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A comparison between two electronic apex locators: an *ex vivo* investigation

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Abstract

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Aim To compare *ex vivo* the performance of the Apex Finder and the Root ZX apex locators, with and without irrigant, in canals having different diameters.

Methodology Sixty canals in 60 teeth were prepared using stainless steel hand files and 0.04 taper NiTi rotary instruments. During preparation the narrowest diameter of the canal was transported to the apical root surface. The canals were irrigated with RC-Prep and 5% NaOCl solution. Six groups were obtained, each with 10 canals having the same diameter of foramen, either 0.15, 0.20, 0.25, 0.40, 0.60 and 0.80 mm. A size 15 K-file was advanced into each canal until its tip was observed under ×10 magnification to reach the foramen and the corresponding length recorded. The measurements were performed to an accuracy of 0.25 mm as a base unit of length. The teeth were then fixed to a plastic bar suspended over a glass container filled with 0.9% NaCl solution. Each apex locator was tested when the K-file was at the foramen, or 0.5, 1.0, 1.5 and 2.0 mm short; with the root apex immersed into the solution; with the canal dry or irrigated with NaCl. To evaluate the accuracy of both electronic apex locators (EALs) each electronically determined distance was compared with the actual length and the data analysed using the General Linear Model and the Student *t*-test.

Results Out of 2400 measurements 100 were electrically unstable, all with the Root ZX. In total, 521 measurements located the position of the file tip beyond the apex, in general, in high conductive conditions with the Root ZX and in low conductive conditions with the Apex Finder. No significant difference in terms of accuracy was found between the two EALs when the file tip was at the foramen (Root ZX mean +0.12 mm, SD 1.22 mm; Apex Finder mean +0.57 mm, SD 1.16 mm). Comparing all the measurements performed with the file tip within 2 mm of the foramen, in all the different conditions tested, the accuracy was affected ($P < 0.025$) by diameter of the foramen, type of EAL, distance to the apex, and by several interactions.

Conclusions Under the different *ex vivo* conditions both EALs provided accurate measurements when the file tip was at the foramen. The accuracy of the Apex Finder was negatively influenced by high conductive conditions, whilst the Root ZX provided inaccurate and unstable measurements mostly in low conductive conditions.

Keywords: electronic apex locators, impedance, root canal length.

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Introduction

The cemento-dentinal junction (CDJ) within a root canal is the position at which root canal instrumentation and filling should preferably end (Ricucci & Langeland 1998). Unfortunately, the CDJ is not a constant feature and can only be detected in histological sections (Ponce & Fernandez 2003). At the same time, the apical constriction has several morphological variations (Dummer *et al.* 1984) and cannot be detected radiographically (Stein *et al.* 1990). Thus, in clinical practice, the minor apical foramen, i.e. the

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narrowest portion of the canal system, has been considered the preferred landmark for the apical end-point for root canal treatment (Nekoofar *et al.* 2006). Modern electronic apex locators (EALs) can determine a position within 0.5 mm of the foramen in >90% of occasions (Frank & Torabinejad 1993, Czerw *et al.* 1995, Venturi & Breschi 2005), despite the fact that such measurements depend upon electrical properties of the tooth which have not been studied thoroughly (Križaj *et al.* 2004).

The development of EALs stemmed from the findings of Suzuki (1942) that the electrical resistance between the periodontal ligament and the oral mucosa of dogs *in vivo* was a constant value. Sunada (1962) introduced this 'biological characteristics theory' into clinical practice with an EAL that used direct current. However, this method produced polarization effects on the electrodes, a drawback that led to the development of EALs using a single frequency of alternating current (Inoue 1973). These EALs could measure the canal length within 0.5 mm of the foramen on 75% of occasions (Fouad *et al.* 1990, Hembrough *et al.* 1993) in 88% of canals (Hembrough *et al.* 1993).

Subsequently, it was claimed (Ushiyama 1983, Huang 1987) that, *in vivo*, EALs mainly measured the contact resistance with tissue fluids, i.e. physical effects rather than a tissue resistance as contemplated by the 'biological characteristics theory'. As a result, EALs began to be evaluated for accuracy with various laboratory models using roots immersed in conductive solutions (Aurelio *et al.* 1983, Huang 1987, Katz *et al.* 1991, Kobayashi & Suda 1994, Czerw *et al.* 1995).

The major disadvantage of EALs using alternating current was that the accurate location of the foramen required the canal to be free of electrically conductive material (Ushiyama 1983, Ushiyama *et al.* 1988). This led to the development of multifrequency EALs supplied by alternating current, usually within a range from 400 Hz to 10 kHz (Kobayashi & Suda 1994). These EALs should function more accurately especially with conductive solutions inside the canal (Pratten & McDonald 1996, Dunlap *et al.* 1998). However, their accuracy within 0.5 mm of the apical constriction has been found to be similar to the accuracy of previous EALs: from 82% (Pagavino *et al.* 1998) to 100% (Czerw *et al.* 1995) with the Root ZX locator (J. Morita Corp., Kyoto, Japan), and 90% (Frank & Torabinejad 1993) with the Endex locator (Osada Electric Co., Tokyo, Japan).

Various methods have been used to measure the impedance of biological tissues (Tsai *et al.* 2002). Impedance measurements with the alternating current EALs basically identify the variation of electrical circuit resistance as the file approaches the apical constriction. Impedance measurements with the multifrequency EALs aim to detect variations of capacitance (Kobayashi & Suda 1994). Since measurements of resistance are generally easier and more reliable than measurements of capacitance (Godin *et al.* 1991, Ackmann 1993, Ward *et al.* 1998) it may be helpful to investigate if the alternating current EALs could provide more exact measurements from clean canals than can be obtained with multifrequency EALs in conductive environments. Recently, Venturi & Breschi (2005) compared *in vivo* the alternating current Apex Finder (Endo Analyzer 8001; Analytic Technology, Redmond, WA, USA) with the multifrequency based Root ZX. They reported that the Root ZX, more frequently than the Apex Finder, did not provide stable measurements in some stages of canal preparation, especially when the canal contents were of low conductivity, but in some cases also with NaOCl inside the root canals.

The aim of this *ex vivo* study was to compare the Apex Finder and the Root ZX in canals with and without irrigant and different foramen diameters. The null hypothesis tested was that the two EALs produced different results under the same experimental conditions.

Materials and methods

Selection of teeth

Sixty extracted teeth that had not been root filled were selected. A standardized radiograph was exposed for each tooth in buccolingual projection to allow proper selection. The teeth did not contain metallic restorations and the roots were not resorbed, fractured or had open apices. The specimens included eight maxillary lateral incisors, 30 disto-buccal roots of maxillary first molars, and 22 mandibular incisors, to give a total of 60 canals.

The teeth were extracted and immersed in 2.5% NaOCl for 10 min, then root planed with curettes (Hu-Friedy Mfg. Co., Chicago, IL, USA). After a short rinse in tap water, the teeth were stored in 0.9% sterile NaCl solution.

Teeth preparation

All teeth were treated by the same operator using ×4.3 magnification (Zeiss telescopes, Carl Zeiss Jena GmbH, Zeiss Group, Jena, Germany). The cusps were flattened with a tapered diamond bur in a high-speed handpiece under water irrigation to create a stable reference point. A conventional endodontic access cavity was prepared in all teeth.

Canal patency was assessed using a size 0.6 stainless steel K-file (F.K.G. Dentaire, La Chaux-de-Fonds, Switzerland) inserted into each root canal before instrumentation and irrigation of the canal system. Coronal flaring of the canal was performed using stainless steel Hedström files sizes 8 and 10 (F.K.G. Dentaire). A size 10, 0.04 taper NiTi Mtwo (Sweden & Martina, Due Carrare, Padova, Italy) rotating instrument was used for preliminary enlargement of the most narrow canals. Then ProFile.04 taper rotary NiTi instruments, sizes 15–40 (Dentsply Maillefer) were used to obtain four groups of 10 roots having apical canal diameters of 0.15, 0.20, 0.30 or 0.40 mm. The remaining two groups of ten roots were instrumented to have apical canal diameters of 0.60 and 0.80 mm using stainless steel hand K-files (F.K.G. Dentaire) sizes 60 and 80. The diameters of the apical canal preparations were controlled through stereomicroscopic observation. Lubrication was provided with RC-Prep (Hawe Neos Dental, Bioggio, Switzerland) and canals were irrigated with 5% NaOCl solution. During canal instrumentation apical patency was maintained with a size 06 K-file (F.K.G. Dentaire) through the foramen. During the preparation phase the apical third of the canals was enlarged, to remove the anatomic constriction and transport the minor diameter to the external root surface.

At the end of instrumentation, a size 15 K-file was advanced into the canal until its tip was observed to reach the foramen under ×10 magnification with a stereomicroscope (Zeiss Stemi 2000-C, Carl Zeiss GmbH). The silicone stopper on the file was set to the flat anatomical tooth landmark, the file was removed and the distance between the stopper and the file tip, corresponding to the actual length, was measured to an accuracy of 0.25 mm, i.e. using 0.25 mm as a base unit of length.

A glass container was filled with sterile 0.9% NaCl solution and the roots of each group, with equal apical diameter, were fixed to a plastic bar using acrylic resin. The *ex vivo* measurements were performed in each root canal with both the Root ZX and the Apex Finder. With each EAL, an electrode was connected to a K-file inserted into the root canal having a size just smaller than the K-file that engaged the apex; the other electrode was immersed into the saline solution.

Measurements with the Root ZX and the Apex Finder locators were made with the K-file at the foramen (0.00), and 0.5, 1.0, 1.5, 2.0 mm short of the apex. F corresponded to a measurement beyond the foramen. Before insertion, the distance between the rubber stopper and the file tip, corresponding to each distance to the apex, was adjusted using a graduated ruler and measured under ×10 magnification. The accuracy was again 0.25 mm.

Under ×10 magnification, each file was inserted and advanced into the canal until the silicone stopper was set to the flat anatomical tooth landmark. The experimental protocol was that used by Huang (1987), and the roots were suspended so that (Fig. 1):

(1) the apex touched lightly the surface of the saline solution; the root canal remained dry;
(2) the most apical 3 mm of the root were immersed into the saline solution; the root canal remained dry;
(3) the apex touched lightly the surface of the saline solution; the root canal was filled with saline solution;
(4) the most apical 3 mm of the root were immersed into the saline solution; the root canal was filled with saline solution using a syringe with a 30-gauge needle (KerrHawe SA, Bioggio, Switzerland).

To evaluate the accuracy of both EALs the actual length was subtracted from the electronically determined distance, reading it on the EAL display and recording the results in tabular form as positive (for

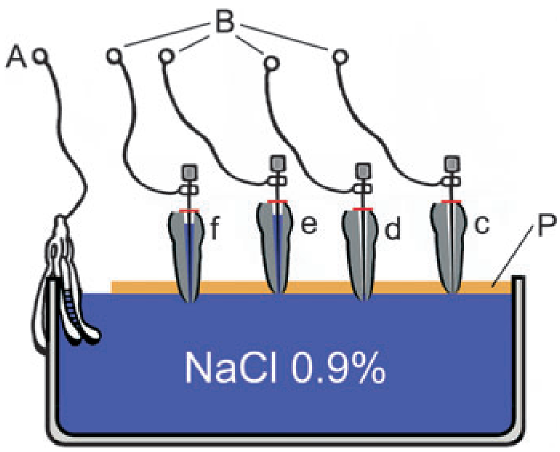

Figure 1 (A) Electrode immersed into the saline solution; (B) electrode connected to a K-file inserted into the root canal; (P) plastic bar supporting the teeth fixed with acrylic resin; (c) the apex touched lightly the surface of the saline solution and the root canal was dry; (d) the most apical 3 mm of the root were immersed into the saline solution and the root canal was dry; (e) the apex touched lightly the surface of the saline solution and the root canal was filled with saline solution; (f) the most apical 3 mm of the root were immersed into the saline solution and the root canal was filled with saline solution.

measurements exceeding the known length), negative (measurements short of the known length), or correct (measurement coinciding with the known length).

The data were analysed statistically with the General Linear Model (*P*-value set at 0.05). The General Linear Model allowed the statistical analysis of the influence of the endodontic parameters [apex diameter, condition of the apex (touching the surface of the saline solution, or immersed 3 mm into it)], condition of the canal (dry or not), and real distance to the foramen of the file tip on the precision of the EALs measurements, calculated as the difference between each EAL measurement and the measurement under the stereomicroscope of the actual length. First, the accuracy of all the measurements in the most apical 2 mm, then the accuracy of only the measurements in the most apical 1 mm were statistically analysed. They were analysed separately to determine whether there was a significant statistical difference when the comparisons were performed on only a part of the variables within the groups.

The analyses investigated the influence of each single parameter as well their combination, thus revealing multiple parameter effects. The Student *t*-test was used to compare the data obtained with the two EALs (*P*-value was set at 0.025).

Results

Mean and standard deviations of the accuracy of the measurements with the two EALs in the most apical 2 mm are shown in Tables 1–5. Mean and standard deviations of the accuracy of the two EALs in the most apical 1 mm are shown in Table 6. The significant differences ($P \leq 0.025$) found in the various conditions are also reported.

In two situations a comparison of the accuracy of the two EALs was impossible. A total of 100 of 2400 measurements, all with the Root ZX (Table 7) were unstable electrically and no measurement was possible. This happened, in general, in low conductive

Table 1 Mean and standard deviation of the accuracy of the measurements with the two EALs in the most apical 2 mm. Real distance to the apex 0.0 mm

Real distance to the apex	Apex diameter	Apex versus solution	Canal content	Root ZX Mean	Root ZX SD	Apex Finder Mean	Apex Finder SD	*P*-value	Comments
0.00	0.15	Touching	Dry	0.00	–	0.00	–	–	All the measurements corresponded to the working length
0.00	0.15	Touching	Wet	0.00	–	0.00	–	–	
0.00	0.15	Immersed	Dry	0.00	–	0.00	–	–	
0.00	0.15	Immersed	Wet	0.00	–	0.00	–	–	
0.00	0.20	Touching	Dry	0.00	–	0.00	–	–	
0.00	0.20	Touching	Wet	F	–	0.00	–	–	All the measurements of the Root ZX were beyond the foramen (F), whilst all the measurements of the Apex Finder were accurate
0.00	0.20	Immersed	Dry	F	–	0.00	–	–	
0.00	0.20	Immersed	Wet	F	–	0.00	–	–	
0.00	0.25	Touching	Dry	F	–	0.00	–	–	
0.00	0.25	Touching	Wet	F	–	0.00	–	–	
0.00	0.25	Immersed	Dry	F	–	0.00	–	–	
0.00	0.25	Immersed	Wet	F	–	0.00	–	–	
0.00	0.40	Touching	Dry	F	–	F	–	–	All the measurements of the EALs were beyond the foramen (F)
0.00	0.40	Touching	Wet	F	–	F	–	–	
0.00	0.40	Immersed	Dry	F	–	F	–	–	
0.00	0.40	Immersed	Wet	F	–	F	–	–	
0.00	0.60	Touching	Dry	F	–	F	–	–	
0.00	0.60	Touching	Wet	F	–	F	–	–	
0.00	0.60	Immersed	Dry	F	–	0.00	–	–	All the measurements of the Root ZX were beyond the foramen (F), whilst all the measurements of the Apex Finder were accurate
0.00	0.60	Immersed	Wet	F	–	F	–	–	All the measurements of the EALs were beyond the foramen (F)
0.00	0.80	Touching	Dry	F	–	F	–	–	
0.00	0.80	Touching	Wet	F	–	F	–	–	
0.00	0.80	Immersed	Dry	F	–	F	–	–	
0.00	0.80	Immersed	Wet	F	–	F	–	–	

Table 2 Mean and standard deviation of the accuracy of the measurements with the two EALs in the most apical 2 mm. Real distance to the apex 0.5 mm. The background is grey when there is a significant difference ($P \leq 0.025$)

Real distance to the apex	Apex diameter	Apex versus solution	Canal content	Root ZX		Apex Finder		*P*-value	Comments
				Mean	SD	Mean	SD		
0.50	0.15	Touching	Dry	+1.70	0.23	+2.10	0.59	0.0091	The Root ZX was more accurate
0.50	0.15	Touching	Wet	+2.70	0.26	+2.10	0.42	0.1762	
0.50	0.15	Immersed	Dry	+3.00	–	+2.50	0.30		Variable results without significative difference were found
0.50	0.15	Immersed	Wet	+2.60	0.25	+2.90	0.24	0.9167	
0.50	0.20	Touching	Dry	+2.20	0.31	+0.30	0.11	0.0040	The Apex Finder showed better accuracy
0.50	0.20	Touching	Wet	−0.50	–	+0.30	0.09		The Root ZX always measured −0.5, whilst the Apex Finder provided variable results
0.50	0.20	Immersed	Dry	−0.50	–	+0.90	0.12		
0.50	0.20	Immersed	Wet	−0.50	–	+1.20	0.15		
0.50	0.25	Touching	Dry	−0.50	–	−0.10	0.31		
0.50	0.25	Touching	Wet	−0.50	–	−0.10	0.57		
0.50	0.25	Immersed	Dry	−0.50	–	−0.00	0.17		
0.50	0.25	Immersed	Wet	−0.50	–	−0.20	0.08		
0.50	0.40	Touching	Dry	−0.50	–	+0.10	1.18		
0.50	0.40	Touching	Wet	−0.50	–	F	–		Each EAL always provided the same value. The Root ZX provided mean value of −0,5 whilst all the measurements of the Apex Finder were wrongly beyond the apex (F)
0.50	0.40	Immersed	Dry	−0.50	–	F	–		
0.50	0.40	Immersed	Wet	−0.50	–	F	–		
0.50	0.60	Touching	Dry	−0.50	–	−0.50	–		All the EALs measurements were equal to −0.5
0.50	0.60	Touching	Wet	−0.50	–	−0.50	–		
0.50	0.60	Immersed	Dry	−0.50	–	+0.20	0.15		The Root ZX always gave −0.5, thus it was not possible a comparison
0.50	0.60	Immersed	Wet	−0.50	–	−0.50	–		All the EALs measurements were equal to −0.5
0.50	0.80	Touching	Dry	−0.50	–	−0.50	–		
0.50	0.80	Touching	Wet	−0.50	–	F	–		Each EAL always provided the same value The Root ZX provided mean value of −0.5 whilst all the measurements of the Apex Finder were wrongly beyond the apex (F)
0.50	0.80	Immersed	Dry	−0.50	–	F	–		
0.50	0.80	Immersed	Wet	−0.50	–	F	–		

conditions (with canal dry, with apical diameter <0.40 mm, with the file tip 1 mm or more short to the foramen).

Moreover, 521 of the 2400 measurements of the two EALs indicated that the file tip was beyond the foramen. With the file tip 0.5 mm or more from the foramen, this happened only with the Apex Finder (in high conductive conditions, i.e. with apical diameter of 0.80 mm and canal irrigated). With the file tip at the foramen this happened in all the experimental groups with the Root ZX (except with apical diameter of 0.15 mm, and in one group with apical diameter of 0.20 mm), and with the Apex Finder when the apical diameter was wider than 0.40 mm.

The apical canal diameter ($P \leq 0.025$), the specific EAL ($P \leq 0.025$), and the distance of the file tip to the apex ($P \leq 0.025$), when evaluated separately, significantly affected the accuracy of the measurements in the most apical 2 mm. Moreover, several interactions also affected the accuracy of the EAL measurements in the most apical 2 mm (always $P \leq 0.025$): those between the EAL and all the other factors; between the apex diameter and all the other factors; between the EAL, the apex diameter and the condition of the apex; between

Table 3 Mean and standard deviation of the accuracy of the measurements with the two EALs in the most apical 2 mm. Real distance to the apex 1.0 mm. The background is grey when there is a significant difference ($P \leq 0.025$)

Real distance to the apex	Apex diameter	Apex versus solution	Canal content	Root ZX Mean	Root ZX SD	Apex Finder Mean	Apex Finder SD	*P*-value	Comments
1.00	0.15	Touching	Dry	–	–	+2.30	0.18		The Root ZX did not provide stable measurements
1.00	0.15	Touching	Wet	+2.50	–	+2.20	0.50		The Root ZX always gave +2.5
1.00	0.15	Immersed	Dry	+2.50	–	+2.60	0.40		
1.00	0.15	Immersed	Wet	+2.50	–	+2.50	0.37		
1.00	0.20	Touching	Dry	–	–	+0.30	0.18		The Root ZX did not provide stable measurements
1.00	0.20	Touching	Wet	+1.03	0.12	+0.50	0.13	0.07997	
1.00	0.20	Immersed	Dry	−0.80	0.07	+1.10	0.11	0.2372	
1.00	0.20	Immersed	Wet	+0.30	0.24	+1.10	0.14	0.1601	
1.00	0.25	Touching	Dry	+1.60	0.23	−0.10	0.08	0.0059	The Apex Finder showed better accuracy
1.00	0.25	Touching	Wet	+1.00	0.19	+0.10	1.72	0.0001	The Apex Finder showed better accuracy
1.00	0.25	Immersed	Dry	+0.70	0.14	+0.10	0.14	1.0000	
1.00	0.25	Immersed	Wet	+0.70	0.12	−0.40	0.09	0.5069	
1.00	0.40	Touching	Dry	+0.20	0.10	+0.20	2.04	0.0001	The Root ZX showed better accuracy
1.00	0.40	Touching	Wet	+0.20	0.10	F	–		All the measurements of the Apex Finder were wrongly beyond the apex (F)
1.00	0.40	Immersed	Dry	+0.10	0.15	F	–		
1.00	0.40	Immersed	Wet	0.00	0.28	F	–		
1.00	0.60	Touching	Dry	+0.10	0.12	−0.90	0.05	0.0225	The Root ZX showed better accuracy
1.00	0.60	Touching	Wet	+0.80	0.16	−0.65	0.05	0.0023	The Apex Finder showed better accuracy
1.00	0.60	Immersed	Dry	−0.10	0.12	+0.30	0.12	0.8647	
1.00	0.60	Immersed	Wet	+0.10	0.13	−0.90	0.04	0.0031	The Root ZX showed better accuracy
1.00	0.80	Touching	Dry	+1.00	0.20	−0.70	0.09	0.0276	
1.00	0.80	Touching	Wet	+0.30	0.24	−1.00	–		The Apex Finder always gave −1
1.00	0.80	Immersed	Dry	+0.50	0.14	F	–		All the measurements of the Apex Finder were wrongly beyond the apex (F)
1.00	0.80	Immersed	Wet	+0.80	0.19	F	–		

the EAL, the apex diameter and the condition of the canal; between the condition of the apex, the apex diameter and the condition of the canal; between all the five factors. The effects of these interactions are complex and are shown in detail in Tables 1–5.

In the most apical 1 mm the accuracy of the EALs was evaluated in relation to the real distance of the file tip to the apex, in relation to the apex diameter, in relation to the condition of the apex, and finally to the condition of the canal.

Considering the real distance to the apex, no significant difference of accuracy was found between the EALs when the file tip was at the apical foramen (Root ZX mean +0.12 mm, SD 1.22 mm; Apex Finder mean +0.57 mm, SD 1.16 mm), or 1 mm short to the apex (Root ZX mean +1.60 mm, SD 1.26 mm; Apex Finder mean +1.61 mm, SD 1.21 mm). A significant difference ($P \leq 0.025$) was found when the file tip was 0.5 mm from the apex (Root ZX mean +0.74 mm, SD 0.86 mm; Apex Finder mean +0.46 mm, SD 1.32 mm).

No significant difference of accuracy was found by varying the conditions of the apex or the conditions of the canals. The diameters of the apices affected the accuracy of the EALs with complicated effects that are difficult to summarize, as shown in Table 6.

Discussion

Because of the presence of unstable measurements, some groups had incomplete data and the ANOVA test was not applicable. For this reason, the statistical analysis was performed with the General Linear Model that can be

Table 4 Mean and standard deviation of the accuracy of the measurements with the two EALs in the most apical 2 mm. Real distance to the apex 1.5 mm. The background is grey when there is a significant difference ($P \leq 0.025$)

Real distance to the apex	Apex diameter	Apex versus solution	Canal content	Root ZX		Apex Finder			
				Mean	SD	Mean	SD	*P*-value	Comments
1.50	0.15	Touching	Dry	–	–	+2.50	0.10		The Root ZX does not provide stable measurements
1.50	0.15	Touching	Wet	+2.00	–	+1.90	0.24		The Root ZX always gave +2
1.50	0.15	Immersed	Dry	–	–	+2.30	0.33		The Root ZX does not provide stable measurements
1.50	0.15	Immersed	Wet	+2.00	0	+2.20	0.43		The Root ZX always gave +2
1.50	0.20	Touching	Dry	–	–	+0.20	0.13		The Root ZX does not provide stable measurements
1.50	0.20	Touching	Wet	+0.80	0.23	+0.60	0.18	0.5242	
1.50	0.20	Immersed	Dry	−0.00	0.14	+0.90	0.16	0.5931	
1.50	0.20	Immersed	Wet	+1.30	0.16	+1.30	1.19	0.5902	
1.50	0.25	Touching	Dry	–	–	−0.10	0.09		The Root ZX did not provide stable measurements
1.50	0.25	Touching	Wet	+1.30	0.15	−0.40	0.07	0.0316	
1.50	0.25	Immersed	Dry	+1.20	0.10	+0.20	0.14	0.4206	
1.50	0.25	Immersed	Wet	+0.70	0.14	0.00	0.12	0.6053	
1.50	0.40	Touching	Dry	+0.70	0.12	−0.70	0.27	0.0306	
1.50	0.40	Touching	Wet	+0.08	0.11	−1.50	–		The Apex Finder always gave −1.5
1.50	0.40	Immersed	Dry	+0.10	0.16	−1.50	–		
1.50	0.40	Immersed	Wet	+0.10	0.15	−1.50	–		
1.50	0.60	Touching	Dry	+0.20	0.11	−1.20	0.08	0.3871	
1.50	0.60	Touching	Wet	+1.10	0.15	−0.80	0.12	0.4280	
1.50	0.60	Immersed	Dry	−0.30	0.14	+0.30	0.10	0.2428	
1.50	0.60	Immersed	Wet	+0.50	0.21	−1.20	0.07	0.044	The Root ZX showed better accuracy
1.50	0.80	Touching	Dry	+1.00	0.19	−0.80	0.17	0.7284	
1.50	0.80	Touching	Wet	+0.70	0.22	−1.20	0.10	0.0297	
1.50	0.80	Immersed	Dry	+0.70	0.20	F	–		All the measurements of the Apex Finder were wrongly beyond the apex (F)
1.50	0.80	Immersed	Wet	+1.00	0.30	−1.70	0.38	0.0007	The Root ZX showed better accuracy

used to analyse groups having different numbers of independent identically distributed variables.

Several factors have been reported to affect the accuracy of EALs *in vivo*: presence of conductive solutions inside the root canal (Huang 1987, Meredith & Gulabivala 1997, Križaj *et al.* 2004), periapical pathosis (Abbott 1987), diameter of apical foramen (Stein *et al.* 1990, Fouad *et al.* 1993), shape and volume of the measuring probe (Vachy *et al.* 1985), operator ability (De Moor *et al.* 1999). Laboratory-based studies have allowed the evaluation of some of these factors (Križaj *et al.* 2004). Various laboratory models have been suggested: immersion in agar solutions or gels (Aurelio *et al.* 1983, Czerw *et al.* 1995), or in saline solutions (Huang 1987); embedding in alginate (Katz *et al.* 1991), or in a sponge soaked with saline solution (Goldberg *et al.* 2002). In the present study, a 0.9% solution of NaCl was used according to Kobayashi & Suda (1994) to obtain a good contact with the K-file. The electrode–electrolyte interface impedance when the electrolyte is a biological tissue is similar to 0.9% NaCl, and this solution has become a benchmark since its ionic content is equivalent to that of blood plasma (Pallas-Areny & Webster 1993).

Nguyen *et al.* (1996) reported that the apical constriction could be identified with the Root ZX even when this anatomic landmark had been eliminated. Moreover, Lee *et al.* (2002) found that most of the file tips ended at the major foramen regardless of the existence of a detectable CDJ, suggesting that the major foramen was more reproducible, for accuracy studies, compared with the CDJ. Thus, in the present study, the apical constriction was eliminated and the minor diameter was transported to the outer apical surface, to avoid

Table 5 Mean and standard deviation of the accuracy of the measurements with the two EALs in the most apical 2 mm. Real distance to the apex 2.0 mm. The background is grey when there is a significant difference ($P \leq 0.025$)

Real distance to the apex	Apex diameter	Apex versus solution	Canal content	Root ZX Mean	Root ZX SD	Apex Finder Mean	Apex Finder SD	*P*-value	Comments
2.00	0.15	Touching	Dry	–	–	+2.20	0.17		The Root ZX did not provide stable measurements
2.00	0.15	Touching	Wet	+1.50	–	+1.70	0.12		The Root ZX always gave +1.5
2.00	0.15	Immersed	Dry	–	–	+1.80	0.12		The Root ZX did not provide stable measurements
2.00	0.15	Immersed	Wet	+1.50	–	+1.50	0.34		The Root ZX always gave +1.5
2.00	0.20	Touching	Dry	–	–	+0.60	0.18		The Root ZX did not provide stable measurements
2.00	0.20	Touching	Wet	+0.40	0.24	+0.50	0.12	0.0371	
2.00	0.20	Immersed	Dry	+1.30	0.26	+1.20	0.18	0.2873	
2.00	0.20	Immersed	Wet	+1.30	0.24	+1.30	0.13	0.0851	
2.00	0.25	Touching	Dry	–	–	+0.20	0.23		The Root ZX did not provide stable measurements
2.00	0.25	Touching	Wet	+1.40	0.16	−0.60	0.13	0.6515	
2.00	0.25	Immersed	Dry	+1.20	0.32	+1.20	0.17	0.0797	
2.00	0.25	Immersed	Wet	+1.40	0.16	−1.30	0.12	0.4972	
2.00	0.40	Touching	Dry	+0.70	0.16	−0.50	0.19	0.6504	
2.00	0.40	Touching	Wet	+1.50	0.16	−1.70	0.13	0.5335	
2.00	0.40	Immersed	Dry	−0.20	0.15	−1.90	0.07	0.0085	The Root ZX showed better accuracy
2.00	0.40	Immersed	Wet	+2.10	0.22	−1.90	0.14	0.1992	
2.00	0.60	Touching	Dry	+1.60	0.17	−1.50	0.07	0.0195	
2.00	0.60	Touching	Wet	+1.05	0.26	−0.90	0.15	0.1168	
2.00	0.60	Immersed	Dry	−0.20	0.09	+0.20	0.15	0.1636	
2.00	0.60	Immersed	Wet	+1.70	0.18	−1.40	0.10	0.0799	
2.00	0.80	Touching	Dry	+1.30	0.29	−1.50	0.19	0.2047	
2.00	0.80	Touching	Wet	+1.40	0.16	−1.50	0.08	0.0785	
2.00	0.80	Immersed	Dry	+1.30	0.27	F	–		All the measurements of the Apex Finder were wrongly beyond the apex (F)
2.00	0.80	Immersed	Wet	+1.30	0.27	−1.50	0.19	0.0281	

differences of apical morphology between the specimens. Under these conditions, no significant difference was found between the two EALs when the file tip was at the actual working length (mean values: +0.12 mm with Root ZX, and +0.57 mm with Apex Finder).

The accuracy of the two EALs was evaluated with different foramen diameters, by varying the distance of the file tip from the apex, with and without the immersion of the most apical 3 mm of the roots in saline solution, and with and without saline solution within the root canals. The statistical analysis demonstrated that the accuracy of the measurements was affected primarily, rather than by variations of a single parameter, but by many interactions between them.

The EALs provided 521 of 2400 (21.7%) incorrect measurements that exceeded the apical foramen. The Apex Finder provided these errors in wet canals with both suspended and immersed apices, or in dry canals with immersed apices and large diameters, i.e. in high conductive conditions as would be expected with this type of EAL (Huang 1987). In contrast, the Root ZX produced similar measurement errors mainly with small foramina, or apices suspended over the solution and dry canals. The Root ZX gave consistently accurate recordings of −0.5 mm when the file tip was placed 0.5 mm short of the foramen for apical sizes 20 upwards. These results are not surprising, for the Root ZX has been developed to function in conditions of high conductivity (Kobayashi & Suda 1994).

It has been claimed that wide apical diameters might affect the accuracy of EAL measurements (Huang 1987, Kovacevic & Tamarut 1998). In the present

Table 6 Mean and standard deviation of the accuracy of the two EALs considering only the measurements in the most apical 1 mm. The background is grey when there is a significant difference ($P \leq 0.025$)

Apex diameter	Apex versus solution	Canal content	Root ZX Mean	Root ZX SD	Apex Finder Mean	Apex Finder SD	*P*-value	Comments
0.15	Touching	Dry	+0.85	0.88	+1.48	1.12	0.2885	
0.15	Touching	Wet	+1.75	1.27	+1.45	1.10	0.4541	
0.15	Immersed	Dry	+1.83	1.33	+1.70	1.25	0.7407	
0.15	Immersed	Wet	+1.71	1.24	+1.83	1.35	0.6550	
0.20	Touching	Dry	+1.09	1.14	+0.18	0.18	0.0000	The Apex Finder showed better accuracy
0.20	Touching	Wet	+0.26	0.79	+0.27	0.24	0.3314	
0.20	Immersed	Dry	−0.63	0.14	+0.66	0.49	0.0000	The Root ZX showed better accuracy
0.20	Immersed	Wet	−0.08	0.46	+0.77	0.57	0.0000	The Root ZX showed better accuracy
0.25	Touching	Dry	+0.53	1.07	−0.07	0.19	0.0000	The Apex Finder showed better accuracy
0.25	Touching	Wet	+0.26	0.79	0.00	1.01	0.2700	
0.25	Immersed	Dry	+0.09	0.61	+0.02	0.12	0.0000	The Apex Finder showed better accuracy
0.25	Immersed	Wet	+0.10	0.22	−0.29	0.37	0.0000	The Root ZX showed better accuracy
0.40	Touching	Dry	−0.26	0.35	+0.11	0.34	0.0000	The Apex Finder showed better accuracy
0.40	Touching	Wet	−0.14	0.37	F	–		All the measurements of the
0.40	Immersed	Dry	−0.21	0.31	F	–		Apex Finder were wrongly
0.40	Immersed	Wet	−0.26	0.31	F	–		beyond the apex (F)
0.60	Touching	Dry	−0.18	0.34	−0.68	0.19	0.0140	The Root ZX showed better accuracy
0.60	Touching	Wet	+0.13	0.26	−0.57	0.28	0.0000	The Root ZX showed better accuracy
0.60	Immersed	Dry	−0.29	0.23	+0.15	0.16	0.0578	
0.60	Immersed	Wet	−0.18	0.34	+0.69	0.20	0.0221	The Root ZX showed better accuracy
0.80	Touching	Dry	+0.24	0.78	−0.61	0.13	0.0000	The Root ZX showed better accuracy
0.80	Touching	Wet	−0.10	0.46	−1.00	–		The Apex Finder always gave the same measurement value
0.80	Immersed	Dry	0.00	0.51	F	–		All the measurements of the
0.80	Immersed	Wet	+0.17	0.71	F	–		Apex Finder were wrongly beyond the apex (F)

study, variations in the diameter did influence the EAL measurements, but without a clear relationship: when the foramen was 0.20 and 0.80 mm, the measurement errors were greater with the Apex Finder; when the foramen was 0.25 and 0.40 mm the measurement errors were greater with the Root ZX.

Since in two groups the most apical 3 mm of the root were immersed into the saline solution, the capillary action of saline has to be taken into account as a potential cause of measurement error. Capillarity is observed when water rises in narrow tubes (capillaries): the narrower the tube, the higher the rise. Capillarity is caused by relative difference in adhesion of liquid to solid and cohesion among liquid molecules. If the former is larger than the latter, capillary rise would occur. When water is considered, the rise within a glass pipe can be calculated with the formula $h = 0.30/d$, where h is the height of water column depending on capillarity and r is the diameter of the tube. With the 0.9% NaCl solution used in this study, if the root canal is cylindric, the rise can be calculated to be from 0.36 mm (with diameter of the foramen equal to 0.80 mm) up to 2.00 mm (with diameter of the foramen equal to 0.15 mm). It should be investigated

Table 7 Unstable measurements. Under the conditions reported there was no possibility to obtain a stable definite value

Real distance to the apex	Apex diameter	Apex versus solution	Canal content	Root ZX Mean	Root ZX SD	Apex Finder Mean	Apex Finder SD	*P*-value	Comments
1.00	0.15	Touching	Dry	–	–	+2.30	0.18	–	The Root ZX did not provide stable measurements
1.00	0.20	Touching	Dry	–	–	+0.30	0.18	–	The Root ZX did not provide stable measurements
1.50	0.15	Touching	Dry	–	–	+2.50	0.10	–	The Root ZX did not provide stable measurements
1.50	0.15	Immersed	Dry	–	–	+2.30	0.33	–	The Root ZX did not provide stable measurements
1.50	0.20	Touching	Dry	–	–	+0.20	0.13	–	The Root ZX did not provide stable measurements
1.50	0.25	Touching	Dry	–	–	−0.10	0.09	–	The Root ZX did not provide stable measurements
2.00	0.15	Touching	Dry	–	–	+2.20	0.17	–	The Root ZX did not provide stable measurements
2.00	0.15	Immersed	Dry	–	–	+1.80	0.12	–	The Root ZX did not provide stable measurements
2.00	0.20	Touching	Dry	–	–	+0.60	0.18	–	The Root ZX did not provide stable measurements
2.00	0.25	Touching	Dry	–	–	+0.20	0.23	–	The Root ZX did not provide stable measurements

whether the 0.04 taper shape might slightly reduce this effect, as well as whether the adhesion either of saline to dentine or of water to glass might give different results.

The diameter of the apex is not the only anatomical characteristic in the apical third of the root canal affecting the impedance measurements. Križaj *et al.* (2004) reported that when the diameter of the canal at the apical foramen is small, approximately 0.2 mm, the resistance of the canal from the apical foramen to the file tip is increased and a part of the current might flow through the dentine (Križaj *et al.* 2004). The reduction of impedance due to current flow directly through the dentine could reduce the accuracy of determining the canal length (Križaj *et al.* 2004). It was also suggested that electrical parameters of a tooth change with age (Tagami *et al.* 1992).

The distance of the file tip from the foramen affected the accuracy of measurements with both EALs. According to previous reports (Kobayashi & Suda 1994, Pilot & Pitts 1997) the accuracy increased as the file tip approached the foramen. The Apex Finder provided stable measurements also when the file tip was retracted 1–2 mm from the apex, although with decreasing accuracy and only under conditions of low conductivity. With saline inside the root canals the Apex Finder frequently did not function adequately when the diameters of the apices were ≥0.4 mm. In contrast, the Root ZX seemed to detect changes of impedance when the canals were filled with saline, but mostly when the probe tip was close to the apex. Križaj *et al.* (2004) reported that the advantage of multifrequency methods for exact determination of the root canal length, by taking the ratio between impedances measured (or simulated) at two (or more) frequencies, cannot be applied for determination of the distance from the tip of the file to the apical foramen, since the plots of ratios were not linear and more difficult to predict.

It has been reported that increased dentine conductivity and decreased solution conductivity both enhance the efficacy of the impedance method for determination of the root canal length, and that the precision of the method is improved in a dry canal (Pilot & Pitts 1997, Križaj *et al.* 2004). However, the third generation EALs have been developed to function with conductive solutions inside the root canal, i.e. in the conditions that frequently caused measurement errors with the 'resistance-based' EALs (Ushiyama 1983, Huang 1987, Kobayashi & Suda 1994, Meredith & Gulabivala 1997, Nekoofar *et al.* 2006).

Indeed, it is crucial to understand the different problems resulting from measuring reactive rather than resistive components. EALs such as the Apex Finder basically perform resistance measurements, aimed to reveal the variation in electrical circuit resistance that occurs as the file approaches the apical constriction. The Root ZX operates at frequencies of 8 and 400 Hz. The ratio between the two frequencies should have a definite value, indicating the location of the file tip in the canal even when it is full of conductive solutions. The Root-ZX performs impedance measurements mainly aimed to detect capacitance variations (Kobayashi & Suda 1994). But Meredith & Gulabivala (1997) found no relation between the capacitive components and the root canal length. They found that the series resistances were the main component of the complex impedance of root canals.

The impedance of a geometrical system, in this case the tooth and the surrounding environment, is related to conductor length and geometrical size, its cross-sectional area and signal frequency (Nyboer 1972). At low frequencies (<1000 Hz) most of what is being measured is the ionic fluid properties, which are primarily conductance values, whilst at higher frequencies permittivity, and thus capacitance, forms a larger portion of the electrical impedance measured (Hope & Iles 2004). Capacitance is a parameter that is related to both the electrical properties of the materials involved in the system and the system geometry itself, and may be easily affected by their modifications.

In the present study, 100 unstable measurements (4.2% of 2400 measurements) were all experienced with the Root Zx and frequently appeared to be related to slight movements of the file tip inside the canal; this might have been due to geometric variations of the equivalent electrical circuit within the laboratory model during the measuring procedure. In a previous *in vivo* study (Venturi & Breschi 2005), the Root ZX and the Apex Finder gave a greater number of unstable measurements, 134 (20.9%) of a total of 640. The convenient homogeneity of electrode impedances found in electrolyte solutions does not exist in the case of living tissues and that has important implications concerning the accuracy of impedance measurement methods (Pallas-Areny & Webster 1993). It is reasonable to suppose that the EALs were more easily affected in the *in vivo* setting by changes of dielectric properties of the circuit. Venturi & Breschi (2005) also reported that with NaOCl inside the root-canals the Apex Finder gave almost all the unstable measurements, and in contrast that the Root ZX gave unstable measurements in a variety of different conditions very difficult to detect and understand.

In the present study K-files with different sizes were used. Nguyen *et al.* (1996) found that electronic working length determination was not influenced by the size of the measuring file used, whilst Vachy *et al.* (1985) reported opposite results. Once again, since the capacitance is affected by the electrical properties of the materials involved in the system, the Root ZX might have been influenced more than the Apex Finder by the sizes of the K-files used.

Conclusions

Under the different *ex vivo* conditions both EALs provided accurate measurements when the file tip was at the foramen. The accuracy of the Apex Finder was negatively influenced by high conductive conditions, whilst the Root ZX provided inaccurate and unstable measurements mostly in low conductive conditions. The conclusions of this study should be restricted to this particular laboratory methodology and the tested EALs. Data, such as the unstable measurements all recorded with the Root ZX locator, although less frequently observed in the present laboratory than in a previous *in vivo* study, suggest that the Root ZX might be influenced by different conditions very difficult to detect and understand.

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