layer, and killing microorganisms, but both solutions have high surface tension, limiting their penetration into canal irregularities. Moreover, their interaction consumes the available chlorine and reduces NaOCl's effectiveness (31).

The combined use of NaOCl and HEDP was recently proposed, with several studies reporting the enhanced antimicrobial activity of this mixture compared to NaOCl alone (32,33). Due to its increasing use and reported advantages and the limited literature on this topic, we investigated this approach in our study. NaOCl, a commonly used irrigant due to its strong antimicrobial and tissue-dissolving capabilities, has raised concerns because of its electroconductive nature, which could potentially interfere with electronic measurements (11,34). Diemer et al. (34) demonstrated that different concentrations of sodium hypochlorite do not compromise the accuracy of apex locator readings. Our study supports this finding and further expands the current knowledge by that the EAL accuracy remains unaffected even when NaOCl is used in conjunction with continuous chelation protocols. This novel finding broadens the existing understanding by demonstrating that apex locator accuracy is maintained even under continuous chelation conditions—a factor not previously addressed in the literature. Based on our findings, the combined use of NaOCl and HEDP solutions does not affect the accuracy of IALs and appears to be a viable option in clinical practice.

Our study is inherently limited by the lack of vital tissue and the absence of electroconductive substances, such as blood and saliva, that are typically present in clinical settings. Moreover, the electrical resistance of the alginate used to simulate the periodontal ligament does not fully replicate the properties of actual periodontal tissues. Our results' applicability is also confined to the particular tooth type and EAL models tested in this study.

Conclusion

Within the limitations of this in vitro study, neither the thermal treatment of NiTi file systems nor the use of different irrigating solutions, including NaOCl alone or combined with HEDP, significantly influenced the accuracy of the IALs during root canal preparation. The findings indicate that the combined use of NaOCl and HEDP represents a safe and effective irrigation strategy that does not compromise working length determination, supporting its potential clinical applicability in endodontic practice.

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