THE OPERATION PRINCIPLES OF ELECTRONIC ROOT CANAL LENGTH-MEASURING DEVICES

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ABSTRACT

Contemporary endodontics is unimaginable without electronic apex locators (EALs), devices that enable a clinician more accurate and time-saving positioning of the internal foramen, the preferable end-point of the root canal instrumentation and obturation in comparison to radiological method thus reducing the patient's exposure to radiation. The intention of this paper is to describe the electrochemical basis of operating principles of EALs and, also, to provide their classification based on operating principles together with their advantages and limits. Being familiar with these data, a therapist could achieve the best possible results with particular EAL in different conditions present in root canal under the treatment.

Key words: electronic apex locator, root canal length measurement, periapical tissue, tissue impedance

Introduction

The first idea of electronic method for determining the root canal length was founded by Custer research in 1918 [1]. He observed possible to determine the position of the root canal apical orifice benefiting from the fact that electric conductivity of the tissue surrounding the root tip is greater than the conductivity inside the root canal. It is also easier to detect the difference if the canal is dry or filled with non-conducting fluid such as ethanol. In other words, enamel, dentine and cement are insulators, while soft tissues including the periodontal ligament are conductors. In 1942, the research based upon the idea was taken over by Suzuki [2] who studied the flow of direct current through dog teeth. He found that there was a constant value of resistance between the instrument in the root canal and the electrode on the oral mucosa which, he assumed, could be used for measuring the length of the canal. Sunada [3] used those principles to manufacture a simple device for measuring the length of the canal using direct current. He established that the resistance value for oral mucosa and the periodontal ligament is constant in the entire periodontal ligament and has a value of 6,5 kΩ. He also established that the patient's age, type and shape of the teeth as well as the diameter of the canal do not affect that value [4].

The characteristics of the root canal electrical circuit

In order to explain the electrical flow inside the root canal, it is necessary to understand the basics principles of electro - chemistry. Two basic terms mostly encountered regarding electronic apex locators (EAL) are electrical resistance and impedance. When discussing direct current, electrical resistance (R) is the resistance of the material to the motion of electrons and is defined with Ohm's law as the ratio between voltage and current $R=U/I$. The equivalent of resistance when discussing alternating current is impedance $Z=U\sim/I\sim$, somehow more complicated term. If an electrical circuit features a resistor and a capacitor in series, the impedance Z of said circuit will be comprised of ohm resistance and capacitive resistance and its value is dependent on frequency. It means that, considering a constant amplitude voltage, the current will change depending on the frequency of the connected voltage. In biological impedance, an additional problem is in the fact that it is non-linear, meaning that its values also change depending on the amplitude of the voltage. The root canal is surrounded by dentine and cement which are insulators to the flow of electric current. On the internal physiological foramen, tissue within the canal, pulp tissue, transforms into periodontal tissue which conducts electricity. The tissue within the canal (pulp tissue or fluid) represents resistance (R), the value of which depends on the length (l), resistivity (ρ) and the cross-section of the area: $R=l_x\rho/A$. When an endodontic instrument approaches the root canal terminus the resistance between the tip of the instrument and the apical area of the canal decreases, because the effective length of the resistive material in the canal decreases (**Figure 1**) [5].

The electric equivalent scheme of electricity passing through root canals is more complicated than the resistor-capacitor model described above and the exact model is not easy to explain, especially when anisotropic values of dentine dielectric properties

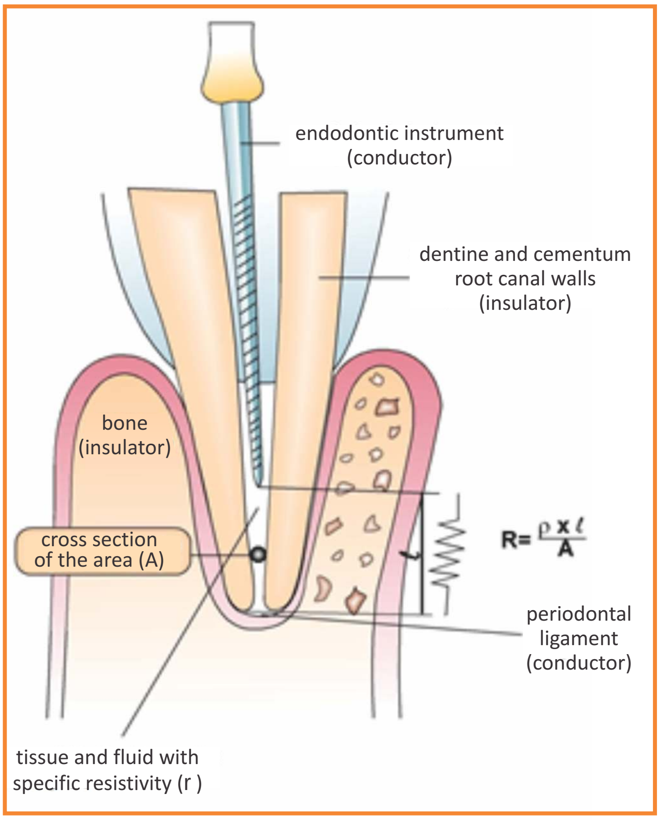

Figure 1. Schematic view of a tooth with regards to electrical conductivity and resistance during instrumentation of root canals.

are considered [6]. When emerging a metal electrode (equivalent to an endodontic instrument) into electrolyte, an electrochemical reaction called polarization occurs on the contact surfaces of the electrode and electrolyte, being the principle of operation for batteries. The metal electrode has a certain internal potential j m, and the electrolyte j s, with j m > j s. The occurring changes try to compensate for the differential in potential and to bring the system into electrochemical equilibrium. The potential difference can be compensated in two ways. The first way is to orientate dipole molecules near the surface of the electrolyte which will create surface potential differential Dx, and the second is redistribution of electrified particles. The electrons cross from the metal into the electrolyte where they combine with ions from the electrolyte. The result is an electric double layer, and a surplus of positive ions near the metal surface and a surplus of negative ions in the electrolyte. Between the electrode and electrolyte, a source of voltage is created, which depends on the types of metal and electrolyte. The necessary potential differential Dy is created to establish the following equality: j m - j s = Dj = Dx + Dy , the consequence of which is voltage. Aside from forming polarization voltage, the electrode-electrolyte transition also represents resistance to electric flow [7-10].

The basic electrochemical double layer model formed in such way was given by H.L.F. Helmholz and G. Quincke. They assumed that strong adhesive forces act between unlikely charged particles keeping them at distance d, equal to the distance between the metal surface and the center of the negatively charged ion. (**Figure 2a**) [11].

This situation corresponds to a parallel-plate capacitor separated by distance d which has constant capacity (C_H) per surface unit where ε represent dielectric constant; and potential decreases linearly from j m to j s. The capacity of the capacitor does not depend on electro-lyte type and imposed voltage which does not corres-pond to reality.

The next model was proposed by G.Gouy and D.L.Chapman who assumed that the charge on the side of the electrolyte is not bound to the surface of the electrode but is spaced according to the law of statistical distribution (**Figure 2b**) [11].

In the electric aspect, the double layer formed between the electrode and electrolyte can be explained

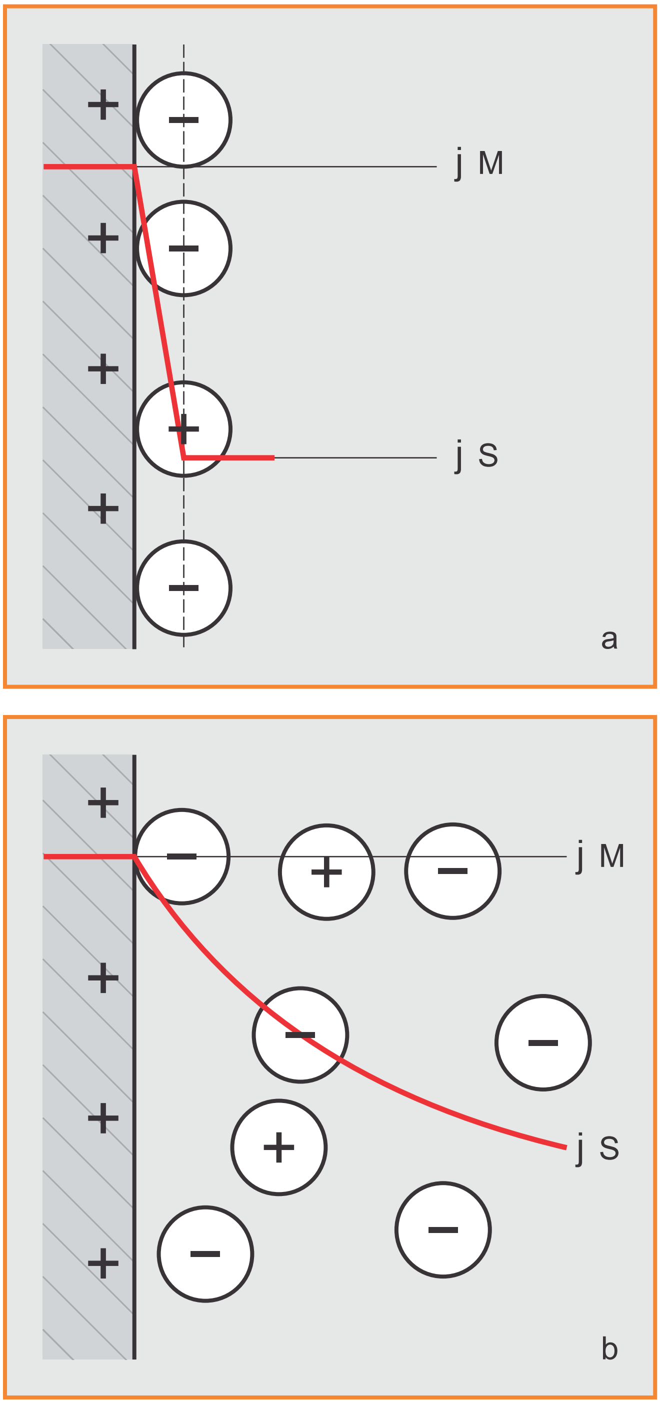

Figure 2.
Helmholtz electric double layer model (a)
and Gouy-Chapman's model (b)

as a voltage source with a voltage value depending on the value of polarization voltage (U_{pol}) connected in series with the parallel connection of a resistor and a capacitor. If transferred to a root canal, then endodontic instrument immersed into electrolyte root canal represents such an electrode and has certain impedance which can be represented by parallel connection of a resistor and a capacitor [10]. In simple words, current goes through the root canal

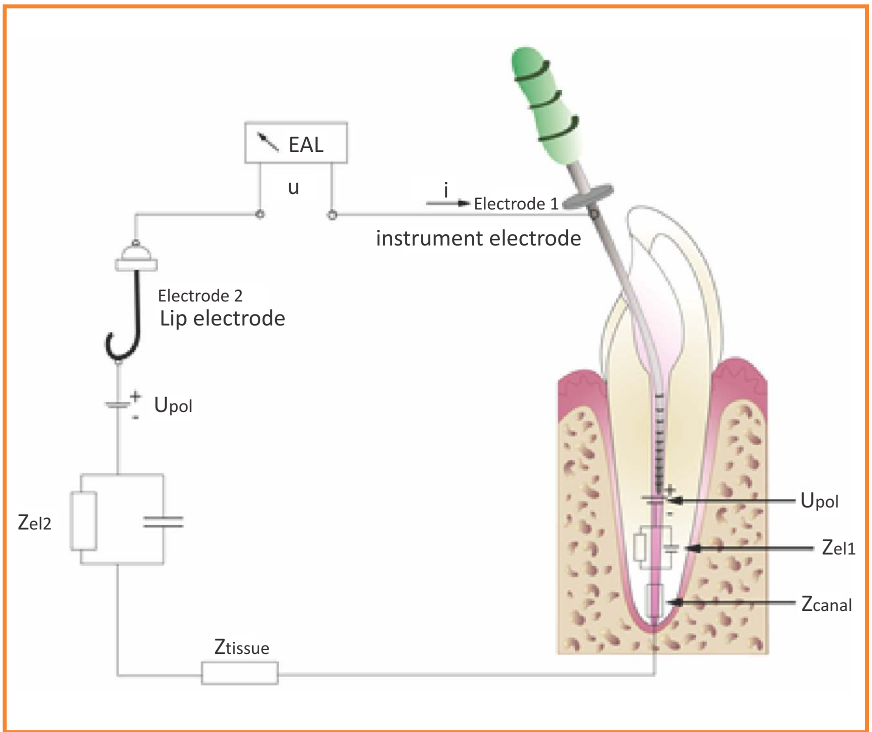

Figure 3.
Electric circuit during measuring with an alternating current. The EAL (electronic apex locator) provides voltage, and a circuit is closed via the endodontic instrument, the root canal, tissue in the periapex and surrounding structures, and the electrode tip. U_{pol} is voltage created as a consequence of immerging the electrode in the electrolyte (in this case the canal with i's characteristics), Z_{el1} is the impedance of the endodontic instrument, Z_{canal} is the impedance of the root canal which changes dependent on the position of the instrument in respect to the apical opening and the filling of the canal. Z_{tissue} refers to the impedance of the tissue around the root of the tooth and Z_{el2} is the impedance of the electrode attached to the lip. Upol also forms at the contact point of the lip electrode and the tissue, which in this case, acts as electrolyte.

and periodontal mucosa and the lip electrode enables closure of the electric circuit (**Figure 3**).

Considering that the surface area of the electrode used for closing the circuit (being attached to the lip) and the surface area of the tissue to which it is connected to, are much larger, their impedance is considerably smaller than the impedance of the measuring electrode (the endodontic instrument), thus, it's influence can be ignored. Therefore, Stare et al. [10] suggested much simpler circuit model for apex locator measurements as a series of electrode impedance and root canal resistance. The impedance of the electrodes is a consequence of the double layer between the electrode and electrolyte and can be described as a parallel connection of a resistor (Rp) and a capacitor (Cp). Furthermore, in alternating current circuits, the polarization potentials Upol don't affect the measurement, so the simplest depiction of the measurement circuit is a three component equivalent (**Figure 4**), where Rp and Cp correspond to measuring electrode (endodontic instrument) impedance, and Re corresponds to root canal resistance.

Classification of devices for determining root canal length (EAL)

Although literature usually cites generation-based classification with 5 electronic apex locator generations [12], and in recent times the sixth generation is mentioned [13,14], for educational purposes it is more appropriate to classify the devices according to their method of operation.

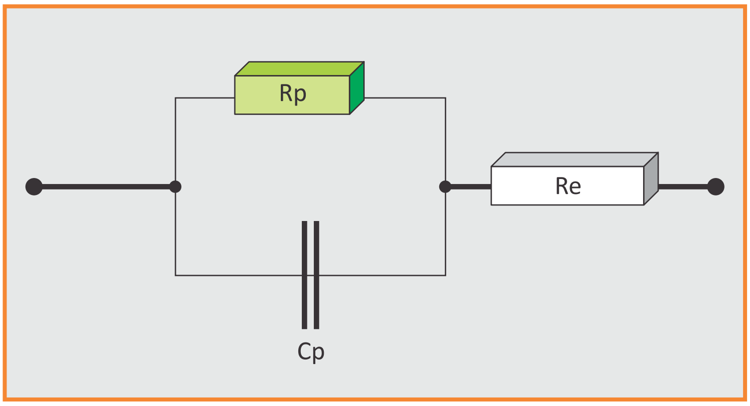

Figure 4.
Simplified electric model of a tooth: Rp and Cp – impedance of the measuring electrode,
Re – the resistance of the electrolyte – root canal [10].

Devices which measure electrical resistance using direct current are based on the assumption that the circuit between the endodontic instrument and the electrode on the lip can be figure out using the simple resistor model. Although many apex locators based on electric resistance measurement are relatively accurate in dry-canal conditions, powerful electrolytes, heavy bleeding, pus, or pulp tissue affect measurement results [15,16]. As soon as the instrument makes contact with electric conducting fluid, polarizations voltage appears, changing the current in measuring circuit and varies the tissue resistivity, leading to inaccurate localization of the internal opening. Another drawback of the direct current device is the fact that the patient may experience electric shock. These devices belong to the first generation of apex locators and are no longer in use. A representative of this generation is The Root Canal Meter (Onuki Medical Co., Tokyo, Japan) [17,18].

Polarization potential influence can be eliminated by introducing alternating current used in modern EALs [19]. The advantage of alternating current is lower measurement sensitivity and better performance in wet-canal conditions.

Devices based on the comparison of periodontal ligament and oral epithelia impedance: According to the assumption that impedance created as a result of resistance and capacity between the oral mucosa and gingival sulcus is equivalent to the impedance between the periodontal ligament (at the end of the canal) and the oral mucous membrane, devices were developed to measure these two impedance and to identify the end of the canal when these two values become equal [20].

One design has electrodes in the canal and the gingival sulcus connected to an oscillator circuit that changes frequency due to the change of impedance when moving the electrode. An instrument with plastic coating is inserted into the gingival sulcus and the "sound of the gingival crack" is measured. When a conventional endodontic instrument is inserted into the root canal and the sound the instrument makes becomes identical to the "gingival crack" sound, the work length is determined by fixing a stopper according to the reference point. A disadvantage of these devices is the need for individual calibration requiring a high level of precision [21]. The device needs to be calibrated individually for every tooth in its periodontal sulcus. A representative of this device type is Sono-Explorer (Hayashi Dental Supply, Tokyo, Japan) [5].

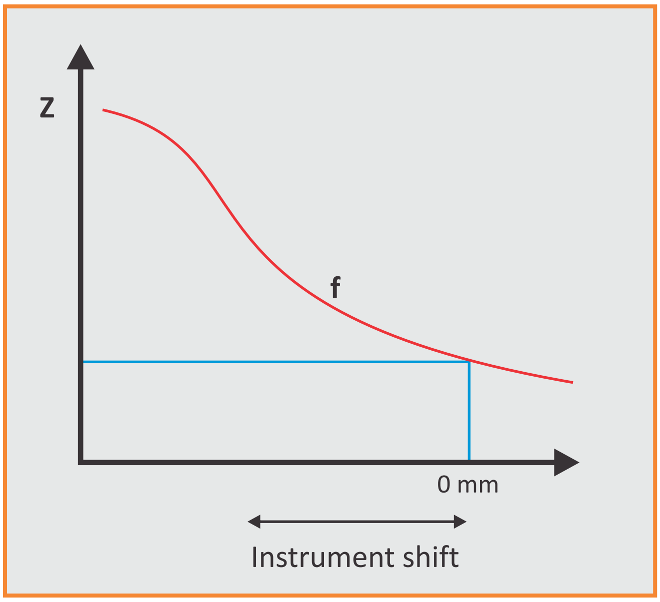

Figure 5.
Measuring of total impedance: Based on a large number of measurements, an average value of the total impedance is calculated at a certain position of the instrument near the root canal opening. Z –impedance, f – frequency

Devices that measure absolute impedance values: Those devices use alternating current with a frequency of several hundred to a thousand Hz. The effects of electrode impedance were tried to be reduced with the selection of current and frequency, and these devices do not require calibration before measurement. Their main drawback is an increased influence of electrolyte so either dry or wet canals are required, it is depending on calibration. A graphic depiction of the change in impedance depending on the position of the instrument tip is shown in **Figure 5**.

Device based on capacitive elements measurements use alternating 400 Hz current. In order to reduce influence of capacitive parameter variability in the canal, an isolated endodontic instrument is used. Given that a capacitor's capacity is directly proportionate to its surface area, insulator covers most of the instrument and reduces its capacity. Unfortunately, such a device cannot be used in a narrow canal because the material covering the instrument is easily abraded, leading to measurement errors. The device is Endocater (Yamuraura Seisokoshu, Japan) [22,23].

Devices based on voltage gradient measurement (impedance difference in three points): The first generations of locators defined constant resistance as the ending of the root canal. In several surveys, it was attempted to determine constant resistance or impedance in order to locate the ending of the root canal. However, it was discovered that there is neither single reference impedance nor constant resistance for all root canals. According to that, Ushiyama [24] suggested measuring differences in impedance or voltage between segments of a special multiple segment electrode making its way through the root canal. He concluded that a sudden change of value determines the position of the instrument on the apical constriction - the narrowest segment of the canal. Measuring voltage gradient prevents the presence of powerful electrolytes to disrupt measurements. Disadvantage of devices based on this principle is that they require use of special bipolar electrodes being hard to insert into the root canal. Thus, such devices are still not commercially available.

Devices that measure impedance differences of two frequencies: To improve the accuracy of measurements and to reduce the influence of different parameters, in 1984, a device was developed uses two frequencies for measurements. It measures the impedance at each frequency and calculates the difference between the two values. In fact, it measures the difference in voltages at two frequencies which is proportional to the differences in impedance. When an instrument nears the end of the root canal, the value of capacity grows, likely because of the change of morphology of the apical segment of the root canal. The value of the first frequency used in these devices is five to ten times greater than the second frequency. Impedance at different frequencies behaves differently when moving the electrode in the canal and when moving it closer to the apical opening (**Figure 6**). Calibration of the system is necessary in the coronary segment of the root canal to remove the influence of dielectric materials in the canal.

The disadvantage of these locators is that, if they are calibrated for wet canals, they cannot determine the canal ending in dry conditions. A representative of this type EALs is Endex or Apit (Osada Electric Co., Tokyo, Japan) [25,26].

Devices that measure the ratio of impedance at two frequencies determine the location of the instrument inside the canal by measuring the impedance at low and at high frequency. Because of the effects of captivity, the total impedance is reduced by increasing frequency ($X_c=1/2\pi * f * C$). If the ratio of impedance at two frequencies is used as a measure for the displacement of the electrode, rather than their absolute value, then it does not depend on the electrolyte in the canal. This occurs because of the fact that the electrolyte fluid is determined by its dielectric constant. It affects the dividend and the divisor in the equation in the same way, so the ratio remains constant. Therefore, the accuracy of measurement does not depend on the presence of fluid in the canal or on the fact that the pulp is vital or necrotic. The lack of a narrowing caused by an open apical foramen or by an impassable canal affects the accuracy in reading the root canal ending. The representative of this group is Root ZX (J. Morita, Tokyo, Japan) [27-30].

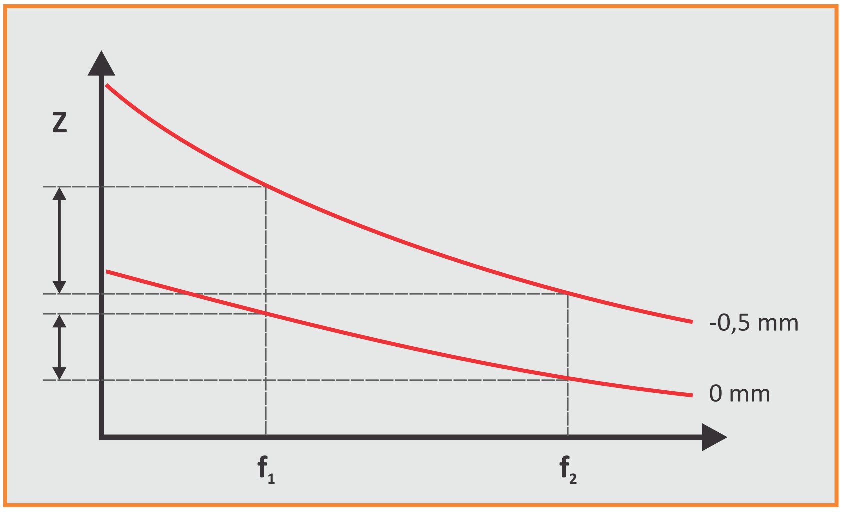

Figure 6.
Graphic depiction of impedance differences when measuring at different frequencies. When the instrument is 0,5 mm away from the outer opening the impedance difference at the two frequencies has a certain value (ΔZ1), which is different from the impedance difference at the two frequencies when the instrument is at the outer opening (ΔZ2).

Devices which use multiple frequencies are reflections of the aspiration to further develop apex locators. The principle for these devices operation is similar to devices using two frequency ratios. Up to five different frequencies are used, and devices measure both components (phase and amplitude) of the impedance for each frequency. They are then analyzed and the apical constriction is determined by the sudden change of the dominant component of impedance (capacity or resistance). Devices belonging to this group of apex locators are Apex Finder AFA (All Fluids Allowed) and Neosono Ultima EZ (Satelec Inc., Mount Laurel, NJ, USA).

Devices based on determining the elements of impedance also measure the impedance at two frequencies but use those measurements to determine the equivalent resistance and capacity. For that purpose experimental tables have been constructed with statistically calculated values at different positions. The device uses a complex signal of two frequencies to measure resistance and capacity. Provided values are then compared with earlier calculated values in tables and the position of the instrument in the canal is determined. The device is Elements Diagnostic Unit and Apex Locator (SybronEndo, Anaheim, CA, USA) [31, 32].

Devices that adapt to conditions in the canal by determining moisture conditions in the canal using mathematical analysis while penetrating into the canal, thus adapting the measuring method for either dry or wet canal. These devices are called adaptive apex locators. Measurements provided from these apex locators show the same values in the same canal independently from the contents of the canal, being it dry or wet [13,14].

Conclusion

Today, EALs are priceless aid in everyday endodontic work. Without them it is not advisable to be engaged in an endodontic procedure. Although absolute accuracy in determining apical constriction and the place up to which instrumentation and root canal filling should be exerted are not possible because of the nature of biological measurement itself, many in vivo and in vitro researches have shown that their accuracy is equal to or greater than the accuracy of the radiological method, which can reduce patient exposure to radiation without negative effects on treatment outcomes [33-38]. Knowing the operating principles of EALs enables the operator to adapt the measurement conditions to those that best suit certain device type and provide the most accurate results, allowing the practitioner to assess the accuracy of results from each individual measurement.

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Declaration of interest

Authors declare no conflict of interest.

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