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THE DENTAL CLINICS OF NORTH AMERICA

Dent Clin N Am 48 (2004) 35–54

Electronic apex locator

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Locating the appropriate apical position always has been a challenge in clinical endodontics. The cemento-dentinal junction (CDJ), where the pulp tissue changes into the apical tissue, is the most ideal physiologic apical limit of the working length. It also is referred to as the minor diameter or the apical constricture. However, the CDJ and apical constricture do not always coincide, particularly in senile teeth as a result of cementum deposition, which alters the position of the minor diameter. Therefore, setting the apical constricture as the apical limit of the working length, where it is easy to clean and shape or obturate the canal, is recommended [1,2].

The apical constricture of the root also does not coincide with the anatomic apex. It is deviated linguo-buccally or mesio-distally from the root [3–5]. If the exit deviates bucco-lingually, it is very difficult to locate accurately the position of the apical foramen using only roentgenograms, even with multidirected angles. Frequently, a file needs to be inserted into the canal to force it through the apical foramen, in order for the exit to be verified.

The electronic apex locator (EAL) machine has attracted a great deal of attention because it operates on the basis of the electrical impedance rather than by a visual inspection. The EAL is one of the breakthroughs that brought electronic science into the traditionally empirical endodontic practice. EALs are particularly useful when the apical portion of the canal system is obscured by certain anatomic structures, such as impacted teeth, tori, the zygomatic arch, excessive bone density, overlapping roots, or shallow palatal vaults. Indeed, EALs currently are being used to determine the working length as an important adjunct to radiography. EALs help to reduce the treatment time and the radiation dose, which may be higher with conventional radiographic measurements. In addition, EALs

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doi:10.1016/j.cden.2003.10.005

were reported to be an accurate and reproducible method as the newest third-generation type and can acknowledge a root perforation. However, some questions still exist as to whether the accuracy of EAL can be affected by the different types of electrolytes [19,43,45], the types of electronic working mechanism, and the conditions of the root canal, such as pulp vitality [20,31,34], or foramen size [51,52]. This article reviews the history and the working mechanism of the currently available EALs, and suggests the correct use of an apex locator for a better canal length measurement.

History of EALs

Traditional-type apex locators (resistance or impedance type)

In 1918, Cluster [6] first put forth the idea that the root canal length could be determined by using the electrical conductance. Little was done with this idea until 1942 when Suzuki [7] reported a device that measured the electrical resistance between the periodontal ligament and the oral mucosa. He discovered that in dogs, the electrical resistance between the root canal instrument inserted into a root canal and an electrode applied to the oral mucous membrane registered a consistent value of approximately 6.5 Kω. These principles were not examined further until Sunada [8] performed a series of experiments on patients and reported that the electrical resistance between the mucous membrane and the periodontium was consistent, regardless of the age of the patients or the shape and type of the teeth. In 1987, Huang [9] reported that this principle is not a biologic characteristic, but rather a physical principle.

Inoue [10] reported a modification that incorporated the use of an audiometric component that permitted the device to relate the canal depths to the operator via low-frequency audible sounds. One of the most widely used apex locators in the 1970s and 1980s, the Sono-Explorer (Union Broach, New York, New York), was developed using this modification. By 1975, newer units such as the Neosono (Amadent, Cherry Hill, New Jersey) and many other resistance-type apex locators became available. They have improved circuitry, are more compact, and are easier to operate [11]. However, these resistance-type EALs often yield inaccurate results when electrolytes, excessive moisture, vital pulp tissue, exudates, or excessive hemorrhage are present in the canals [12–14]. (The effect of the canal contents on the accuracy of an EAL is discussed later in this article.)

A new apex locator, the impedance type, was developed in the late 1980s to improve the resistance-type apex locators. The impedance-type EAL uses the electronic mechanism that the highest impedance is at the apical constricture, which is the narrowest portion of the canal where the impedance changes drastically, when a canal is thought of as being a long hollow tube [15]. However, a question also was raised as to whether this mechanism could be applied to the real root canal with various anatomical complications [16].

The Endocator (Hygienic Corporation, Akron, Ohio) was an example of an impedance-type apex locator. This device used a large file coated with Teflon, which was difficult to use in narrow canals; in addition the Teflon peeled off in curved canals. Another disadvantage with this device was that the patient sometimes felt uncomfortable due to the high current used, and the calibration had to be done before using the device [17].

Frequency-dependent apex locators

The newest type of EAL was introduced in the early 1990s in an effort to obtain a more accurate canal length measurement in various canal circumstances. It uses more advanced technology and measures the impedance difference between the two frequencies or the ratio of two electrical impedances. In 1990, Yamashita [18] reported on a device that calculated the difference between two impedances from two different frequencies, which were generated with composite sine wave current sources, and was marketed as the Endex (Osada Electric Co., Tokyo, Japan). It works by comparing the difference in impedances using the relative value of two alternating currents at frequencies of 1 and 5 kHz. As the file moves toward the apex, the difference becomes greater and shows the greatest value at the apical constricture, allowing for a measurement of that location. The major advantage of this device is that it works well regardless of the presence of pus or electroconductive environments in the canal [19,20]. However, a disadvantage is that a calibration needs to be done each time.

In 1991, Kobayashi et al [21] reported on the "ratio method" for measuring the root canal length, which was the basic working mechanism of the Root ZX (J. Morita Corp., Tustin, California) [21]. This device measures the impedances of 0.4 kHz and 8 kHz at the same time, calculates the quotient of the impedances, and expresses this quotient in terms of the position of the file inside the canal. This quotient is barely affected by the electrical conditions inside the canal [14]. In addition, it is unnecessary to calibrate this device each time because the microprocessor automatically controls the calculated quotient to have a relationship with the file position and the digital read out when the file is inserted into the coronal portion of the canal [22]. This device was reported to be quite accurate in various conditions [23–25].

The AFA (all fluids allowed) Apex Finder Model 7005 (Analytic Endodontics, Orange, California) is another type of frequency-dependent EAL, which uses five different frequencies (0.5, 1, 2, 4, 8 kHz). The Bingo 1020 (Forum Engineering Technologies, Rishon Lezion, Israel) uses two separate frequencies, 400 Hz and 8 kHz, but only a single frequency at a time. The use of a single-frequency signal eliminates the need for filters that separate the different frequencies of the complex signal. In addition, the position of the file tip in the Bingo 1020 is calculated based on the measurements of the root mean square value of the signal. The manufacturers claim that a combination of these two techniques increases the measurement accuracy [37].

Apex locators with other functions

EALs with additional functions were developed in the late 1990s. The Solfy ZX (J. Morita Corp.), which is a combination of an ultrasonic hand piece and a Root ZX, was designed to prevent overinstrumentation by stopping the ultrasonic vibration when the file reaches the required location. The Tri Auto ZX (J. Morita Corp.) is a Root ZX with a cordless rechargeable electric hand piece that uses a Ni-Ti rotary file with 260 to 280 revolutions per minute (rpm) [26]. When the file has reached the required location, this device allows the file to rotate back out of the canal, thereby preventing overinstrumentation. In addition, it also prevents the fracture of the Ni-Ti rotary file by allowing the file to rotate back out if it goes over the set auto-torque-reverse mechanism threshold of 40 to 80 g/cm [26]. This unique function appears to be quite useful as the Ni-Ti rotary file becomes more popular. However, based on our clinical experience, large sized rotary files had a tendency to slow down the rpm speed, possibly due to the low torque setting. In addition, it has the disadvantage that the number of rpm reduces with increasing pressure due to the limitation of the rechargeable battery.

Recently, the Dentport ZX (J. Morita Corp.) was introduced to the market. The Dentaport ZX is comprised of two modules—the Root ZX module and the Tri Auto ZX module. Both functions can be used by exchanging the back cover. In the Tri Auto ZX module, it appears that the file was easily controlled when using the hand piece at 50 to 800 rpm and a torque ranging from 30 to 500 g/cm. One advantage of the Dentport ZX is that it has an auto apical slow-down function—when the rotary file reaches the apical constricture, the rpm slows down allowing for a careful sculpture of the apical portion. However, further research is needed to determine the effect of a file fracture when the rpm changes inside the canal.

Devices that combine an apex locator and an electrical pulp tester also have been marketed. One example is the Elements Diagnostic Unit (Sybron-Endo, Orange, California). It has a separate monitor called a "Satellite," which can be clipped to the patient's napkin or other surface.

General accuracy of frequency-dependent EALs

Before the era of frequency-dependent EALs, the accuracy of traditional EALs was inconsistent and affected by many variables [9,16,27–29]. With traditional-type EALs, the accuracy depends more on the individual operator's skill and the various canal conditions, such as the existence of electroconductive solution. One of the alleged advantages of frequency-dependent EALs is that it operates accurately, even under different wet canal conditions. According to recent publications [34,42,57], the accuracy of frequency-dependent EALs is much higher than that of traditional-type EALs (simple-resistance type or impedance type). A number of experiments were conducted using both in in vivo and in vitro models (Table 1). Most of the EAL measurements were compared with the actual tooth length.

In vivo studies

Arora and Gulabivala [20] compared the accuracy of Endex in the presence of vital and nonvital pulp tissue and commonly encountered canal electrolytes (pus, NaOCl, water) with that of a traditional-resistance type EAL, the RCM Mark II (Evident Dental Co., Ltd., London, United Kingdom). The overall accuracy of the Endex (71.7%) was higher than that of the RCM Mark II (43.5%), at a $\pm$0.5-mm clinical tolerance.

A similar study [30] compared the Apit (Osada Electric Co., Los Angeles, California) with a traditional-type EAL (Odontometer, L. Goof Co., Hörrsholm, Denmark) in vivo. The Apit tended to yield more reliable results than did the Odontometer. The average deviation of the Apit was 0.14 mm (range = 0.85 to $-$0.65 mm) with a 93% accuracy at a $\pm$0.5-mm clinical tolerance, whereas the average deviation of the Odontometer was $-$0.36 mm (range = 0.35 to $-$2.45 mm) with a 73% accuracy at a $\pm$0.5-mm clinical tolerance. This difference was statistically significant ($P < 0.001$).

In another in vivo experiment using vital or necrotic pulps, Mayeda [31] reported that all measurements were within a narrow range ($-$0.86 mm to 0.50 mm), with an 88% accuracy at a $\pm$0.5-mm clinical tolerance when measured from the apical foramen. Shabahang et al [23] examined 26 root canals of the vital teeth to evaluate the performance of the Root ZX. After measuring the distance between the tip of the endodontic file and the apical foramen, they found that the Root ZX located the apical foramen precisely in 17 canals (65.4%), was short in 1 canal (3.8%), and was overextended in 8 canals (30.8%). However, the accuracy was 96.2% at a $\pm$0.5-mm clinical tolerance. Vajrabhaya and Tepmongkol [24] tested the Root ZX under clinical conditions using vital and nonvital pulp, and reported 100% accuracy when less than 1 mm from the apical foramen and less than 0.5 mm beyond the foramen were used as the acceptable range.

Several experiments have used radiographic lengths as a reference. Frank and Torabinejad [32] compared the Endex with radiographic measurements. They reported that the Endex located the apical constriction accurately within a $\pm$0.5-mm clinical tolerance in 89.64% of 185 moist canals. Similar results were obtained when the Endex was tested on a human cadaver [33]. The mean of the absolute values of the deviations from the apical constriction for the apex locator (0.259 mm) was significantly lower than that for the radiographic method (0.578 mm). Eighty-nine percent of the EAL was within a $\pm$0.5-mm clinical tolerance whereas 70% was in the

Table 1
Accuracy of frequency-dependent apex locators

Reference	Year	Study type	EAL	N (canals)	Comparison	Accuracy[a]
Frank et al [32]	1993	Patient—radiograph	Endex	185	Radiographic apex	89.6%
Mayeda [31]	1993	Patient—extract	Endex	33	Apical foramen—M	87.9%
Felippe and Soares [52]	1994	Extracted teeth	Endex	350	Apical foramen—D	96.5%
Arora and Gulabivala [20]	1995	Patient—extract	Endex	61	Apical foramen—M	71.7%
Czerw et al [41]	1995	Extracted teeth	Root ZX	30	Apical foramen—D apical	100%
Pratten and McDonald [33]	1996	Cadaver—extract	Endex	27	Constriction—M	89%
Lauper et al [30]	1996	Patient—extract	Apit	30	Apical foramen—M	93%
Shabahang et al [23]	1996	Patient—extract	Root ZX	26	Apical foramen—M	96.2%
Vajrabhaya and Tepmongkol [24]	1997	Patient—extract	Root ZX	20	Apical foramen—M	100%
Ounsi [59]	1998	Extracted teeth	Endex	34	Apical foramen—D apical	84.56%
Dunlap et al [50]	1998	Patient—extract	Root ZX	34	Constriction—M	82.3%
Pagavino et al [25]	1998	Patient—extract	Root ZX	29	Apical foramen—SEM	82.75%
Ibarrola et al [58]	1999	Extracted teeth[b]	Root ZX	16	Apical constriction—M	87.5%
Ounsi and Naaman [49]	1999	Extracted teeth	Root ZX	36	Major diameter—D	84.72
Lee et al [47]	2002	Patient—extract	Newly designed	31	CDJ—M	92%
Meares and Steiman [42]	2002	Extracted teeth	Root ZX	40	Apical foramen—D	83%
Neekoofar et al [57]	2002	Extracted teeth[c]	Neosono Ultima EZ	54	Apical foramen—D	94.4%
Pommer et al [34]	2002	Patient—radiograph	AFA apex finder	152	Radiographic apex	85.5%[d]
Kielbassa et al [40]	2003	Patient—extract[e]	Root ZX	105	Minor diameter—D	64.8%[f]

Abbreviations: D, direct view (magnifier); M, microscope; SEM, scanning electron microscope.
[a] Within 0.5 mm.
[b] Preflared canal.
[c] Ni-Ti file was used.
[d] Radiographic apex -1 ± 0.5 mm.
[e] Primary teeth.
[f] Within 1 mm.

radiographic length. The recently marketed AFA Apex Finder [34] also showed a high accuracy in clinical situations. When compared with radiographic measurements, in 86% of the roots evaluated, the file tip position (as indicated by the Apex Finder) was located within 0.5 mm of a point 1.0 mm short of the radiographic apex.

In vitro studies

Felippe and Soares [52] tested the Apit in an isotonic saline container model and found that 96.5% of 350 human teeth located the apical foramen at a ±0.5-mm clinical tolerance. Brunton et al [35] performed an in vitro experiment to determine whether the use of an EAL (Analytic AFA) could reduce radiograph exposure. In the group that did not use the EAL (25 teeth), 14 retake radiographs were required to determine the working length, whereas in the group that used the EAL, no retake radiographs were required. The EAL was extremely accurate in locating the apical foramen with all the teeth tested within a ±0.5-mm clinical tolerance. In contrast, only 15 (60%) teeth tested using radiographs alone were within the ±0.5-mm clinical tolerance of the anatomic apex. El Ayouti et al [36] reported that the electronic working length measured by the Root ZX reduced the percentage of overestimation to 21% compared with radiograph only.

Recently, the Bingo 1020 was introduced to dental practice. Kaufman et al [37] compared this new frequency-dependent EAL with the Root ZX and found that the Bingo 1020 was consistently more accurate than was the Root ZX, although both units measured the tooth length with great accuracy.

Digital radiography was compared with the Apit EM-S3 in a well-controlled in vitro model [38]. The electronic method was satisfactory in 67.8% of cases with a ±0.5-mm clinical tolerance, versus 50.6% and 61.4% for the conventional and digital radiologic methods, respectively. The authors [38] concluded that none of the techniques were totally satisfactory in establishing the true working length.

The ±0.5-mm clinical tolerance is considered to be the strictest acceptable range. Therefore, measurements attained within this tolerance were considered to be highly accurate. However, some authors [39,40] prefer the ±1-mm range. Shabahang et al [23] reported that because root canals frequently lack a well-delineated apical constriction, an error tolerance of ±1 mm can be deemed clinically acceptable.

Accuracy of frequency-dependent EALs in different electrolytes

A major advantage of frequency-dependent EALs is that they operate even with a high electroconducting irrigant such as sodium hypochlorite. The operation is based on the principle of the relative difference or a quotient of two or more impedances generated at each different frequency. Although frequency-dependent EALs enhance the measurement accuracy, several questions as to whether the different electrolytes in the canal or the size of the root canal affect the accuracy still remain.

Many studies showed promising results with this third-generation device; most of these studies focused on the Endex (Apit) and the Root ZX. Frank and Torabinejad [32] compared the Endex measurements with the radiographic measurements in 185 root canal lengths. They found that the Endex located the apical constriction accurately within the ±0.5-mm clinical tolerance in 89.64% of moist canals. The presence of an apical radiolucency or a restoration; the length of the canal; the type of moisture; and the pulpal and periapical conditions, such as hemorrhage, exudate, or sodium hypochlorite, did not influence the results. However, the measurements obtained in the dried canals presented a variety of inconsistent and nonpredictable results. The authors [32] explained that this was due most likely to the operators not drying the canals completely. When the dried canal was compared with a distilled water–filled canal [41] in an in vitro saline–gelatin model, the Root ZX showed no difference between the distilled water and dry canal.

To determine whether the concentration of sodium hypochlorite influenced the accuracy of the Root ZX, Meares and Steiman [42] flushed the canal with 2.125% and 5.25% sodium hypochlorite and the measurements from the in vitro model then were compared with the actual canal lengths. No significant differences were found between the experimental groups. The authors [42] suggested that the Root ZX was not adversely affected by the presence of sodium hypochlorite.

In contrast, there is still a concern as to whether high electroconductive irrigants such as blood, saline, a local anesthetic solution, irrigant fluids, and sodium hypochlorite can affect the accuracy of the EAL performance. Several studies warned that a high electroconductive solution might affect the accuracy. Fouad [19] compared the accuracy of the Endex with that of the traditional-type EALs with regard to the effects of the fluids in the canal and the variation in the foramen size. The accuracy of the Endex at the ±0.5-mm clinical tolerance was 73% in the smaller apical foramens and 57% in the larger foramens. When the Endex was used in the dry canals, it showed a 90% accuracy in the smaller foramens but only a 57% accuracy was observed in the larger apical foramens. The author [19] suggested that the complete drying of the canal is not likely to be achieved clinically because some degree of moisture is bound to be present in the canals due to the hydration of dentin from the surrounding periodontium or as a result of the incomplete drying using the paper point.

Jenkins et al [43] evaluated the accuracy of the Root ZX in vitro in the presence of a variety of endodontic irrigants, 2% lidocaine with 1:100,000 epinephrine, 5.25% sodium hypochlorite, RC Prep (Premier Dental Product, Philadelphia, Pennsylvania), liquid ethylenediaminetetraacetic acid (EDTA), 3% hydrogen peroxide, and Peridex (Zila Pharmaceuticals, Inc., Phoenix, Arizona). The results showed that the Root ZX reliably measured the canal lengths to within 0.31 mm, regardless of the irrigants. However, the largest deviation from the actual canal length was obtained with NaOCl. The authors [43] stated that considering the widespread utility of NaOCl as an intracanal irrigant, the increased variance of this irrigant should be considered.

Pilot and Pitts [44] conducted a sophisticated study on the prediction error of the EAL (Sono Explorer Mark IV, Union Broach). They evaluated the impedance change at different locations in the root canal system with various frequencies and canal irrigants and calculated the prediction error when the EAL was used in these various conditions in vivo. No significant difference was noted in the prediction error at different frequencies ($P > 0.05$). However, the prediction error was significant with respect to the different irrigants (RC Prep, 70% isopropyl alcohol, 14.45% EDTA sodium solution, normal saline, and 5.25% NaOCl) ($P < 0.02$). A higher prediction error was apparent for the more conductive solutions, such as NaOCl. These results suggest that although the working mechanism is unclear, the different electroconductivities somehow affect the EAL measurement. When the electrical resistance of the most frequently used irrigants were measured, NaOCl was much higher (10 times), whereas H_2O_2 was much lower (50 times), than saline [28]. It was speculated that the change in the electroconductivity shifts the quotient curve of the frequency ratio.

Kim et al [45] reported that there were tendencies toward a short measurement in a high electroconductive solution such as NaOCl, whereas longer measurements were in the lower electroconductive solution. These tendencies were expressed by a voltage difference. To minimize the measurement errors, they developed a new circuit that could automatically compensate for the voltage differences in the different irrigating solutions. As a result of this compensation, the errors were significantly reduced, on average from 0.54 mm to 0.18 mm in the H_2O_2 solution and from −0.33 mm to −0.01 mm in the NaOCl solution in an in vitro study. The accuracies based on a ±0.5-mm clinical tolerance were improved for the H_2O_2 and NaOCl solutions from 71.1% to 91.1% and from 82.2% to 100%, respectively. Briefly, the impedance ratios and voltage differences were obtained from the three different irrigating solutions (saline, NaOCl, and H_2O_2) in an extracted tooth model, using the conventional impedance ratio method with two sinusoidal waves (0.5 and 10 kHz). From a total of 45 root canals examined in each solution, the distributions of the voltage differences and the measurement errors were obtained. The voltage differences measured were generally larger in H_2O_2 and smaller in NaOCl when compared with saline. The measured lengths were generally longer in H_2O_2 and shorter in NaOCl compared with saline. The impedance ratio of the two different frequencies represented the position of the file, whereas the voltage difference represented the status of the fluid in the root canal. Each irrigant

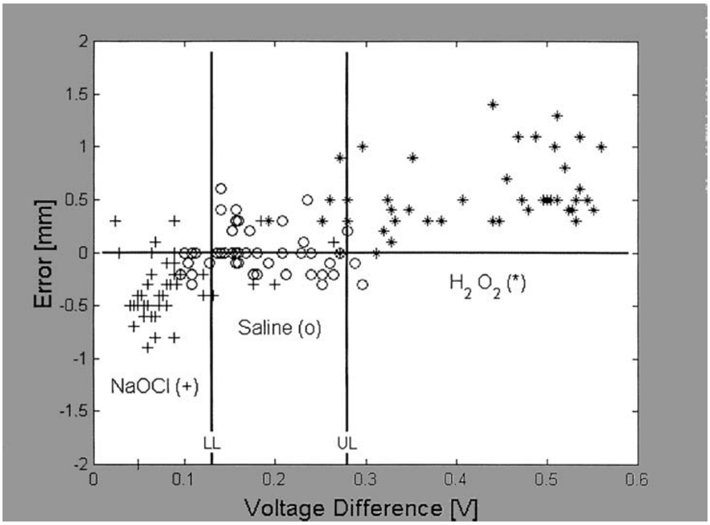

Fig. 1. Distributions of voltage difference versus error for the three solutions in the canal. "LL" and "UL" are decision boundaries that classify a smaller voltage difference solution (NaOCl) and a larger voltage difference solution (H_2O_2) for 45 extracted root canals (in vitro).

was classified statistically using a Bayes linear classifier (Fig. 1). The compensating value was determined in proportion to the difference between the measured voltage difference and either the "upper limit (UL)" or "lower limit (LL)," which then was added or subtracted to the impedance ratio for compensation. Therefore, during the actual determination of the working length, the file would go deeper in a higher electroconductive condition such as NaOCl, whereas it would go less deep in a lower electroconductive condition such as H_2O_2.

When this compensation circuit was tested in clinical situations, Nam et al [46] reported that the mean error was 0.14 ± 0.27 mm from the constriction point, and 95.2% of the measurements were within the clinical tolerance of ±0.5 mm. Lee et al [47] also reported promising results from the compensation circuit. When the distances from the major foramen and CDJ were measured, the average distance of the measurements was -0.13 mm from the major foramen with a range of -0.28 to 0.46 mm. The average distance from the detectable 26 CDJ samples was 0.18 mm with a range of -0.98 to 0.65 mm. The measurement accuracies were 94% (29/31) from the major foramen and 92% (24/26) from the CDJ with a ±0.5 mm tolerance. There were no differences between either the smaller (<#25) and larger apical foramens ($\geq$#25), or the vital and nonvital pulps, respectively.

Measurements can change as a result of different measuring methods such as what point of the unit the operator uses as a reference and whether to use the major diameter or the constriction point from the EAL reading. The operation manual of the Root ZX [48] recommends that the file be inserted until the meter reads 0.5 mm. The file then is advanced with a slow clockwise turn until the word "APEX" begins to flash. When the apex is reached, the file is turned slowly counterclockwise until the meter reads 0.5 mm, and the measurement is then read. The manual also advises that 0.5 to 1 mm be subtracted from the EAL measurements, as indicated by the "0.5" mark on the meter, to place the filling material above the apical seat. However, several authors have questioned using the 0.5 mark. Some recommend that the APEX mark be used instead of the 0.5 or 1.0 mark [25,49].

Ounsi and Naaman [49] performed an in vitro experiment to evaluate the performance of the Root ZX at two different settings: the 0.5 and APEX marks. The results showed that if the 0.5 mark was selected, the mean value of the difference between the EAL and actual length was outside of the ±0.5-mm clinical tolerance (50%). However, when the APEX mark was selected, the mean value was within this tolerance range (84.72%). Therefore, they discouraged the use of the 0.5 mark as advised by the manufacturer, and suggested that the canal length be measured when the "APEX" mark is reached [49].

Another study [25] evaluated the accuracy of the Root ZX in two foramen locations: with the foramen at the end of the root tip and with the foramen deviated from the main axis. The clinical accuracy was 82.75% with a tolerance level of ±0.5 mm when the measurements were read at the APEX mark. In 28 out of 29 examined teeth, the file tip protruded beyond the apical foramen with a range between 0.12 mm and 0.85 mm. The authors of this study [25] recommended the withdrawal of the instrument by approximately 0.5 to 1 mm to avoid overpreparation.

Similar results were reported for the Endex. Arora and Gulabivala [20] compared the accuracy of the Endex in the presence of vital and nonvital pulp tissue and commonly encountered canal electrolytes (pus, NaOCl, water) with that of a traditional-type EAL, the RCM Mark II. In general, longer readings occurred with the Endex (80.3%) than with the RCM Mark II (50.8%). The authors [20] suggested that the manufacturer's calibration of the Endex resulted in an overinstrumentation of the canal length. Mayeda [31] found that the Endex consistently located a point that was closer to the major diameter than the apical constriction. Because one third of the measurements were long, and another one third were right at the apical foramen, most of the measurements would actually be beyond the apical constriction. The results indicated that the accuracy of all measurements were within a narrow range (−0.86 mm to 0.50 mm), with 88% at the ±0.5-mm clinical tolerance from the major apical foramen. However, if the readings from the apical constriction instead of the major foramen were counted, the accuracy would fall to 70% for vital tissue and 69% for necrotic tissue.

In an in vivo study with a newly designed compensation circuit, Lee et al [47] reported that most measurements (19/25) were beyond the CDJ. The reason for this was attributed to the fact that the machine reads the largest gradient of the impedance ratio at the point where the periodontal ligaments meet. However, the question as to how the measurements could be reproduced consistently is more important than where to read the measurements. No matter where the machine points, if the machine pointing is consistent and the position and the average distance between the file tip and the true CDJ are known, then an accurate length can be obtained by subtracting the average distance directly from the machine reading. In this study [47], the authors used the SDs to evaluate the measurement consistency. Eighty-one percent of the major foramen and 65% of the CDJ measurements were within 1 SD, and 97% of the major foramen and 92% of the CDJ measurements were within 2 SDs. Again, these results showed that the measurements from the major foramen were more consistent than were those from the CDJ. The authors [47] suggested that SDs be used to test the accuracy along with the average discrepancy with the ± 0.5-mm clinical tolerance.

Effect of pulpal vitality on the accuracy of EAL

Most studies [24,31,47] have reported that pulpal vitality does not affect EAL accuracy. Mayeda et al [31] conducted a study to determine whether the pulp status (ie, vital or necrotic) makes a difference in the determination. In this in vivo study, 33 teeth, both vital and necrotic, were measured using the Endex apex locator and then were radiographed. The results indicated that all the measurements were within a narrow range (-0.86 mm to 0.50 mm). There was no statistical difference in the measurements between the vital and necrotic canals (vital group, mean $= -0.057$, SD $= 0.32$ mm, range $= -0.71$ to 0.5; nonvital group, mean $= -0.11$, SD $= 0.35$ mm, range $= -0.86$ to 0.43). Similar results were supported by succeeding investigations with the Root ZX [24] and the newly designed circuit [47].

There have been several disagreements on the effect of pulpal vitality on the accuracy of EAL. When the influence of root canal status on the determination of root canal length using the AFA Apex Finder in vital and necrotic canals was compared, the results showed a higher accuracy for determining the apical constriction in vital canals (93.9%) than in necrotic canals (76.6%), and this difference was statistically significant ($P \leq 0.05$) [34]. The authors [34] suggested that in necrotic cases with inflammatory root resorption, the apical constriction might be altered or even nonexistent with no viable periodontal tissue to respond to the EAL, which would cause a lower accuracy. Arora and Gulabivala [20] reported that the Endex provided a better reading in vital tissues (88.9%), whereas the readings for necrotic pulp were substantially lower (45.4%) within a ± 0.5-mm clinical tolerance. In a study using the Root ZX, Dunlap et al [50] compared the canal length in vital and necrotic canals. The mean distance from the constriction was 0.21 mm in the vital canals and 0.51 mm in the nonvital canals; 52.9% of the vital versus 23.5% of the nonvital readings of the coronal or right at the apical constriction were measured. However, no statistical difference was found. Two necrotic pulps with a periapical radiolucency measured greater than 1.5-mm error beyond the constriction. It was conceived that these periapical radiolucencies lacked a periodontal ligament and the periapical bone may have caused the abnormally long reading. The authors also speculated that apical resorption by the long-standing periapical radiolucency may have resulted in the destruction of the apical constriction.

Effect of foramen size on the accuracy of EAL

In general, there is a consensus that the file size does not affect the accuracy of EALs. Nguyen et al [51] conducted an in vitro experiment to observe the effect on the measurement of the relative diameters of the file and the root canal using the Root ZX. The length of the enlarged canals was measured using small-sized files and large files matching the canal diameter. The initial canal length (IL) was measured using the EAL by negotiating a size 10 file to the apical constriction. The canal was enlarged to size 60 with the rotary files, and the final length (FL) measurements then were obtained using a size 10 file and a size 60 file. The position of the file tip was observed histomorphometrically after the apical 4 mm of the canal was exposed by grinding the buccal aspect of the root. Differences between the FL-10, FL-60, and IL were similar.

In an in vitro experiment [52], the Apit also was used to evaluate the possible influence of the size of the instrument on the measurements. The actual lengths, which were taken with a #15 file, were compared with the EAL lengths obtained using the size comparable to the diameter of the root canal. In all the teeth measured, the results with the larger files were the same as or less than 0.5 mm different from the results obtained with the #15 files. When the initial file sizes were grouped according to the file size #25, Lee et al [47] reported that there were no differences between the smaller (<#25) and larger apical foramens (≥#25).

Effect of resorption on the accuracy of EAL

The use of EALs in apical resorption is under question because of the possible destruction of the apical constricture and the loss of the surrounding periodontal tissue. Goldberg et al [39] conducted an experiment to evaluate the accuracy of the Root ZX apex locator in determining the working length in teeth with 50 simulated apical root resorptions. The measurements were accurate in 62.7% of cases with a ±0.5-mm clinical tolerance when compared with direct visual measurements. The authors [39] also reported that there were differences between the operator's measurement abilities, suggesting that the accuracy of the EAL in apical resorption may depend more on the operator's experience. However, Shabahang et al [23] reported that the Root ZX could locate the root end consistently, even with the resorption lacunae.

Accuracy in primary teeth

The location of the actual apical foramen in the primary teeth, which are in the process of physiologic resorption, provides a great challenge to clinicians. However, conventional methods are not always applicable because the apical aperture is exposed to continuous and sometimes irregular resorption. In these instances, it is even more imperative to minimize the periapical damage to protect the succedaneous tooth bud.

Katz et al [53] tested the Root ZX in extracted teeth to determine whether this device could detect the tooth length in mature primary teeth that already had a different degree of root resorption. They reported that the Root ZX had an accuracy that was similar to the actual length and the radiograph film. They also stated that the use of the Root ZX was quick, comfortable, and accurate, and was preferred over the radiographic method. Kielbassa et al [40] conducted a similar study using the Root ZX, but in vivo. They reported that the device had a sufficient accuracy, with a tendency to slightly underestimate the root canal length just short (average = −0.98 mm) of the apex. The tooth, the root canal type, the status of the periapex, and the clinical conditions did not influence these results.

Detection of root perforation

The early detection and immediate treatment of an iatrogenic perforation is most important for making a good prognosis [54]. Radiographic detection often hinders the existence of the perforation, particularly when it occurs bucco-lingually [55]. Kaufman et al [56] compared the abilities of the Root ZX, Apit III (Endex), and Sono Explorer Mark II in detecting a root perforation. When tested on 30 extracted human teeth in vitro, all the tested EALs were clinically acceptable, where the tip of the file ended 0.06 mm to 0.60 mm short of the external outline of the root surface. Therefore, the use of an EAL for making an early detection of a root perforation appears to be very effective.

Effects of different metal types

The question as to whether different types of metal can affect the accuracy of EALs has been raised, but this does not appear to be a problem. Nekoofar et al [57] evaluated the accuracy of the Neosono Ultima EZ (Amadenat) using two different types of metal: nickel-titanium and stainless steel. The accuracy of the nickel-titanium and stainless steel was 94% and 91%, respectively, and there was no statistically significant difference.

Clinical suggestions

Conventional radiograph still is needed

Recent publications regarding frequency-dependent EALs appear to agree that EALs are more reliable than is conventional radiography. Whether to trust EALs or radiography depends on how familiar the operator is with each method. We tend to trust EALs more when there is a stable electronic sign with reasonably controlled exudates and without any metallic restorations. However, when the sign is unstable—particularly with metallic restorations, severely undermined caries, severe exudation, or a wide-open apex—a comparison of the EAL reading with the radiograph is strongly recommended. Besides, EALs only provide the electronic impedance and not the canal shape. To obtain anatomic information of the roots and canals, a radiograph still is mandatory in an endodontic procedure.

Working length is changing continuously

The working length changes constantly throughout the root canal treatment. During the canal preparation procedure, the file inadvertently may go beyond the apical foramen, breaking the apical constriction and creating an oval-shaped exit, which leaves a thin wall at the coronal part of the dentin. As the file tip touches the most coronal margin of the oval exit, the unit will show an apex sign, thereby measuring a shorter length (Fig. 2B) than the initial working length (Fig. 2A). This may occur more frequently because the use of a rotary instrument is increasing in the endodontic practice. A straightening of the curved canal can be another cause. We measured the changes in the working lengths between before and after canal shaping from 5000 root canals using frequency-dependent EAL and showed that there were some changes in the working lengths (Table 2). EALs were useful in confirming the working length not only during the endodontic procedure but also in the final working immediately before the obturation. When EALs are used to verify the final working length, the following things should be considered. First, the apical area may become too enlarged leaving an extremely or stripped thin dentin wall. Care needs to be taken so as not to break the apical seat or the remaining thin dentin wall. A file size that fits snuggly inside the apical canal is recommended. When the final EAL is used in a dried canal situation, the file position may become directly in contact with the apical soft tissue, where the meter sign of the EAL drops sharply to the APEX mark. In this case, it is advised to subtract 0.5 to 1 mm, depending on the size of the apical foramen (usually, a larger subtraction for a larger-sized foramen).

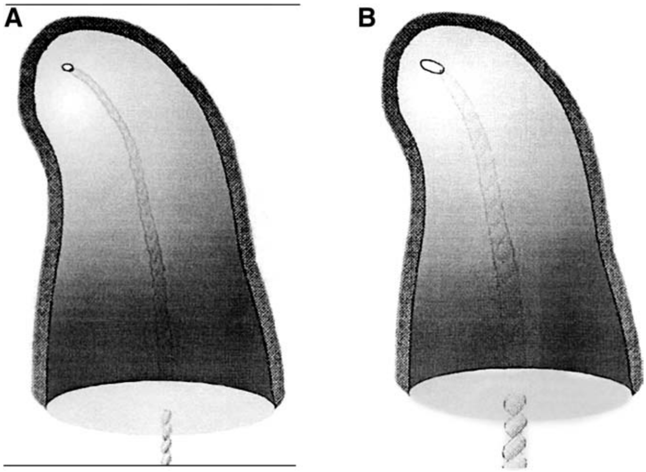

Fig. 2. As the file tip touches the most coronal margin of the oval exit, the unit shows the apex sign. (*A*) Initial sign of apex. (*B*) Sign of apex after canal preparation.

Common Problem Solving

The following are problems frequently encountered by general practitioners when using EALs.

Unstable electronic signal with rapid wandering signs

An unstable electronic signal with rapid wandering signs is the most frequent malfunction of an EAL and occurs most frequently when the file touches the metallic restorations or when there is a cervical leak through the subgingival caries. Removing the metallic restoration or simply blowing air onto the wet chamber usually solves this problem.

Table 2
Difference of the working lengths between before and after canal shaping

Root	Difference (mm)
Upper central incisor	0.3
Upper lateral incisor	0.4
Upper canine	0.4
Upper premolar buccal root	0.3
Upper premolar palatal root	0.5
Upper molar mesio-buccal root	0.4
Upper molar palatal root	0.4
Lower central incisor	0.2
Lower lateral incisor	0.1
Lower canine	0
Lower first premolar	0.4
Lower first molar mesio-buccal root	0.4

Sharp drop of the signal at the apical foramen

The normal operation of an EAL is demonstrated by the smooth and gentle movement of the signal from the orifice to the apical foramen. Sometimes, the signal remains remote from the APEX mark and then drops abruptly as it reaches the apical foramen, which makes it very difficult to locate the apical foramen precisely. This mostly occurs with a very dry canal. When the file tip is at the extremely dried point, there is little or no electric contact, even at higher frequencies. As soon as it meets with the apical tissue, a sudden circuit breaks out, which brings the signal to the APEX mark. When this occurs, gentle irrigation of the canal will reiterate the normal operation of the unit. When an EAL is used in dry conditions, such as for the final working-length verification immediately before the obturation, the operator must judge carefully the appropriate position from the sharp dropping.

Apex sign from the beginning; severely bleeding or exudating canal

At times, the signal reaches the APEX mark far before the file enters the supposed foramen area. The cause of this phenomenon is too much electrolyte in the canal. This phenomenon occurs most often with extreme bleeding and actively draining pus or exudates from the canal. When this happens, the canal should be irrigated gently with sodium hypochlorite or saline until the drainage becomes reasonably controlled. The canal may need to be blot dried in some cases.

Premature reading, open apex

When there is an open or blunderbuss-type foramen, the meter tends to read short from the true apical foramen. A premature reading is probably due to the sharp drop in the gradient of the impedance ratio at the thin dentin wall. As described previously, the machine reads the largest gradient change in the impedance ratio wherever the file tip meets. The total impedance is the sum of the impedance created apically and of the dentin wall. Because the dentin wall has a much lower electrical capacitance than does the apical foramen, the impedance change depends mainly on the distance between the file tip and the apical foramen. When the dentin wall becomes extremely thin, the impedance of the root dentin wall affects the total impedance between the file tip and the lip clip, which renders a premature reading.

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