International Endodontic Journal

doi:10.1111/j.1365-2591.2011.01855.x

Comparison of working length determination with radiographs and four electronic apex locators

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Abstract

Vieyra JP, Acosta J. Comparison of working length determination with radiographs and four electronic apex locators. *International Endodontic Journal*, **44**, 510–518, 2011.

Aim To evaluate the accuracy of the Root ZX, Elements-Diagnostic, Precision AL and Raypex 5 electronic apex locators when compared to radiographs for locating the apical constriction.

Methodology The apical constriction of 693 canals in 245 maxillary and mandibular teeth was located *in vivo* with four electronic apex locators (EALs) and radiographically. After extraction the actual location of the apical constriction was determined visually and with magnification. A paired samples *t*-test, X2 test and a repeated measure ANOVA at the 0.05 level of significance were used to determine differences between the groups.

Results For anterior teeth, the Root ZX, Elements, Precision AL, Raypex 5 and radiographs located the apical constriction 89.09%, 83.63%, 85.45%, 81.81% and 32.72% of the time, respectively. For premolar teeth, the Root ZX, Elements, Precision AL, Raypex 5 and radiographs located the apical constriction 75%, 61.60%, 64.28%, 61.60% and 32.14% of the time, respectively. For molar teeth, the Root ZX, Elements, Precision AL, Raypex 5 and radiographs located the apical constriction 69.01%, 50.49%, 65.40%, 43.93% and 14.59% of the time, respectively. There was no statistically significant difference between the four EALs ($P = 0.05$).

Conclusion Measuring the location of the apical constriction using the four apex locators was more accurate than radiographs and would reduce the risk of instrumenting and filling beyond the apical foramen.

Keywords: apical constriction, electronic apex locator, working length determination.

Received 29 October 2010; accepted 1 December 2010

Introduction

The removal of all pulp tissue, necrotic material and microorganisms from the root canal system is essential for success following root canal treatment. Root canal preparation and filling should not extend beyond the tooth root nor leave uninstrumented areas inside the root canal.

Anatomically, the apical constriction (Kuttler 1955), is a logical location for working length (WL) since it often coincides with the narrowest diameter of the root canal (AAE 2003). However, locating the apical constriction (AC) clinically is problematic. Dummer *et al.* (1984) concluded that it is impossible to locate the AC clinically with certainty because of its position and topography. The cementodentinal junction (CDJ) has also been suggested as the location for WL because it represents the transition between pulpal and periodontal tissue (Grove 1931). The location of the CDJ is widely accepted as being 0.50–0.75 mm coronal to the apical foramen (Ricucci & Langeland 1998) but, as with the AC, the exact location of the CDJ is impossible to identify clinically. In general, the CDJ is considered to be co-located with the minor foramen (AC) (Stein *et al.* 1990); however, this is not always the case (Dummer *et al.* 1984).

WL is defined as 'the distance from a coronal reference point to the point at which canal preparation and filling should terminate' (AAE 2003).

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Radiographic determination of WL has limitations such as distortion, shortening and elongation, interpretation variability and lack of three–dimensional representation. Even when a paralleling technique is used elongation of images has been found to be approximately 5% (Vande *et al*. 1969). Accurate determination of WL during root canal treatment is a challenge.

A WL 1 mm short of the radiographic apex may result in over or under instrumentation because of the variability in distance between the apical foramen and the radiographic apex (Gutiérrez & Aguayo 1995). Thus, this often used 'rule' is not predictable or reliable.

Methods of determining the WL include tactile sensation, knowledge of root canal lengths and anatomy, assessment of preoperative radiographs, and electronic apex locators (EALs) (Heo *et al.* 2008). Radiography has been considered as the traditional and most appropriate method of obtaining information on the anatomy of the root canal and its surrounding tissues (Bramante & Berbert 1974, Forsberg 1987).

Plain-film periapical radiographs are still essential aids for diagnosis, for working films (e.g. measuring the length of root canals, fitting gutta-percha cones), to verify the final fill, and for follow-up comparisons at recall examinations.

Custer (1918) was the first to determine WL electronically. Suzuki (1942) investigated the electrical resistance properties of oral tissues and developed the first electronic apex locator. The device was resistance-based and measured the resistance between two electrodes to determine the location of an instrument in the canal. Later devices were impedance-based (Nekoofar *et al.* 2006) and used multiple frequencies. More recently resistance and capacitance-based devices emerged that measure resistance and capacitance, directly and independently.

The Root ZX (J. Morita Co., Tokyo, Japan) uses the 'ratio method' to locate the minor foramen (AC) (Kobayashi & Suda 1994) by the simultaneous measurement of impedance using two frequencies. The Root ZX claims to work in the presence of electrolytes and nonelectrolytes and requires no calibration (Kobayashi 1995) and was able to measure in an *ex vivo* study the correct WL (±0.5 mm) in 97.37% of cases (Plotino *et al.* 2006).

The Elements-Diagnostic (SybronEndo, Sybron Dental, Orange, CA, USA) uses multiple frequencies, in an attempt to eliminate the influence of canal conditions and was able to determine the correct WL (±0.5 mm) in 94.28% (Plotino *et al.* 2006) or 82.19–85.62% (Briseño-Marroquín *et al.* 2008) of cases.

The Raypex 5 (VDW, Munich, Germany) was able to detect the correct WL (±0.5 mm) in 80–85.59% of cases (Briseño-Marroquín *et al.* 2008) and in 80% of all cases within the same limits (Wrbas *et al.* 2007).

The Precision Apex Locator (PAL) (Precision Apex Locator, Operation Manual. Brasseler USA, Savannah, GA, USA) is a new EAL whose accuracy has not been tested and reported in the literature to date.

Electronic apex locators have the potential to facilitate the recognition of the instrument inside the canal, allowing more precise *in vivo* determination of WL (Gordon & Chandler 2004).

Current EALs have a high reliability, high accuracy and high reproducibility in locating the major apical foramen regardless of the electrolyte (Jenkins *et al.* 2001).

In addition to improving WL accuracy (Nekoofar *et al.* 2006) EALS address concerns about radiation as they have the potential to reduce the number of radiographs taken during root canal treatment (Pagavino *et al.* 1998).

Modern EALs can locate the apical foramen and the AC with high precision, it is unclear how accurate these devices are as they approach the apical region and how precise the meter readings correlate with the file position. The precision of measurement might also depend on the file size and the dimensions of root canal and foramen.

The purpose of this study was to evaluate *in vivo* the accuracy and predictability of four EAL for determining WL as compared to radiographs: RootZX, Elements-Diagnostic Unit, The Raypex 5 and The PAL.

Materials and methods

Two hundred and forty-five teeth (693 canals) with fully formed apices and without apical resorption were used (Table 1). All teeth gave positive responses to hot and cold tests and were extracted for periodontal or

Table 1 Distribution of 245 teeth (693 canals)

		No. of canals	
	Tooth	Maxillary	Mandibular
Central Incisor	(17)	13	4
Lateral Incisor	(26)	21	5
Canine	(12)	9	3
Premolar	(28)	19	9
Molar	(162)	309	301
Total	245	371	322

prosthodontic reasons. Ethical approval for the study (obtained from Tijuana's School of Dentistry) and an informed consent was signed by the patients.

After local anaesthesia, rubber dam isolation and access cavity the canals were flared coronally with size 1 and 2 Orifice Shapers (Dentsply Tulsa Dental, Tulsa, OK, USA) using 3% sodium hypochlorite for irrigation. The final rinse was aspirated but no attempt was made to dry the canals. The AC of each tooth was located first with the four EALs and then radiographically.

The AC was located with the Root ZX according to the manufacturer's Operation Instructions (J. Morita Corp. 2005). A size 15 stainless steel K-file was advanced in the canal until the LCD showed a flashing bar between APEX and 0.5 with corresponding symbol and a flashing tooth with the audible signal indicating that the AC had been located. It is not necessary to set the device on zero before measuring each individual canal.

The microprocessor calibrates ROOT ZX automatically, preparing it ready to use immediately after turning on the main switch. No set up is required and no resetting is required for multiple measurements. Automatic calibration insures accuracy and eliminates the effects of changes in temperature, moisture inside the canal (J. Morita Corp. 2005).

Two silicone stoppers (two were used to prevent movement) on the file were positioned at the reference point. The file was removed from the canal and the length measured to the nearest 0.01 mm with a digital caliper (Fig. 1). This was the insertion length.

The AC was located with the Elements-Diagnostic EAL per the manufacturer's Instruction Guidelines (Sybron-Endo 2006). The same size 15 file used for the Root ZX was advanced in the canal to just beyond the foramen, as indicated by the '0.0' on the LCD display. The file was then withdrawn until the reading showed a consistent '0.5' with corresponding symbol and audible signal indicating that the AC had been reached. The stoppers were positioned at the reference point and the insertion length measured as described above.

The AC was located with the Raypex 5 when all three green bars were reached. According to manufacturer's instructions, then the insertion length was measured as above.

The AC was located with the PAL according to the manufacturer's Operation Manual (Brasseler USA 2006). The AC was located when the ''0.5'' mark was reached and a constant audible tone was heard. Then the insertion length was measured as above.

After the four EAL had located the AC on the same tooth with the same size 15 file the AC was located radiographically by advancing the file until its tip was thought to be 1.0 mm from the radiographic apex as estimated from the pretreatment radiograph. A radiograph was exposed and if the tip was not 1.0 mm from the radiographic apex the file was repositioned and another radiograph taken to ensure that it was. The file was removed and after the insertion length was measured it was re-inserted to this length (1 mm from the radiographic apex) and cemented in place with Fuji II LC dual-cure glass–ionomer cement (GC Corp., Tokyo, Japan). The file handle was removed with a high speed bur and after the tooth was extracted without disturbing the file, it was placed in 6% NaOCl for 20 min to clean the root surface and stored in a 1% Thymol solution. All clinical procedures were conducted by the principal investigator. The sequence

Figure 1 Digital caliper used in the present study. Apical view of tooth 25 under 20 × magnification.

Figure 2 Apical view of tooth 7 under 20 × magnification.

of use for the four EAL was varied between the teeth (Figs 2 and 3).

After the tooth was removed from the Thymol and with the file still cemented in place, the apical 5 mm of the root was ground parallel to the long axis of the canal with a fine diamond bur and abrasive discs. When the file became visible, additional dentine was removed, whilst viewing the process under 20 × magnification with an OPMI Pico microscope (Carl Zeiss, Munich, Germany) until the file tip and the apical foramen were in focus (Fig. 4).

Image tool 3.0 (Image Tool Software Copyright), UTHSCSA University of Texas Health Science Center San Antonio, USA, were use to complete the measurements. A digital photograph was taken and stored in Adobe Photoshop 5.5 (Adobe Systems Inc., San Jose, CA, USA) (Fig. 5).

The distance of the file tip from the AC (narrowest part of the canal) was measured and recorded as being −1.0 or −0.5 mm from the AC; at the AC, or +0.5 mm or +1.0 mm from the AC. A minus symbol (−) indicated a file short of the AC; A plus symbol (+) indicated it was through the AC. Since the insertion length was already known, the actual length to the AC was determined by adding or subtracting the distance of the file tip from the AC to the insertion length.

After the actual length (distance from reference point to the AC) was determined the distance of the file tip from the AC was calculated for the four EAL by comparing the insertion length with the actual length. The difference was recorded as −1.0 or −0.5 mm, etc., from the AC as shown in Tables 2–5.

The distances of the file tip from the AC obtained by the EAL and the distances obtained radiographically were compared using a paired samples *t*-test, chi-square test and a repeated measure ANOVA evaluation at the 0.05 level of significance.

Results

The percentage of measurements at the AC; 0.5 and 1.0 mm short of the AC; 0.5 and 1.0 mm through the AC was recorded as shown in Tables 6–9.

For anteriors, premolars and molars: no measurements were 1.0 mm short of the AC. For anteriors and premolars: No measurements were 0.5 mm short of the AC (Tables 5–8).

There was no statistically significant difference amongst the four EALS.

Discussion

The goal of this study was to evaluate *in vivo* the accuracy and predictability of the Root ZX, Elements-Diagnostic Unit, Raypex 5 and PALs for determining WL as compared to radiographs.

Figure 3 Position of the k file in the canal.

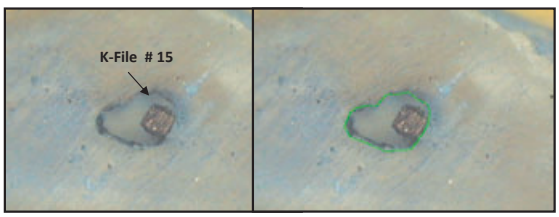

Figure 4 Using the software Image tool 3.0 (Image Tool Software Copyright), UTHSCSA.

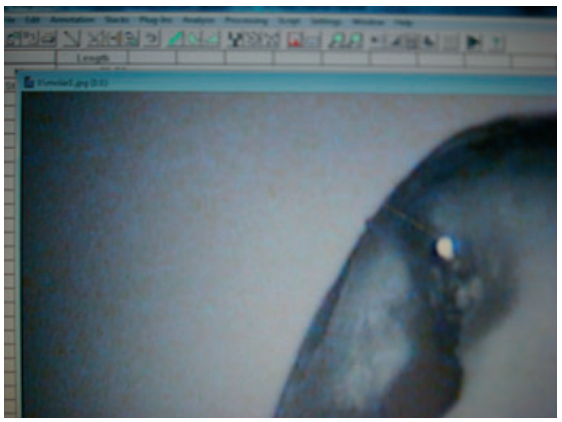

Figure 5 Using the software image tool 3.0 UTHSCSA. Digital caliper used in this study.

Table 2 Distance of file tip from the apical constriction determined by Root ZX, Elements, Precision AL, Raypex 5 and Radiograph (55 anterior teeth)

Group	-1.0 n = 55 (%) Variance Std. Deviation	-0.5 mm n = 55 (%) Variance Std. Deviation	AC n = 55 (%) Variance Std. Deviation	+0.5 mm n = 55 (%) Variance Std. Deviation	+1.0 mm n = 55 (%) Variance Std. Deviation
Root ZX	-	-	49 (89.09%) 0 .099/0.314	6 (10.90%) 0.100/0.340	-
Elements	-	-	46 (83.63%) 0 .139/0.373	9 (16.36%) 0.151/0.380	-
Precision A L	-	-	47 (85.45%) 0.127/0.355	8 (14.54%) 0.112/0.350	-
Raypex 5	-	-	45 (81.81%) 0.152/0.389	10 (18.18%) 0.152/0.390	-
Radiograph	-	-	18 (32.72%) 0.609/0.780	26 (47.27%) 0.810/0.94	11 (20%) 0.153/0.382

AC: Apical Constriction.
(+) and (–) values indicate file tip beyond (+) or short (–) of the AC.
p = 0.05.

Table 3 Distance of file tip from the apical constriction determined by Root ZX, Elements, Precison AL, Raypex 5 and Radiograph (28 premolars)

Distance from AC (mm)	Root ZX n = 28 (%) Variance Std. Deviation	Elements n = 28 (%) Variance Std. Deviation	Precison AL n = 28 (%) Variance Std. Deviation	Raypex 5 n = 28 (%) Variance Std. Deviation	Radiograph n = 28 (%) Variance Std. Deviation
–1.0	–	–	–	–	–
–0.5	–	–	–	–	–
AC	21 (75%) 0.194/0.440	17 (61.60%) 0.247/0.497	18 (64.28%) 0.238/0.487	17 (61.60%) 0.247/0.497	9 (32.14%) 0.702/0.838
+0.5	7 (25%) 0.198/0.492	11 (39.28%) 0.201/0.501	10 (34.71%) 0.198/0.498	11 (39.28%) 0.189/0.499	9 (32.14%) 0.756/0.989
+1.0					10 (35.71%) 0.761/0.994

AC: Apical Constriction.
(+) and (–) values indicate file tip beyond (+) or short (–) of the AC.
p = 0.05.

Historically, radiographs have been the primary means for determining WL. However, they have inherent limitations, being two-dimensional images of three-dimensional objects. A WL is obtained radiographically by positioning the tip of a file a certain distance, usually 1.0 mm, from the radiographic apex. This method lacks accuracy because the 1.0 mm is measured from the end of the root (radiographic apex) rather than the end of the canal (apical foramen). Wrbas *et al.* (2007) urged caution to avoid over estimating WL because the foramen frequently was not at the apex. Gutiérrez & Aguayo (1995) recorded a wide variability in distances between the foramen and radiographic apex ranging from 0.20 to 3.40 mm. They stated that over instrumentation of the canal must be a common and unnoticed occurrence.

There is general agreement in the endodontic community that WL should be located at the AC. Kuttler (1955), found that the AC averaged 0.5–0.75 mm from the apical foramen and that the distance increased with age because of cementum deposition. Chapman (1969) and Dummer *et al.* (1984) found that the AC was located 0.5–1.0 mm from the apex in 92% and 95% of the examined teeth, respectively. Hassanien *et al.* (2008) detected the AC an average distance of 1.2 mm from the apical foramen. In light of these studies, it would seem that there is ample justification to establish a WL 1.0 mm short of the radiographic apex. Unfortunately, this assumption is not always accurate in locating the AC and caution should be used because a WL 1 mm short of the radiographic apex and believed to be close to the AC may actually be beyond

Table 4 Distance of file tip from the apical constriction determined by Root ZX, Elements, Precison AL, and Raypex 5

Distance from Apical Constriction (mm)	Root ZX n = 610 Canal						Elements n = 610 Canal						Precision AL n = 610 Canal						Raypex 5 n = 610 Canal					
	MB	ML	D	DB	DL	Pa	MB	ML	D	DB	DL	Pa	MB	ML	D	DB	DL	Pa	MB	ML	D	DB	DL	Pa
−0.5	3	4	-	-	1	-	9	11	23	12	13	11	4	1	2	2	1	1	13	22	32	17	19	21
AC	85	51	75	73	53	84	70	54	64	30	38	52	83	49	69	71	49	78	66	51	54	24	31	42
+0.5	49	46	28	18	17	23	51	51	23	32	31	29	46	39	47	27	17	24	53	54	23	31	34	21
+1.0	-	-	-	-	-	-	2	-	-	-	-	4	-	-	-	-	-	-	-	2	-	-	-	-
(p = 0.05)	0.40	0.20	0.85	0.0	0.0	0.0	0.40	0.20	0.85	0.0	0.0	0.0	0.40	0.20	0.85	0.0	0.0	0.0	0.40	0.20	0.85	0.0	0.0	0.0

AC: Apical Constriction.
(+) and (−) values indicate file tip beyond (+) or short (−) of the AC.

the foramen. When this happens an instrument passing through a necrotic pulp and through the foramen will most likely carry bacteria and toxins into the apical tissues (Siqueira *et al.* 2002, Siqueira & Barnett 2004). Receiving an indication from an EAL when the AC or foramen is located would be very helpful in avoiding this mishap.

The use of an EAL to determine WL has gained in popularity. Even though the user must be aware of the possible sources of error (metallic restorations, salivary contamination, dehydration, etc.), this and other studies have shown that the accuracy of EAL are superior to radiographs (Van de Voorde & Bjorndahl 1969, Pratten & McDonald 1996, Venturi & Breschi 2007). An *in vivo* study (Shabahang *et al.* 1996) the Root ZX was within 0.5 mm of the minor foramen (AC) 96% of the time, a value similar to this study (100%). In general, this study also agrees with others (Usun *et al.* 2008) that EAL are more accurate than radiographs and greatly reduce the risk of instrumenting and filling short of or beyond the apical foramen.

Being 1.0 mm through the AC increases the risk of over instrumentation and filling. In this study, using a radiographically determined WL 1.0 mm from the radiographic apex resulted in 20% of the anterior teeth, 35.7% of the premolars and 23.44% of the molars being 1.0 mm through the AC. In comparison, no EAL measurements for anterior and premolar teeth were 1.0 mm through the AC and for molars it was only 0%, 0.98%, 0%, and 0.32% for the Root ZX, Elements, Precision AL, Raypex 5, respectively.

The limitations and disadvantages of using only the radiographic method to determine WL are well known. However, since the joint use of radiographs together with EAL results in greater accuracy (ElAyouti *et al.* 2002), radiographic verification of WL length is still desirable (Fouad *et al.* 1990).

Conclusion

Under clinical conditions EALs identified the AC with greater accuracy than radiographs. In addition, only 0.6% (average) of the EAL measurements were 1.0 mm through the AC whereas with radiographs it was 31.4%. A WL 1.0 mm through the AC will, in some cases, results in instrumenting and filling beyond the foramen. A WL 0.5 mm short of, or at the radiographic apex, would further increase the likelihood of this happening. EALS can increase the accuracy of WL determination.

Table 5 Distance of file tip from the apical constriction determined by Root ZX, Elements, Precison AL, Raypex 5 and Radiograph (162 molars)

Distance from AC (mm)	Root ZX n = 610 Variance Std. Deviation	Elements n = 610 Variance Std. Deviation	Precison AL n = 610 Variance Std. Deviation	Raypex 5 n = 610 Variance Std. Deviation	Radiograph n = 610 Variance Std. Deviation
−1.0	–	–	–	–	–
−0.5	–	–	–	–	–
AC	8 (1.31%)	79 (12.95%)	11 (1.8%)	124 (20.32%)	113 (18.52%)
	0.276/0.525	0.877/0.936	0.315/0.561	1.169/1.084	1.400/1.183
+0.5	7 (1.14%)	11 (1.80%)	10 (1.63%)	11 (1.80%)	9 (1.47%)
	0.244/0.605	0.315/0.561	0.198/0.498	0.315/0.561	0.189/0.484
+1.0					10 (1.63%) 0.198/0.498

AC: Apical Constriction.
(+) and (−) values indicate file tip beyond (+) or short (−) of the AC.
p = 0.05.

Table 6 Percentage of measurements at the AC with the four EALS

Anteriors:	RZX: 89.1%	E: 83.6%	P: 85.4%	RAY: 81.8%	R: 32.72%
Premolars:	RZX: 75.0%	E: 61.6%	P: 64.3%	RAY: 61.6%	R: 32.1%
Molars:	RZX: 69.0%	E: 50.5%	P: 65.4%	RAY: 43.9%	R: 14.6%

Root ZX= (RZX); Elements= (E); Precision AL= (P); Raypex 5 = (RAY) and radiograph=(R).

Table 7 Percentage of measurements at 0.5mm short of the AC with the four EALS

Anterior and Premolar teeth: No measurements were 0.5 mm short of the apical constriction					
Molars:	RZX: 1.3%	E: 11.1%	P: 1.8%	RAY: 20.3%	R: 18.5%

Root ZX= (RZX); Elements= (E); Precision AL= (P); Raypex 5 = (RAY) and radiograph=(R).

Table 8 Percentage of measurements at 0.5mm through the AC with the four EALS

Anteriors:	RZX: 10.9%	E: 16.4%	P: 14.5%	RAY: 18.2%	R: 47.3%
Premolars:	RZX: 25.0%	E: 39.3%	P: 34.7%	RAY: 39.3%	R: 32.1%
Molars:	RZX: 29.7%	E: 35.6%	P: 33.4%	RAY: 37.0%	R: 42.0%

Root ZX= (RZX); Elements= (E); Precision AL= (P); Raypex 5 = (RAY) and radiograph=(R).

Table 9 Percentage of measurements at 1.0mm through the AC with the four EALS

Anteriors:	RZX: 0.0%	E: 0.0%	P: 0.0%	RAY: 0.0%	R: 20.0%
Premolars:	RZX: 0.0%	E: 0.0%	P: 0.0%	RAY: 0.0%	R: 35.7%
Molars:	RZX: 0.0%	E: 0.98%	P: 0.0%	RAY: 0.32%	R: 38.5%

Root ZX= (RZX); Elements= (E); Precision AL= (P); Raypex 5 = (RAY) and radiograph=(R).

No significant difference was apparent comparing the accuracy of the four EALS. All achieved a clinically acceptable determination of WL and were significantly more accurate than radiographs.

Acknowledgements

We thank Dr E. Steve Senia and Dr Michael Hülsmann for their valuable assistance in reviewing this manuscript.

References

Akisue E, Gavini G, de Figueiredo JA (2007) Influence of pulp vitality on length determination by using the Elements Diagnostic Unit and Apex Locator. *Oral Surgery, Oral Medicine and Oral Pathology, Oral Radiology and Endodontology* **104**, 129–32.

American Association of Endodontists (2003) *Glossary of endodontic terms*, 7th edn. http://aae.org/uploadedFiles/Publications_and_Research/Member_Publications/03GlossaryofEndoTerms_Web(1).pdf.

Bernardes RA, Duarte MA, Vasconcelos BC (2007) Evaluation of precision of length determination with 3 electronic apex locators: Root ZX, Elements Diagnostic Unit and Apex Locator, and Romi APEX D-30. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology and Endodontology* **104**, 91–4.

Bramante CM, Berbert A (1974) A critical evaluation of some methods of determining tooth length. *Oral Surgery, Oral Medicine, & Oral Pathology* **37**, 463–73.

Briseño-Marroquín B, Frajlich S, Goldberg F, Willershausen B (2008) Influence of instrument size on the accuracy of different apex locators: an in vivo study. *Journal of Endodontics* **34**, 698–702.

Custer LE (1918) Exact method of locating the apical foramen. *Journal of National Dental Association* **5**, 815–9.

Chapman C (1969) A microscopic study of the apical region of human anterior teeth. *Journal of the British Endodontic Society* **3**, 52–5.

Dummer PMH, McGinn JH, Rees DG (1984) The position and topography of the apical canal constriction and apical foramen. *International Endodontic Journal* **17**, 192–8.

ElAyouti A, Weiger R, Löst C (2002) The ability of Root ZX apex locator to reduce the frequency of overestimated radiographic working length. *Journal of Endodontics* **28**, 116–9.

Forsberg J (1987) Radiographic reproduction of endodontic working length comparing the paralleling and the bisecting-angle techniques. *Oral Surgery, Oral Medicine and Oral Pathology, Oral Radiology, and Endodontology* **64**, 353–60.

Fouad AF, Krell KV, McKendry DJ, Koorbusch GF, Olson RA (1990) Clinical evaluation of five electronic root canal length measuring instruments. *Journal of Endodontics* **16**, 446–9.

Gordon MPJ, Chandler NP (2004) Electronic apex locators: a review. *International Endodontic Journal* **37**, 425–37.

Grove CJ (1931) The value of the dentinocemental junction in pulp canal surgery. *Journal of Dental Research* **11**, 466–8.

Guise GM, Goodell GG, Imamura GM (2010) In vitro comparison of three electronic apex locators. *Journal of Endodontics* **36**, 279–81.

Gutiérrez JH, Aguayo P (1995) Apical foraminal openings in human teeth. *Number and location. Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontology* **79**, 769–77.

Hassanien EE, Hashem A, Chalfin H (2008) Histomorphometric study of the root apex of mandibular premolar teeth: an attempt to correlate working length measured with electronic and radiograph methods to various anatomic positions in the apical portion of the canal. *Journal of Endodontics* **34**, 408–12.

Heo MS, Han DH, An BM (2008) Effect of ambient light and bit depth of digital radiograph on observer performance in determination of endodontic file positioning. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontology* **105**, 239–44.

Jenkins JA, Walker WA, Schindler WG, Flores CM (2001) An in vitro evaluation of the accuracy of the Root ZX in the presence of various irrigants. *Journal of Endodontics* **27**, 209–11.

Kobayashi C (1995) Electronic canal length measurement. *Oral Surgery, Oral Pathology, Oral Medicine, Oral Radiology, and Endodontology* **79**, 177–9.

Kobayashi C, Suda H (1994) New electronic canal measuring device based on the ratio method. *Journal of Endodontics* **20**, 111–4.

Kuttler Y (1955) Microscopic investigation of root apexes. *Journal of the American Dental Association* **50**, 544–52.

Nekoofar MN, Ghandi MM, Hayes SJ, Dummer PMH (2006) The fundamental operating principles of electronic root canal length measurement devices. *International Endodontic Journal* **39**, 595–609.

Pagavino G, Pace R, Baccetti T (1998) An SEM study of in vivo accuracy of the Root ZX electronic apex locator. *Journal of Endodontics* **24**, 438–41.

Pascon EA, Marrelli M, Congi O, Ciancio R, Miceli F, Versiani MA (2009) An in vivo comparison of working length determination of two frequency-based electronic apex locators. *International Endodontic Journal* **42**, 1026–31.

Plotino G, Grande NM, Brigante L, Lesti B, Somma F (2006) Ex vivo accuracy of three electronic apex locators: Root ZX, Elements Diagnostic Unit and Apex Locator and ProPex. *International Endodontic Journal* **39**, 408–14.

Pratten DH, McDonald NJ (1996) Comparison of radiographic and electronic working lengths. *Journal of Endodontics* **22**, 173–6.

Precision Apex Locator (2006) Operation Manual. Savannah, GA: Brasseler USA.

Ricucci D, Langeland K (1998) Apical limit of root canal instrumentation and obturation, part 2: a histological study. *International Endodontic Journal* **31**, 394–409.

J. Morita Corp. (2005) *Root ZX II. Operation instructions*. Kyoto, Japan: J. Morita Corp.

Shabahang S, Goon WWY, Gluskin AH (1996) An in vivo evaluation of Root ZX electronic apex locator. *Journal of Endodontics* **22**, 616–8.

Siqueira JF, Barnett F (2004) Interappointment pain: mechanisms, diagnosis, and treatment. *Endodontic Topics* **7**, 93–109.

Siqueira JF Jr, Rôças IN, Favieri A, et al. (2002) Incidence of postoperative pain after intracanal procedures based on an antimicrobial strategy. *Journal of Endodontics* **6**, 457–60.

Stein TJ, Corcoran JF, Zillich RM (1990) The influence of the major and minor foramen diameters on apical electronic probe measurements. *Journal of Endodontics* **16**, 520–2.

Suzuki K (1942) Experimental study on iontophoresis. *Journal of Japanese Estomatology* **16**, 411–29.

Sybron Endo (2006) *Elements Diagnostic: Instruction Guidelines*. Glendora, CA: 1–3.

Tselnik M, Baumgartner JC, Marshall JG (2005) An evaluation of Root ZX and Elements Diagnostic Apex Locators. *Journal of Endodontics* **31**, 507–9.

Usun O, Topuz O, Tinaz C, Nekoofar MH, Dummer PMH (2008) Accuracy of two root canal length measurement devices integrated into rotary endodontic motors when removing gutta-percha from root-filled teeth. *International Endodontic Journal* **41**, 725–32.

Van de Voorde HE, Bjorndahl AM (1969) Estimating endodontic ''working length'' with paralleling radiographs. *Oral Surgery, Oral Pathology, & Oral Medicine* **27**, 106–10.

Venturi M, Breschi L (2007) A comparison between two electronic apex locators: an *ex vivo* investigation. *International Endodontic Journal* **40**, 362–73.

Vieyra JP, Acosta J, Mondaca JM (2010) Comparison of working length determination with radiographs and two electronic apex locators. *International Endodontic Journal* **43**, 16–20.

Wrbas KT, Ziegler AA, Altenburger MJ, Schirrmeister JF (2007) In vivo comparison of working length determination with two electronic apex locators. *International Endodontic Journal* **40**, 133–8.