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ORIGINAL ARTICLE



# Comparison of four electronic root canal length measurement devices

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**ABSTRACT**

**Objective:** The objective of this study is to evaluate the performance of four electronic root canal length measurement devices (ERCLMDs) [Root ZX, Raypex 6, ProPex II, and VDW Gold with ERCLMD] in wet and dry root canals with different major foramen diameters, in association with three file positions within the final 1 mm of canals.

**Materials and methods:** Fifty roots were divided into five groups that were instrumented apically to the terminus diameter using K-files 15, 20, 30, 40, and 60. ERCLMD measurements were made when the file tip was at major foramen, 0.5 mm and 1.0 mm short of the foramen, when the apex touched to the surface of saline or was immersed 3 mm into saline, and when the canal was dry or was irrigated with saline. The differences between the electronic lengths and the actual lengths were calculated. The data were analyzed using the three-, two-, and one-way ANOVA and the LSD test ($p < .05$).

**Results:** Overall, the four ERCLMDs demonstrated 12.8% unstable and beyond the foramen measurements (11.3%). About 85% of the beyond the foramen measurements had foramen diameters 0.40 and 0.60. ERCLMD comparisons related to the file positions in the foramen diameters showed significant differences between ERCLMDs in each foramen diameter ($p < .05$).

**Conclusions:** All ERCLMDs provided highly accurate measurements within the final 1 mm of the foramen. Wet or dry canals and apex conditions did not adversely affect the accuracy of the ERCLMDs' readings. ProPex II located the file positions in the teeth with different foramen diameters more accurately than the other ERCLMDs.

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## Introduction

The apical constriction (minor foramen) is generally considered to be the landmark for ending endodontic instrumentation and canal filling [1]. The minor foramen does not coincide with the anatomical apex and it might be located laterally. In an *in vitro* study, the mean anatomical apex-major foramen (apical foramen) distance and the mean apex-minor foramen distance were found, respectively, 0.38 mm 0.89 mm [2]. Several different techniques that involve radiographic and electronic methods have been used to determine the location of the apical terminus [3]. Because of the hazards of ionizing radiation and to avoid over-instrumentation beyond the apical constriction, electronic working length determination has become an established technique among endodontists. A variety of operating principles and electronic methods have been developed and various ERCLMDs are available in the market.

The Root ZX (J. Morita Co., Tokyo, Japan) measures the impedance values in the canal using two different frequencies (0.4 and 8.0 kHz) and then calculates their quotient value [3,4]. The Root ZX works in the presence of electrolytes and requires no calibration [3]. The Root ZX has shown to be accurate in locating the minor foramen to within 1 mm [5–8].

Raypex 6 (VDW, Munich, Germany) is a multi-frequency ERCLMD. Moscoso et al. [9] reported that 88% of the measurements of the Raypex 6 were accurate to ±0.5 mm and 100% of the measurements were accurate to ±1 mm.

Rather than using the amplitude of the signal, as the other ERCLMDs do, ProPex II (Dentsply Maillefer, Ballaigues, Switzerland) measures the energy of the signal with multi-signal frequencies [7]. As described by Briseño-Marroquín et al. [10], the accuracy of Propex II was 83%, 88%, and 91% with instrument sizes 08, 10, and 15, respectively, with a standard deviation of ±0.5 mm.

VDW Gold (VDW, Munich, Germany) is an endomotor with an integrated ERCLMD that uses two frequencies: 5.5 kHz and 500 Hz. Koçak et al. [11] compared the clinical accuracy of VDW Gold ERCLMD with the conventional radiographic technique. VDW Gold and the conventional radiographic technique were similar in terms of their accuracy within 0–2 mm from the radiographic apex.

Laboratory studies [12,13] and clinical evaluations [14,15] indicated that ERCLMDs provided accurate readings in about 80–100% of canals. Earlier devices were not accurate in root canals containing moisture, vital pulp tissue, blood, exudates, or remnants of intracanal irrigants [16–18]. Multi-frequency ERCLMDs function more accurately especially with conductive solutions inside the canal [19,20]. ERCLMD measurements appeared to be less accurate when the apical foramen diameter was large [12,21]. A number of studies have addressed

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the benefits and clinical performances of a diverse range of ERCLMD models that have been developed in recent years. At the same time, the manufacturers make ambitious claims for their products, so it remains difficult for practitioners to choose the ERCLMDs available in the market. The objective of the present study was to investigate and compare the accuracy of four ERCLMDs in wet and dry root canals with different major foramen diameters and different file positions within the final 1 mm of the canals. The null hypotheses tested were that the distance from AL (1), the apex diameter (2), and the condition of the apex and the condition of the canal (3) do not cause the accuracy differences among the four ERCLMDs.

## Materials and methods

Fifty periodontally involved human maxillary incisors and canines extracted from 45- to 55-year-old patients were selected with the approval of the Ethics in Research Committee of the Dentistry Faculty of İstanbul University, Turkey. Twenty-five extracted maxillary central incisors and 25 extracted maxillary canines that had not been endodontically treated in the past were used. Roots with resorption, fractures, restorations, open apices, or radiographically invisible canals were excluded. The surface and apical part of each tooth were examined for fractures and resorption under a dental operating microscope (Zeiss, Jena, Germany) at ×10 magnification. The teeth were immersed in 5.25% sodium hypochlorite (NaOCl) (Wizard, Rehber Chemistry, İstanbul, Turkey) before calculus and soft tissue debris was removed with curettes (Hu-Friedy Mfg. Co., Chicago, IL). After rinsing in tap water, the teeth were stored in 0.9% NaCl solution (Vacoliter, Eczacıbaşı, İstanbul, Turkey).

The crown of each tooth was sectioned at the cementoenamel junction with a diamond disk (Sunshine, 19 mm (3/4 in.)-fine grit, 0.17 mm thick, Lincoln Dental Supply, NJ) under water irrigation to gain standard root canal access and obtained a fixed, stable point of reference for all of the measurements. The root canal preparations were done by one operator. Patency was checked with a size 08 stainless steel K-file (Dentsply Maillefer, Ballaigues, Switzerland) before the instrumentation and irrigation of the canal system. Pulp tissue was partially removed with barbed broaches (Dentsply Maillefer, Ballaigues, Switzerland). The coronal third of each canal was preflared with Gates–Glidden drills sizes 2–3 (Dentsply Maillefer, Ballaigues, Switzerland), in a crown-down manner. Stainless steel hand K-files sizes 15–60 were used to obtain five groups of 10 randomly selected roots (five from incisors and five from canines) with major foramen diameters of 0.15, 0.20, 0.30, 0.40, and 0.60 mm. RC prep (Premier Dental Products Co., Norristown, PA) was used during instrumentation. After the use of each instrument, the canal was irrigated with 2 mL of 5.25% NaOCl using an endodontic syringe with 27- and 30- gauge needles (Nissho, Osaka, Japan) in an up-and-down motion. Apical patency was maintained with a size 0.8 K-file through the foramen. During the preparation phase, the apical portion of the canals was enlarged to remove the apical constriction and transport the minor foramen to the major foramen [22]. The diameters of the major foramen preparations were checked from the apical side via dental microscope observation.

At the end of instrumentation, the actual canal length (AL) was determined by introducing a size 10 K-file with three silicone stoppers into the canal until the tip of the file was at the major foramen under ×10 magnification using an operating microscope. Three silicone stoppers were used to decrease the chance of stopper movement during the measurements. The distance from the base of the silicone stoppers to the file tip was measured with a digital caliper (Mitutoyo Corp. Tokyo, Japan) to within one-hundredth of an mm and recorded as the actual length. The files and stoppers were only used for five measurements each and then discarded.

Each root was fixed with wax into a hole on the cover of a plastic container, which was filled with sterile 0.9% NaCl solution. The following ERCLMDs were used: Root ZX II, Raypex 6, Propex II, and VDW Gold endomotor with an integrated apex locator (VDW Gold). Each device was calibrated according to the instructions from the manufacturer, and the "apex" indicated by each device was chosen as the apical reference.

For electronic measurements with each ERCLMD, an electrode was connected to a K-file inserted into the root canal with a size just smaller than the K-file that engaged the major foramen the other electrode was immersed into the saline solution. The readings with the ERCLMDs were made at three different lengths: at the major foramen (0.0), 0.5 mm short of the foramen, and 1.0 mm short of the foramen. Before insertion, the distance between the file tip and the stopper was adjusted using a digital caliper and measured under magnification (×2.5) using a loupe (Keeler Ltd, Windsor, UK).

The measurements were considered valid if the instrument remained stable for at least 5 s; otherwise, the value was recorded as an unstable measurement due to the inability of the ERCLMD to reveal a constant reading. The unstable measurements were not evaluated as accurate measurements provided by the ERCLMDs.

The experimental protocol was that used by Venturi and Breschi [22]. Measurements were done for each root in the four following conditions. Each root was positioned in the plastic container.

Condition 1: The apex lightly touched the surface of the saline solution when the root canal was dry.
Condition 2: The most apical 3 mm of the root was immersed into the saline solution when the root canal was dry.
Condition 3: The apex lightly touched the surface of the saline solution, and the root canal was irrigated with saline solution.
Condition 4: The most apical 3 mm of the root was immersed into the saline solution, and the root canal was irrigated with saline solution.

Each ERCLMD was used according to the instructions from the manufacturer and measurements were recorded. The differences between the means of the actual and electronic lengths were calculated. The values were analyzed

statistically with three-, two-, and one-way ANOVA tests. Multiple comparisons were done using dependent variable the least significant difference (LSD) test. Accuracy was only calculated on stable measurements in each group. All the parameters (apex diameter, condition of the apex, condition of the canal, AL and distance to the foramen of the file tip on the precision of the ERCLMDs' measurements) were used in the statistical evaluations. First, the measurements of the file positions from the foramen (0.0, 0.5, and 1 mm) were analyzed. Second, the measurements of the file positions were analyzed to evaluate the effects of the apex diameters. Third, the measurements of the file positions were analyzed to evaluate the effects of the conditions of the apex and the canal. Statistical significance was set at $p < .05$.

## Results

Accuracy was only accepted in stable measurements, which were calculated. Unstable measurements were seen with all the ERCLMDs. There were a total of 42 out of 2400 unstable measurements (1.7%): 12 with Root ZX, 12 with Raypex 6, 10 with Propex II, and 8 with VDW Gold. The unstable measurements occurred with apical diameters of 15 and 20 mm and when the file tip was 1 mm short of the foramen.

Two hundred and sixty-six of the remaining 2358 measurements with all the ERCLMDs (11.3%) revealed that the file tip was beyond the foramen (59 with Root ZX, 68 with Raypex 6, 63 with Propex II, and 76 with VDW Gold). Beyond the foramen measurements mostly occurred at apical diameters of 40 and 60 mm (227 out of 266 measurements, 85.3%; Root ZX 51, Raypex 6 58, Propex II 53, VDW Gold 65).

A total of 308 unstable and beyond the foramen measurements out of 2400 total (12.83%) were recorded by the ERCLMDs (Root ZX 88.2%, Raypex 6 86.7%, Propex II 87.9%, VDW Gold 86.0%) in the study.

Root ZX, Ray Pex 6, ProPex II, and VDW Gold showed, respectively, 9.16, 19.66, 15.33, and 21.66% short measurements (+) than the ALs, and 55.30, 41.16, 45.83, and 41.00% long measurements (−) than the ALs. And 23.66, 25.83, 26.66, and 23.33% exact measurements were recorded with the four ERCLMDs.

A two-way ANOVA was conducted to examine the interaction effect of the distance from AL and the ERCLMDs on the accuracy of measurements. There was a significant two-way interaction ($p < .05$). The means and standard deviations of the file position measurements of the 4 ERCLMDs, as well as statistical analysis of the data with one-way ANOVA are illustrated in Table 1. For instance, the mean difference between the AL and the lengths measured by the Root ZX, Ray Pex 6, ProPex II, and VDW Gold at 0.5 mm were, respectively, −0.13, −0.10, −0.10, and −0.10 mm. The one-way ANOVA indicated statistical differences among the ERCLMDs with the file tip at 0.0 mm and 1 mm short of the foramen. The LSD test was performed for the paired comparisons of the ERCLMDs. Fourteen out of the 18 paired comparisons in the three file positions showed no statistically significant differences between the ERCLMDs. Root ZX and ProPex II showed significantly more accurate differences with Raypex 6 when the file was at the foramen ($p < .05$). Raypex 6 yielded significantly more accurate differences with both Root ZX and VDW Gold when the file tip was 1 mm short of the foramen ($p < .05$).

**Table 1.** Mean and standard deviation for the accuracy of the file position measurements with the four ERCLMDs and statistical analysis of the data with one-way ANOVA.

| Distance from AL (mm) | Root ZX II Mean, SD | Raypex 6 Mean, SD | ProPex II Mean, SD | VDW Gold Mean, SD | $p$* |
|---|---|---|---|---|---|
| 0.0 | −0.08, 0.17 | −0.17, 0.59 | −0.08, 0.28 | −0.11, 0.32 | **.037** |
| 0.5 | −0.13, 0.18 | −0.10, 0.28 | −0.10, 0.28 | −0.10, 0.40 | .721 |
| 1.0 | −0.21, 0.18 | −0.12, 0.30 | −0.18, 0.27 | −0.22, 0.44 | **.006** |

*Bold characters show the significant $p$ values ($p < .05$).
Minus sign indicates measurements long of the AL.

A three-way ANOVA was done to examine the interaction effect of the distance from AL, the ERCLMDs, and apex diameter on the accuracy of measurements. The three-way ANOVA showed that there was a significant interaction ($p < .05$). The means and standard deviations for the accuracy of the file position measurements at the different foramen diameters obtained with the four ERCLMDs, as well as statistical analysis of the data with one-way ANOVA, are illustrated in Table 2. According to the LSD test, 39 out of 90 paired comparisons showed statistically significant differences between the ERCLMDs (Table 3). ProPex II showed (14 times) the most accurate findings compared with the other ERCLMDs, and the lowest number of more inaccurate findings (three times). The rest of ERCLMDs were ranked as Raypex 6 > Root ZX > VDW Gold.

A three-way ANOVA was done to examine the interaction effect of the distance from AL, the ERCLMDs, and conditions on the accuracy of measurements. The three-way ANOVA showed that there was no statistically significant interaction ($p > .05$). The means and standard deviations for the accuracy of the file position measurements at the different conditions obtained with the four ERCLMDs, as well as statistical analysis of the data with one-way ANOVA, are illustrated in Table 4. According to the one-way ANOVA, no statistical significant differences were found among the ERCLMDs in the three file positions regarding the effects of the condition of the apex and the condition of the canal ($p > .05$).

## Discussion

In this study, we aimed to compare the accuracy performances of four novel ERCLMDs, in three file positions within the range of the final 1 mm (at the foramen, 0.5 mm, and 1 mm short of the foramen), in canals with different major foramen diameters (0.15, 0.20, 0.25, 0.30, 0.40, and 0.60 mm, and in wet and dry canal and apex conditions. The first and second null hypotheses of the study were rejected because four out of 18 paired comparisons related to the distance from the AL and 39 out of 90 paired comparisons related to the apex diameter showed significant differences. The third hypothesis related to the wet and dry canal conditions was accepted.

Similar studies have been conducted *in vitro* and *in vivo* to determine the precision of ERCLMDs [22,23]. In *in vitro* studies, several conductive media were used such as

**Table 2.** Mean and standard deviation for the accuracy of the measurements obtained with the four ERCLMDs with the file positions at different apex diameters and statistical analysis of the data with one-way ANOVA.

| Apex diameter(# K-file) | Distance from AL (mm) | Root ZX II Mean, SD | Raypex 6 Mean, SD | ProPex II Mean, SD | VDW Gold Mean, SD | $p$* |
|---|---|---|---|---|---|---|
| 15 | 0.0 | 0.00, 0.09 | +0.39, 1.22 | +0.04, 0.08 | +0.08, 0.16 | **.003** |
| | 0.5 | −0.07, 0.12 | −0.07, 0.14 | 0.00, 0.10 | +0.22, 0.27 | **.000** |
| | 1.0 | −0.15, 0.11 | −0.22, 0.16 | −0.09, 0.10 | +0.23, 0.36 | **.000** |
| 20 | 0.0 | +0.02, 0.05 | −0.01, 0.04 | 0.00, 0.15 | +0.02, 0.11 | .493 |
| | 0.5 | +0.01, 0.10 | −0.01, 0.14 | −0.05, 0.15 | +0.16, 0.24 | **.000** |
| | 1.0 | −0.05, 0.09 | −0.21, 0.39 | −0.13, 0.17 | +0.02, 0.22 | **.000** |
| 30 | 0.0 | −0.05, 0.10 | −0.02, 0.06 | −0.02, 0.08 | −0.03, 0.19 | .752 |
| | 0.5 | −0.14, 0.17 | +0.01, 0.12 | −0.07, 0.18 | −0.06, 0.24 | **.006** |
| | 1.0 | −0.22, 0.20 | +0.09, 0.15 | −0.10, 0.15 | −0.16, 0.28 | **.000** |
| 40 | 0.0 | −0.13, 0.17 | −0.09, 0.16 | −0.06, 0.23 | −0.14, 0.34 | .373 |
| | 0.5 | −0.18, 0.18 | −0.09, 0.25 | −0.01, 0.25 | −0.26, 0.35 | **.000** |
| | 1.0 | −0.28, 0.17 | −0.03, 0.27 | −0.13, 0.30 | −0.41, 0.35 | **.000** |
| 60 | 0.0 | −0.24, 0.22 | −0.36, 0.35 | −0.36, 0.45 | −0.46, 0.37 | .063 |
| | 0.5 | −0.26, 0.21 | −0.35, 0.46 | −0.35, 0.42 | −0.56, 0.32 | **.003** |
| | 1.0 | −0.32, 0.19 | −0.26, 0.29 | −0.43, 0.36 | −0.72, 0.30 | **.000** |

*Bold characters show the significant $p$ values ($p < .05$).
Minus sign shows measurements long of the AL. Plus sign shows measurements short of the AL.

**Table 3.** Paired comparisons of the ERCLMDs with LSD test according the data obtained with the file positions in the different apex diameters.

| Apex diameter (#) | Distance from AL (mm) | Comparisons of ERCLMDs* |
|---|---|---|
| **15** | **0.0** | **Root ZX** versus Raypex 6 |
| | | **Propex II** versus Raypex 6 |
| | | **VDW Gold** versus Raypex 6 |
| | **0.5** | **Root ZX** versus VDW Gold |
| | | **Raypex 6** versus VDW Gold |
| | | **Propex II** versus Root ZX |
| | | **Propex II** versus Raypex 6 |
| | | **Propex II** versus VDW Gold |
| | **1.0** | **Root ZX** versus VDW Gold |
| | | **Raypex 6** versus VDW Gold |
| | | **Propex II** versus Raypex 6 |
| | | **Propex II** versus VDW Gold |
| **20** | **0.5** | **Root ZX** versus VDW Gold |
| | | **Raypex 6** versus VDW Gold |
| | | **Propex II** versus VDW Gold |
| | **1.0** | **Root ZX** versus Raypex 6 |
| | | **VDW Gold** versus Raypex 6 |
| | | **VDW Gold** versus Propex II |
| **30** | **0.5** | **Raypex 6** versus Root ZX |
| | | **VDW Gold** versus Root ZX |
| | **1.0** | **Raypex 6** versus Root ZX |
| | | **Raypex 6** versus Propex II |
| | | **Raypex 6** versus VDW Gold |
| | | **Propex II** versus Root ZX |
| **40** | **0.5** | **Raypex 6** versus VDW Gold |
| | | **Propex II** versus Root ZX |
| | | **Propex II** versus VDW Gold |
| | **1.0** | **Root ZX** versus VDW Gold |
| | | **Raypex 6** versus Root ZX |
| | | **Raypex 6** versus VDW Gold |
| | | **Propex II** versus Root ZX |
| | | **Propex II** versus VDW Gold |
| **60** | **0.5** | **Root ZX** versus VDW Gold |
| | | **Raypex 6** versus VDW Gold |
| | | **Propex II** versus VDW Gold |
| | **1.0** | **Root ZX** versus VDW Gold |
| | | **Raypex 6** versus Propex II |
| | | **Raypex 6** versus VDW Gold |
| | | **Propex II** versus VDW Gold |

*Bold characters show the ERCLMDs which were yielding significantly accurate findings ($p < .05$).

agar-agar [10], alginate [24,25], gelatin [26], a sponge soaked with saline solution [27], and saline solution [22,28]. In this study, saline solution was used as the conductive media, since Venturi and Breschi [22] and Kobayashi and Suda [29] showed that 0.9% NaCl solution provided good contact with the K-file. The electrode–electrolyte interface impedance when the electrolyte is a tissue is closer to 0.9% NaCl, and saline has become a reference solution since its ionic content is equivalent to that of blood plasma [22,30].

In this study, the crowns of teeth were cut to have a flat surface, serving as a stable reference point and preventing inaccurate adjustment of the rubber stoppers to the reference point [17,31–34]. The use of three rubber stoppers minimized the risk of the stopper displacement during the measurements. It should be noted that shortening of tooth samples may influence the accuracy of the ERCLMDs. Saatchi et al. [34] reported that the accuracy of Root ZX was affected by the tooth length and Root ZX yielded higher accuracy in shorter teeth.

In this study, the stainless steel K-files were used during the accuracy measurements because previous studies showed that the type of the file alloy did not affect significantly the accuracy measurements. Nekoofar et al. [35] reported that the accuracy of Neosono Ultima EZ apex locator was 94% with NiTi files and 91% with stainless steel. They noted that the accuracy of the ERCLMD was not influenced significantly by the type of alloy used. Sadeghi and Abolghasemi [36] reported that both stainless steel and NiTi file were suitable for determining working length using Raypex 5 apex locator. A limitation of this and similar *in vitro* studies may be the multiple uses of the files in the same root specimen. Saatchi et al. [34] stated that re-insertion of the file into the root canal may enlarge the major foramen and may influence the accuracy of the ERCLMDs in *in vitro* studies.

Capillary action is the movement of a liquid in narrow tubes (root canal) or along the surface of another material in spite of other forces, such as gravity. The water molecules adhere to the solid surface (adhesion) and also to each other (cohesion), so that each pulls the next one along. Because half of the measurements in each root was performed by immersion the most apical 3 mm into the saline, the capillary action may have caused the saline to rise more than 3 mm, depending on the sizes of the canal and adhesion property of saline to dentin tissue. Another limitation of this study

**Table 4.** Mean and standard deviation for the accuracy of the measurements obtained with the four ERCLMDs with the file positions at different conditions and statistical analysis of the data with one-way ANOVA.

| Condition | Distance from AL (mm) | Root ZX II Mean, SD | Raypex 6 Mean, SD | ProPex II Mean, SD | VDW Gold Mean, SD | *p* |
|---|---|---|---|---|---|---|
| **1** | **0.0** | −0.04, 0.12 | −0.14, 0.59 | −0.03, 0.25 | −0.03, 0.23 | .278 |
| | **0.5** | −0.07, 0.15 | −0.06, 0.26 | −0.03, 0.24 | −0.01, 0.35 | .628 |
| | **1.0** | −0.16, 0.16 | −0.07, 0.29 | −0.09, 0.22 | −0.15, 0.44 | .407 |
| **2** | **0.0** | −0.04, 0.12 | −0.15 0.59 | −0.03, 0.25 | −0.03, 0.23 | .228 |
| | **0.5** | −0.07, 0.14 | −0.08, 0.29 | −0.04, 0.23 | −0.01, 0.35 | .596 |
| | **1.0** | −0.18, 0.17 | −0.07, 0.30 | −0.11, 0.23 | −0.16, 0.44 | .337 |
| **3** | **0.0** | −0.09, 0.18 | −0.19, 0.60 | −0.11, 0.29 | −0.18, 0.37 | .541 |
| | **0.5** | −0.14, 0.19 | −0.13, 0.30 | −0.13, 0.29 | −0.18, 0.43 | .854 |
| | **1.0** | −0.21, 0.20 | −0.14, 0.30 | −0.25, 0.29 | −0.27, 0.43 | .180 |
| **4** | **0.0** | −0.15, 0.21 | −0.21, 0.60 | −0.14, 0.31 | −0.19, 0.37 | .792 |
| | **0.5** | −0.23, 0.21 | −0.14, 0.29 | −0.18, 0.32 | −0.20, 0.44 | .604 |
| | **1.0** | −0.29, 0.19 | −0.19, 0.30 | −0.26, 0.30 | −0.31, 0.45 | .272 |

Minus sign shows measurements long of the AL.

may be that the saline level was higher in the root canals with the smaller diameter than with the larger diameter. Venturi and Breschi [22] stated that the capillary action may be a potential cause of electronic measurement errors.

According to Ibarrola et al. [37] preflaring of root canals can allow the working-length files to more consistently reach the apical foramen. Similar to these studies, the canals were preflared before the working length measurements in the present study.

Usually the major foramen [26] or apical constriction [38] is used as an apical reference point for laboratory-based studies. Lee et al. [39] observed that file tips ended in the area of the major foramen regardless of the cementodentinal junction's presence and that the major foramen is a better level to test for ERCLMD accuracy. Thus, the major foramen might be a more reproducible reference point for laboratory-based studies [22]. In addition, the present study did not control the ability of any device to locate the minor foramen or apical constriction, which was impossible with the study design because all canal sizes 15–60 in the study were made through the instrumentation of hand files to the major foramen, so that the narrowest diameter of the canal was transported to the apical foramen [22]. Clinically, the canal shaping and filling procedures should be ended within the confines of root canal system or within the narrowest apical part of the canal system and not at the major apical foramen. When an ERCLDM shows zero reading, this may indicate that the file is contact with periodontal ligament or the file is in the zone of major foramen [3]. Nekoofar et al. [3] and Cianconi et al. [40] suggested that the subtraction of 0.5 or 1 mm from the file length following zero reading may be a more dependable working length determination because precise determination of apical constriction is not possible with ERCLMDs. In an *ex vivo* study, Aggarval et al. [41] reported that ERCLMDs can exactly locate the minor foramen in 10% of the cases. In the present study, the four ERCLMDs located the exact ALs in 24.87% of the measurements.

Huang [42] and Kovacevic and Tamarut [43] and Herrara et al. [25] reported that wide apical diameters might affect the accuracy of ERCLMD measurements. Venturi and Breschi [22] found that variations in the diameter influenced the ERCLMD measurements but did not show a clear relationship. They observed that the ERCLMDs (Apex Finder and Root ZX) provided 21.7% incorrect measurements that exceeded the apical foramen. The ERCLMDs used in this study showed a total of 11.3% through major foramen measurement. Moreover, almost a clear relationship was detected in this study because most of the beyond the foramen measurements (227 out of 266, 85.3%) were seen at the apical diameters of 0.40 and 0.60 mm with all ERCLMDs.

The distance of the file tip from the major foramen did not generally affect the accuracy of the ERCLMDs' measurements in this study, since there were only significant differences in four out of the 18 paired comparisons, which were seen with the file tip at the foramen and 1 mm short of the foramen. No significant differences were seen among the ERCLMDs when the file tip was 0.5 mm short of the foramen. Both Root ZX and ProPex II showed more accurate measurements than Raypex 6 when the file was at the foramen. On the other hand, Raypex 6 showed better accuracy than Root ZX and VDW Gold when the file was 1 mm short of the foramen.

In the present study, significant differences appeared among the ERCLMDs regarding the accuracy of the measurements between all major foramen diameters and distances to the foramen in the final 1 mm of the canals. Thirty-nine out of the 90 paired comparisons showed significant differences between the ERCLMDs. Specifically, Raypex 6 was less accurate than the others when the diameter was size 0.15 and the file tip was at the foramen, and VDW Gold was less accurate than the other three ERCLMDs when the diameters were 0.40 and 0.60 mm and the file tip was 0.5 and 1 mm short of the foramen. ProPex II exhibited the highest number of more accurate performances in the paired comparisons versus the other ERCLMDs (14 times) and showed the lowest number of comparisons with less accuracy (three times). Specifically, Propex II yielded significantly accurate performances against the other three ERCLMDs when the diameter was size 0.15 and the file tip was 0.5 mm short of the foramen. The accuracy performances of the rest three ERCLMDs were ranked as Raypex 6 > Root ZX > VDW Gold.

Several studies have pointed out that the moisture conditions of the canal and apex may influence the accuracy of ERCLMDs. Huang [42] demonstrated that the moisture content of the root canal influenced the accuracy of the electronic root canal measurements. On one hand, Venturi and Breschi [22] stated that both dry and wet conditions of the canals may affect the accuracy of Apex Finder and Root ZX. On the other hand, Pommer et al. [44] reported that there was no significant correlation between the values of the ERCMDLs and the relative moisture in the canal. In the present study, no significant differences were observed among the ERCLMDs related to the effects of the moisture conditions of both the apex and the canal. In other words, the wet or dry canal and apex conditions did not significantly affect the accuracy of the ERCLMDs used in this study.

Akisue et al. [45] reported that foramen diameter did not influence the accuracy of Root ZX II. Propex II yielded higher accuracy in 0.25 mm foramen size and decreased accuracy as foramen size increased (0.45–0.70 mm). In an *in vivo* study, RayPex 5 and ProPex II showed similar accuracy in terms of locating the major foramen [46]. Cianconi et al. [40] reported that ProPex II was significantly accurate than Root ZX in determining the actual working length. The results of this *ex vivo* study could not be identically compared with the previous studies because different experimental set-ups and study designs and the ERCLMDs were used in the studies.

Forty-two unstable measurements (1.7% of 2400 measurements) were experienced with apical diameters of 15 and 20 mm and when the file tip was 1 mm short of the foramen. In total, 308 (12.83%) unstable and beyond the foramen measurements out of 2400 were recorded in this study. In addition, 1100 long (45.83%), 395 short (16.45%), and 597 (24.87%) exact measurement were noted in this study. Cianconi et al. [40] noted that Endex, Root ZX, and ProPex II yielded long measurements than the ALs, respectively, 15.9%, 37.6%, and 17.8% of the measurements. The order of measurement types recorded with the 4 ERCLMDs in this study was long > exact > short > beyond the foramen > unstable.

According to the results of this study, the accuracy of the four ERCLMDs in showing the final 1 mm of the canals may be clinically between 86% and 88% and these four ERCLMDs may read nearly the location of the file tips within the last 1 mm of the canals. Clinically, the substraction of 0.5 mm from the file length following zero reading with the ERCLMDs may be more reliable working length determination to prevent root canal instrumentation beyond the apical constriction.

## Conclusions

Within the limitations of the present study, the four ERCLMDs found the final 1 mm of the canals in the most of the measurements and showed nearly the location of the file within the last 1 mm. Beyond the foramen readings of the ERCLMDs increased in the teeth with larger foramen sizes. The wet and dry canal and apex conditions did not influence the accuracy of the ERCLMDs. ProPex II may locate the file positions in the teeth with different foramen diameters more accurately than the rest of the ERCLMDs.

## Disclosure statement

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of this article.

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