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REVIEW

The fundamental operating principles of electronic root canal length measurement devices

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Abstract

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It is generally accepted that root canal treatment procedures should be confined within the root canal system. To achieve this objective the canal terminus must be detected accurately during canal preparation and precise control of working length during the process must be maintained. Several techniques have been used for determining the apical canal terminus including electronic methods. However, the fundamental electronic operating principles and classification of the electronic devices used in this method are often unknown and a matter of controversy. The basic assumption with all electronic length measuring devices is that human tissues have certain characteristics that can be modelled by a combination of electrical components. Therefore, by measuring the electrical properties of the model, such as resistance and impedance, it should be possible to detect the canal terminus. The root canal system is surrounded by dentine and cementum that are insulators to electrical current. At the minor apical foramen, however, there is a small hole in which conductive materials within the canal space (tissue, fluid) are electrically connected to the periodontal ligament that is itself a conductor of electric current. Thus, dentine, along with tissue and fluid inside the canal, forms a resistor, the value of which depends on their dimensions, and their inherent resistivity. When an endodontic file penetrates inside the canal and approaches the minor apical foramen, the resistance between the endodontic file and the foramen decreases, because the effective length of the resistive material (dentine, tissue, fluid) decreases. As well as resistive properties, the structure of the tooth root has capacitive characteristics. Therefore, various electronic methods have been developed that use a variety of other principles to detect the canal terminus. Whilst the simplest devices measure resistance, other devices measure impedance using either high frequency, two frequencies, or multiple frequencies. In addition, some systems use low frequency oscillation and/or a voltage gradient method to detect the canal terminus. The aim of this review was to clarify the fundamental operating principles of the different types of electronic systems that claim to measure canal length.

Keywords: apex locators, canal length, endodontics, root canal terminus.

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Introduction

The presence of bacteria and their by-products within the root canal system predisposes to apical periodontitis. In essence, treatment of a microbial inflammatory disease is directed at the elimination of the antigenic source through the elimination of infection (Chugal *et al.* 2003). Root canal treatment involves removing microorganisms from within the pulp space, and the filling of the root canal system to prevent reinfection. Furthermore, restoring the tooth to prevent recontamination and reinfection is essential (Heling *et al.* 2002). In other words, the goal of root canal treatment is to control infection through the debridement, disinfection and filling of the root canal system (Lin *et al.* 2005).

It is generally accepted that root canal treatment procedures should be limited to within the root canal system (Ricucci 1998). To attain this objective the end-point of the root canal system, the canal terminus, should be detected as precisely as possible during preparation of the canal. Therefore, one of the main concerns in root canal treatment is to determine how far instruments should be advanced within the root canal and at what point the preparation and filling should terminate (Katz *et al.* 1991).

Morphology of the root canal terminus

Kuttler (1955) concluded that a root canal had two main sections, a longer conical section in the coronal region consisting of dentine and a shorter funnel-shaped section consisting of cementum located in the

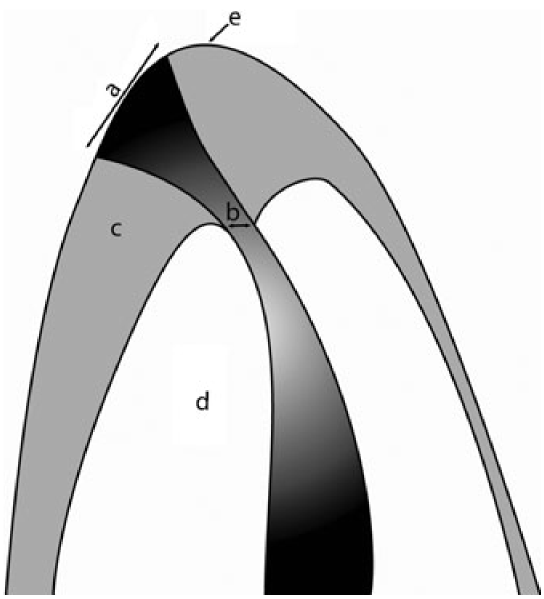

Figure 1 Idealized anatomy of apical portion of root (a) major apical foramen, (b) minor apical foramen (apical constriction) that may be coincident with the cemento-dentinal junction (CDJ), (c) cementum, (d) dentine and (e) root apex.

apical portion. The shape of this apical portion is considered to be an inverted cone (Fig. 1); its base being located at the major apical foramen. The apex of the inverted cone is the minor foramen that is often thought to coincide with the apical constriction regarded as being at or near the cemento-dentinal junction (CDJ) (Kuttler 1958). In other words, the most apical portion of the root canal system narrows from the opening of the major foramen, which is within cementum, to a constriction (minor foramen) before widening out in the main canal to produce an hour-glass shape (Fig. 1).

It is well known that the major apical foramen is not a uniform shape but can be asymmetrical (Blaskovic-Subat *et al.* 1992). Furthermore, its position on the root tip varies. For example, Stein & Corcoran (1990) reported that with increasing age the deviation of the major foramen from the root tip increased, whilst others have reported that the frequency of the deviation depended on the type of teeth (Blaskovic-Subat *et al.* 1992). Moreover, deviation of the foramen can occur as a result of pathological changes, the most common being external root resorption (Malueg *et al.* 1996).

The root canal terminus is considered by many to be the CDJ (Kuttler 1955, 1958, Ricucci 1998, Ponce & Fernandez 2003). In some instances the CDJ coincides with the pulp and periodontal tissue junction, where the pulp tissue changes into apical periodontal tissue (Seltzer 1988). Theoretically, the CDJ is the appropriate apical limit for root canal treatment as at this point the area of contact between the periradicular tissues and root canal filling material is likely to be minimal and the wound smallest (Palmer *et al.* 1971, Seltzer 1988, Katz *et al.* 1991, Ricucci & Langeland 1998). The term 'theoretically' is applied here because the CDJ is a histological site and it can only be detected in extracted teeth following sectioning; in the clinical situation it is impossible to identify its position. In addition, the CDJ is not a constant or consistent feature, for example, the extension of the cementum into the root canal can vary (Ponce & Fernandez 2003). Therefore, it is not an ideal landmark to use clinically as the end-point for root canal preparation and filling.

Defining the canal terminus as the apical constriction and not the CDJ is also problematical, as the topography of the apical constriction is not constant (Dummer *et al.* 1984). Indeed, the apical constriction can have a variety of morphological variations that makes its identification unpredictable. In clinical practice, the minor apical foramen is a more consistent anatomical feature (Katz *et al.* 1991, Ponce & Fernandez 2003) that can be regarded as being the narrowest portion of the canal system and thus the preferred landmark for the apical end-point for root canal treatment.

Determining the root canal terminus

Various techniques have been used for determining the position of the canal terminus and thus measure the working length of root canals. The most popular method has been the use of radiographs. However, although it is generally accepted that the minor apical foramen and apical constriction is on average located 0.5–1.0 mm short of the radiographic apex (Katz *et al.* 1991, Morfis *et al.* 1994) there are wide variations in the relationship of these landmark that would result in under- or over-preparation of canals with an obvious impact on the position of the root filling (Stein & Corcoran 1990, Olson *et al.* 1991). Thus, many studies have shown that canal lengths determined radiographically vary from actual root canal lengths by a considerable amount (Kuttler 1955, 1958, Green 1956, Green 1960, Dummer *et al.* 1984, Forsberg 1987a,b, Martinez-Lozano *et al.* 2001).

The accuracy of radiographic methods of length determination depend on the radiographic technique that has been used (Forsberg 1987a, Katz *et al.* 1991). For example, Sheaffer *et al.* (2003) revealed that higher density radiographs were more desirable for measuring working length. Forsberg (1987b) reported that tooth length determined by the bisecting angle technique, either correctly or incorrectly angulated, was less accurate than the paralleling technique. Although radiographs are a critical and an integral part of endodontic therapy (Vertucci 2005) there is an ongoing need to reduce exposure to ionizing radiation whenever possible (Brunton *et al.* 2002, Pendlebury *et al.* 2004).

It is well known that the major apical foramen is not always located at the radiographic apex of the root; rather, it often lies on the lingual/buccal or mesial/distal aspect. If the major foramen deviates in the lingual/buccal plane (Fig. 2), it is difficult to locate its position using radiographs alone, even with multiplane angles (Schaeffer *et al.* 2005).

One of the innovations in root canal treatment has been the development and production of electronic devices (McDonald 1992) for detecting the canal terminus. Their functionality is based on the fact that the electrical conductivity of the tissues surrounding the apex of the root is greater than the conductivity inside the root canal system provided the canal is either dry or filled with a nonconductive fluid (Custer 1918). Suzuki (1942) indicated that the electrical resistance between a root canal instrument inserted into a canal and an electrode applied to the oral mucous membrane registered consistent values. Based on these findings, Sunada (1962) reported that when the tip of an endodontic instrument had reached the periodontal membrane through the 'apical foramen', the electrical resistance between the instrument and the oral mucous membrane was a constant value. Based on this fundamental principle, these resistance-based devices should be able to detect the periodontal tissue at the 'apical foramen'. Clearly, they do not assess the position of the root apex and the name 'electronic apex locator' is not appropriate; 'electronic apical foramen locator' or 'electronic root canal length measurement device' (ERCLMD) as a generic name would be more appropriate.

The manufacturers of more recent electronic devices claim their products locate the apical constriction (http://www.vdw-dental.com/home_e/index.html,

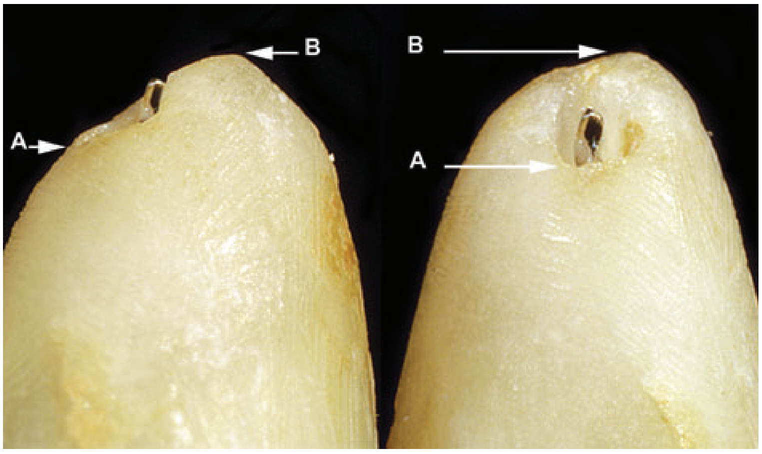

Figure 2 (a) Major apical foramen (apical opening) with protruding instruments; (b) root apex.

http://www.jmoritausa.com/Marketing/pdf/RootZX_IFU.pdf, http://www.averon.ru/english/dental/equipment/apex.htm, http://www.micro-mega.com/anglais/produits/apexpointer/index.php, http://www.parkell.com/master.html, http://www.parkell.com/foramatron.html). Their claims are based on the fact that these newer devices operate using different electronic principles compared with the original resistance-based devices (Kim & Lee 2004). However, the evidence suggests their claims are not correct, for example, Hoer & Attin (2004) reported that accurate determination of the apical constriction was only successful in 51–64% of canals depending on the device used. The probability of determining the position between the minor and major foramen was between 81 and 82% of cases. Welk *et al.* (2003) also reported that the ability of various types of ERCLMDs to determine the 'minor diameter' was between 90.7 and 34.4%.

Because of the hazards of radiation (Katz *et al.* 1991, Brunton *et al.* 2002, Pendlebury *et al.* 2004), the technical problems associated with radiographic techniques (Heling & Karmon 1976, Forsberg 1987a) and to avoid over-instrumentation beyond the canal terminus (ElAyouti *et al.* 2002) electronic working length determination has gained popularity amongst both general dentists and endodontists (Frank & Torabinejad 1993). The electronic method is also more convenient to the patient and has potential to enable root canal treatment to be performed during pregnancy (Trope *et al.* 1985). Unfortunately, most manufacturers do not define the exact nature of their devices nor how they operate electronically. Classifying and describing the devices by 'Generation' is not helpful to clinicians and is better suited to marketing issues. In essence, it is not possible to classify all the various products on the market; rather, only those whose fundamental operating principles have been released by the manufacturer can be categorized (Table 1). Clearly, with the limited information provided by manufacturers the classification of electronic devices used to measure canal length is a matter of controversy and ignorance (Nekoofar 2005).

The aim of this article is to describe the fundamental operating principles of ERCLMDs and classify them on this basis (Table 1). Initially, a review of basic electronics is presented in order to provide an understanding of electronic devices and circuits; the electronic function of ERCLMDs is then discussed.

Atom structure

To understand the basics of electronics, the structure of the *atom*, which is the smallest particle of materials that retain their characteristics, should be defined. Atoms are made of *electrons*, *protons* and *neutrons*. According to the classic Bohr model (Coombs 1999); atoms have a planetary type of structure that comprises a central nucleus surrounded by orbiting electrons. The nucleus consists of positively charged particles called protons and uncharged particles called neutrons. The basic particles of negative charge are called electrons.

Electrons orbit the nucleus of an atom at certain distances from the nucleus. Electrons that are in orbits

Table 1 Categorization of electronic root canal length measurement devices

Type	Name	Manufacturer
Resistance-based ERCLMDs	Endodontic Meter®	Parkell Inc., New York, NY, USA
	Endometer®	
	Faramatron 4®	
	Apex Finder®	
Low frequency oscillation	Sono-Explorer®	Hayashi Dental Supply, Tokyo, Japan
	Sono-Explorer Mark II®	
High frequency devices (capacitance-based devices)	Endocater®	Hygenic Corp., Akron, OH, USA
Capacitance and resistance look-up table	Elements® Diagnostic unit	SybronEndo, Orange, CA, USA
Voltage gradient (difference in impedance with three nodes)	No commercial model available	
Two frequencies, impedance difference	Apit®	Osada, Tokyo, Japan
	Apex pointer®	MicroMega, Besançon, France
	Root ZX®	J. Morita Co., Kyoto, Japan
Impedance ratio (Quotient)	Justy II	Parkell Inc., New York, NY, USA
	Endy 5000	Parkell Inc., New York, NY, USA
Multifrequency	Endo Analyzer® (8005)	SybronEndo, Orange, CA, USA
	AFA Apex Finder® (7005)	SybronEndo, Orange, CA, USA
Unknown	Foramatron® D10	

further from the nucleus are less tightly bound than those closer to the nucleus. This is because the force of attraction between the positively charged nucleus and the negatively charged electron decreases with increasing distance from the nucleus. Therefore, electrons existing in the outermost shell of an atom are relatively loosely bound to the atom. For example, in the copper atom the most outer shell has one electron and when that electron gains sufficient thermal energy it can break away from the parent atom and become a free electron. In copper at room temperature, a large number of these free electrons are present that are not bound to any atom and are free to move. Free electrons make copper an excellent conductor and make electrical current possible. Other conductive materials may have similar characteristics but with different conductivity determined by their atom structure.

Ions and electrolyte

When the number of electrons changes in an atom, the electrical charge will change. If an atom gains electrons, it picks up an imbalance of negatively charged particles and will become negative. If an atom loses electrons, the balance between positive and negative charges is shifted in the opposite direction and the atom will become positive. In either case, the magnitude (+1, +2, −1, −2, etc.) of the electrical charge will correspond to the number of electrons gained or lost. Atoms that carry electrical charges are called ions (regardless of whether they are positive or negative). A cation is an ion that has lost electrons and acquired a positive charge; an anion is an ion that has gained electrons and acquired a negative charge.

Not only do electrons flow along a wire in an electric circuit, but electrons can also be carried through water if it contains ions in solution. Ionic solutions that conduct electricity in a manner similar to wire are called electrolytes. The conductance of electrolytes is the result of the movement of ions through the solution towards the electrodes. When two electrodes in a solution are part of a complete electrical circuit, the cations (+) are attracted to the negative pole (cathode) and the anions (−) are attracted to the positive pole (anode).

The conductivity of any particular ion will be affected by the ease with which the ion can move throughout the water. The ease with which any ion moves through a solution depends on factors such as the total charge and the size of the ion; large ions offer greater resistance to motion through the electrolyte than small ions. The greater the number of ions present, the greater the electrical conductivity of the solution.

Electrical charge, voltage and current

Electrical charge, symbolized by Q, is either positive or negative. The electron is the smallest particle that exhibits negative electrical charge. When an excess of electrons exists in a material, there is a net negative electrical charge, and conversely, a deficiency of electrons forms a net positive electrical charge. Materials with charges of opposite polarity are attracted to each other and materials with charges of similar polarity are repelled.

A certain amount of energy must be used in the form of work to overcome the forces and move the charges a given distance apart. All opposite charges possess a certain potential energy because of the separation between them. The difference in potential energy of the charges is *voltage*. Voltage, symbolized by V, is the driving force in electric circuits and is what establishes current. The unit of voltage is the *volt*. Voltage provides energy to electrons or ions that allows them to move through a circuit. This movement is electrical current characterized by I, which results in work being done in an electric circuit. The measurement unit of current is ampere.

Resistance

When there is a current of free electrons in a material the electrons occasionally collide with atoms. These collisions cause the electrons to lose some of their energy, and thus restrict their movement. The more collisions, the more the flow of electrons is restricted. This restriction varies with the type of material, the property of which is called resistance and is designated as R; it is expressed in the unit of ohms (Ω). However, when electrical current is formed by ions, the current is restricted by other means. When a voltage (potential difference) is applied between two points in an electrolyte, ions between them will be attracted by the opposite charge and so will move between the points and produce a current. The resistance of such electrolytic solutions depends on the concentration of the ions and also on the nature of the ions present, in particular, their charges and mobilities. Thus, resistance is a variable that depends on concentration.

This physical effect is called resistivity which is represented by ρ. For each material, ρ can be a constant value at a given temperature. Thus, the resistance of an object can simply depend on three factors: (i) resistivity, (ii) length and (iii) cross-sectional area. The formula for the resistance of an object of length l and cross-sectional area A is:

$$R = \frac{\rho \times l}{A}. \quad (1)$$

The formula shows that resistance increases with resistivity and length, and decreases with cross-sectional area. In fact, resistivity (ρ) is the parameter that classifies conductive materials from insulators. Insulators cannot conduct electric currents because all their electrons are tightly bound to their atoms. A perfect insulator would allow no charge to be forced through it, however, no such substance is known at room temperature. The best insulators offer high but not infinite resistance at room temperature. For instance, the resistivity of human thorax bone at normal temperatures is approximately 16 000 Ω m^{-1} (Geddes & Baker 1967) whilst for blood it is 100 times less at approximately 162 Ω m^{-1} (Rush *et al.* 1963). Thus, bone is a relatively poor conductor whilst blood is a relatively good conductor of electric current.

Electric circuits and the human body

Current through the body, not voltage, is the cause of an electrical shock. When a point on the body comes in contact with a voltage and another point comes in contact with different voltage, there will be a current through the body from one point to the other. The severity of the resulting electrical shock depends on the amount of voltage and the path that the current takes through the body (Bridges 2002). To measure the effects of current on the human body, the amount of current should be calculated. This is dependent on the potential difference, the impedance driving the potential difference and the resistance within the body between the points of contact (Niple *et al.* 2004). The human body has resistance that depends on many factors, including body mass, skin moisture and points of contact of the body with a voltage potential. The human body does not sense currents less than a few milliamperes (Gandhi 2002). However, about hundred milliamperes of current will cause fatal damage; especially if it is connected for more than several seconds (Bridges 2002).

Ohm's law

Ohm's law describes the mathematical relationship between voltage, current and resistance in a circuit. Ohm determined that if the voltage across a resistor is increased, the current through the resistor will increase and conversely, if the voltage is decreased the current will decrease. Ohm's law also shows that if the voltage (V) is kept constant, less resistance (R) results in more current (I), and more resistance results in less current. Ohm's law can be stated as follows:

$$I = \frac{V}{R} \quad \text{or} \quad V = I \times R \quad \text{or} \quad R = \frac{V}{I}. \quad (2)$$

Electrolyte solutions also obey Ohm's law just as metallic conductors do. From a macroscopic point of view, ionic conduction of solutions is similar to electron conduction through solid objects. In the latter, electrons are moving without ion cores, whilst in the former, charges are moving as ions. Although water itself is a poor conductor of electricity, the presence of ions in solution decreases the resistance considerably. The resistance of such electrolytic solutions depends on the concentration of the ions and also on the nature and size of the ions present.

Direct current and alternating current

Direct current (DC) is a fixed amount of current per unit of time, whereas the amount of an alternating current (AC) alternates with time. The sine wave (or sinusoidal wave) is the fundamental type of alternating current and alternating voltage. Figure 3 is a graph showing the general shape of a sine wave, which can be either an alternating current or an alternating voltage. In fact, when a sinusoidal voltage source is applied to a resistive circuit, it will result in an alternating sinusoidal current.

The current (or voltage) varies with time, starting at zero, increases to a positive maximum, returns to zero, and then increases to a negative maximum before again returning to zero, thus completing a full cycle. The time (in seconds) required for a given sine wave to complete one full cycle is called the period (T).

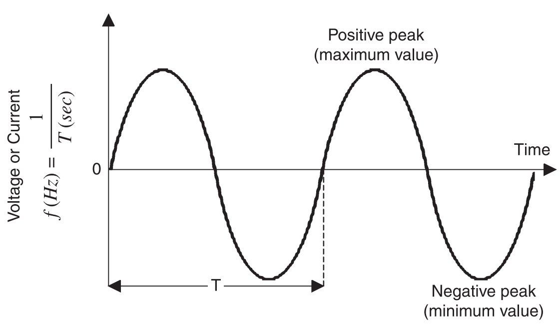

Figure 3 A sine wave as an alternating voltage or current.

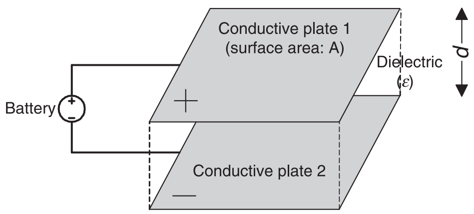

Figure 4 A simple capacitor connected to a battery (DC voltage source).

Frequency is the number of cycles that a sine wave completes in 1 s. The more cycles completed in 1 s, the higher the frequency. Frequency is symbolized by *f* and is measured in units of hertz (*Hz*).

Capacitor

A structure of two conductive materials with an insulator between them forms an electrical device called a capacitor. In its simplest form shown in Fig. 4, a capacitor is constructed of two parallel metal plates separated by an insulating material called a dielectric. When a capacitor is connected to a DC voltage source, electrons (negative charge) move from one plate to another, making one plate acquire a negative charge and the other a positive charge. When the voltage source is disconnected, the capacitor would still retain the stored charge and a voltage will remain across it. The amount of charge that a capacitor can store will determine its capacitance.

The following parameters are important in establishing the capacitance of a capacitor: plate area (A), plate separation (d) and dielectric constant (ε). A large plate area produces a large capacitance and a smaller plate area produces a smaller capacitance. Conversely, the plate separation (d) is inversely proportional to the capacitance, i.e. a greater separation of the plates reduces the capacitance. Finally, the insulating material between the plates (the dielectric) will directly influence the capacity by its dielectric constant (ε) as shown in the equation:

$$C = \frac{\epsilon \times A}{d} \tag{3}$$

As a result of the insulator, a capacitor will block constant DC. However, it allows the AC to pass with an amount of opposition that depends on its capacitance and the frequency of the AC. This opposition is called capacitive reactance (X_C) calculated from the following formula:

$$X_C = \frac{1}{2\pi \times f \times C} \tag{4}$$

where π is almost equal to 3.14, f is the frequency and C is the capacitance. When f is zero (DC), X_C becomes infinite and so blocks the DC. At nonzero frequencies (alternating current) it takes other values and becomes analogous to the resistance of a resistor, hence, Ohm's law applies to capacitive circuits as follows:

$$I = \frac{V}{X_c} \quad \text{or} \quad V = I \times X_c \quad \text{or} \quad X_C = \frac{V}{I}. \tag{5}$$

Impedance and its measurement

In a circuit that has both capacitors and resistors, the total amount of opposition to an alternating current is called impedance which is represented by Z. Again, Ohm's law applies to these circuits:

$$I = \frac{V}{Z} \quad \text{or} \quad V = I \times Z \quad \text{or} \quad Z = \frac{V}{I}. \tag{6}$$

The value of impedance in a circuit that has both resistors and capacitors depends on the resistance values (R) of its resistors and the reactance (X_C) values of its capacitors.

There are several methods to measure the impedance value of a material. The basic method is to apply an electrical current to the material and measure the resulting voltage. According to Ohm's law (equation 6), the division product of the voltage value over the current value gives the value of impedance. If the material comprises resistive elements only, a DC can be enough for this measurement (using equation 2). However, in the presence of capacitive elements, an AC current highlights the capacitive characteristics of the impedance as well as the resistive part. The frequency of the AC current will influence the measured impedance value as the capacitive component of the impedance is variable with frequency (see equation 4).

The use of DC is impractical for measurement of the resistance of an electrolyte, as the electrodes become polarized. The behaviour of electrolytic solutions is of huge technological importance as well as of great scientific interest. However, during electroconductivity measurement, polarization can be prevented by using a high-frequency alternating current, so that the quantity of electricity carried during one half-cycle is insufficient to produce any measurable polarization, although various electrolytes in different conditions may exhibit different conductivities.

It should be added that an impedance, in electrical terms, has two properties: amplitude (or simply value) and phase. For simplicity in the context of this paper, impedance is normally identified with its value. In addition, as mentioned above, there are a number of methods to measure impedance value or phase electrically, e.g. Wheatstone bridge (Lazrak *et al.* 1997), Phase-sensitive detection (Hartov *et al.* 2000), and Sine-wave correlation (Van Driessche *et al.* 1999). Electronic publications will provide more details (Coombs 1999).

Electrical features of tooth structure

Root canals are surrounded by dentine and cementum that are insulators to electric current. At the minor apical foramen, however, there is a small hole in which conductive materials within the canal are electrically connected to the periodontal ligament that is a conductor of electric current. The resistive material of the canal (dentine, tissue, fluid) with a particular resistivity forms a resistor, the value of which depends on the length, cross-sectional area and the resistivity of the materials (Fig. 5). If an endodontic file penetrates inside the canal, and approaches the canal terminus, the resistance between the end of the instrument and the apical portion of the canal decreases, because the effective length of the resistive material inside the canal (*l* in Fig. 5) decreases.

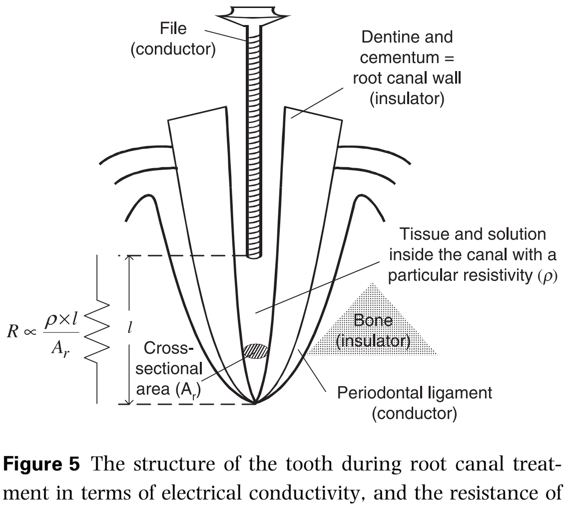

Figure 5 The structure of the tooth during root canal treatment in terms of electrical conductivity, and the resistance of the model.

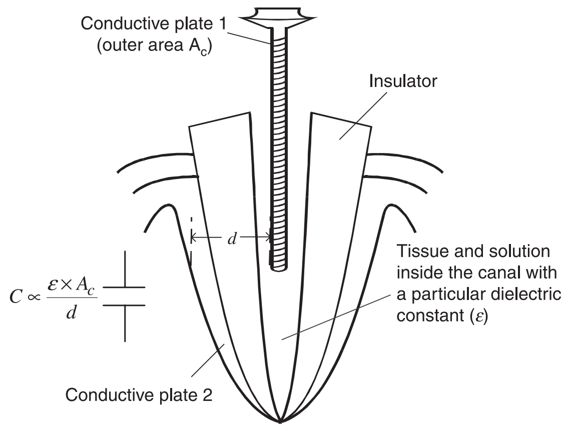

Figure 6 The capacitance of the tooth during root canal treatment.

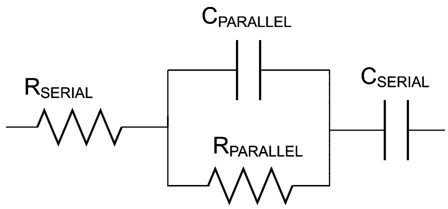

Figure 7 The simplified electronic model of a tooth proposed by Meredith & Gulabivala (1997).

As well as resistive properties, the structure of the tooth has capacitive characteristics. Assume the file, with a specific surface area, to be one side of a capacitor and the conductive material (e.g. periodontal ligament) outside the dentine being the other plate of that capacitor. Tissue and fluid inside the canal, in addition to the cementum and dentine of the canal wall, can be considered as separators of the two conductive plates and determine a dielectric constant ε. This structure forms a capacitor, much more complex than symbolized in Fig. 6.

The electrical structure of the canal is much more complicated than the resistive and capacitive elements described above and the exact modelling of it is not a straightforward task (Meredith & Gulabivala 1997). Meredith & Gulabivala (1997) proposed an equivalent circuit that modelled the root canal system including periapical tissues. They found that the root canal acted as a complex electrical network with resistive and capacitive elements. It exhibited complex impedance characteristics having series and parallel resistive and capacitive components with a simplified model shown in Fig. 7.

Electronic root canal length measurement devices

The fundamental assumption of ERCLMDs is that human tissues have certain characteristics that can be modelled by means of a combination of electrical components. Therefore, by measuring the electrical properties (e.g. resistance, impedance) of that equivalent electric circuit, some clinical properties (such as the position of a file) can be extracted.

Custer (1918) introduced a new electrical approach for locating the canal terminus that was dependent on the fact that the electrical conductivity of the tissues surrounding the apex of the root is greater than the conductivity inside the root canal system, coronal to the canal terminus. Custer (1918) noted that this difference in conductivity values could be detected more easily if the canal was dry or filled with a nonconductive liquid such as alcohol. In other words, he discovered that the electrical resistance, the inverse value of conductivity, near the '*foramen*' was much less than in the coronal region of the root canal. Therefore, Custer (1918) located the position of the '*foramen*' by applying a voltage between the '*alveolus opposite the root apex*' and the '*broach inside the pulp*' and measuring the value of the electrical current (with a '*milammeter*'). In his pioneer experiment, using the technology of that time, Custer's electrical circuit had three '*dry cells*': a '*milammeter*', a negative and a positive electrode. When the circuit was connected, a small positive voltage was applied to the fine insulated '*broach*' which was introduced into the '*pulp*' and slowly penetrated inside it. When the '*broach*' approached the '*foramen*', as a result of a significant increase in the electrical conductivity, the electrical current became more and as a consequence a '*certain movement in the index finger*' of the ammeter was observed. Custer (1918) concluded that this movement, which was proportional to the electrical current and so the electrical conductivity, would be a reliable guide to the position of the broach relative to the '*apical foramen*'. Subsequently, Suzuki (1942) in his experimental study on iontophoresis in dog's teeth indicated that the electrical resistance between a root canal instrument inserted into a canal and an electrode applied to the oral mucous membrane registered consistent values.

Based on Suzuki's finding, Sunada (1962) reported that a specific value of the resistance would determine the position of the root canal terminus. He determined that when the tip of an endodontic instrument had reached the periodontal membrane through the '*apical foramen*', the electrical resistance between the instrument and the oral mucous membrane was approximately equal to 6.5 kΩ. He also claimed that if the reamer perforated the canal wall or floor of the pulp chamber and reached the periodontal membrane, the electrical resistance between the mucous membrane and the perforated periodontal membrane was almost equal to the resistance shown at the apex. In his first *in vivo* experiment, Sunada (1962) used a simple micro-ammeter to measure the length of 71 canals. The micro-ammeter had two electrodes, one attached to the oral mucous membrane, the other to an endodontic instrument positioned in the root canal; the resistance was measured when the tip of the endodontic instrument was situated at the apex (the length of the teeth were already known '*by means of a measuring wire and X-ray*') the resistance of the periodontal membrane was calculated by dividing the voltage by the value of current that the device measured. In other words, dentine, enamel and cementum are electrical insulators, soft tissue, including the periodontal ligament, is a conductor. The device established a circuit in the mouth that originated in the device, ran through an endodontic file via the attached probe, and extended down the canal out of the foramen and into the periodontal ligament. The circuit continued through the patient's mucosa and eventually completed the loop by running into the lip clip that was connected to the device through a return wire.

Sunada (1962) also reported that the patient's age, type or shape of teeth and the diameter of the canal had no influence on the results. The mean value of the resistance of the circuit between the canal terminus and the lip clip was 6.5 kΩ.

Resistance-based ERCLMDs

Resistance-based ERCLMDs relied on the assumption that the circuit between the endodontic file and the lip clip could be modelled by a simple resistive circuit (Fig. 8). Therefore, a small DC was applied to that circuit and the voltage was measured. By dividing the value of the voltage by the value of the current, the resistance value of the circuit was calculated.

Many electronic root canal length measuring devices have since been marketed (Table 1) using the same principles. The differences between them are basically in the design of the electrical circuits and in the mode of their display. However, they can all be classified as 'resistance-based' ERCLMDs.

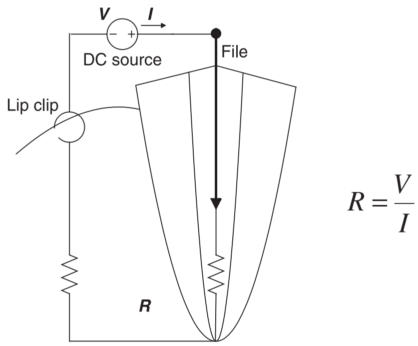

Figure 8 A simple resistive model of the apex, used in resistance-based ERCLMDs.

Although many of the resistance-based ERCLMDs have been shown to be accurate in dry conditions within the canal, it has been reported they were not always accurate when strong electrolytes, excessive haemorrhage, pus or pulp tissue was present (Suchde & Talim 1977, Nekoofar *et al.* 2002, Pommer *et al.* 2002, Tinaz *et al.* 2002). As soon as the file tip touches the electroconductive solution (electrolyte), in these situations, the DC voltage polarizes the tissues and varies its resistivity (Foster & Schwan 1989), thus completing the electrical circuit; the device incorrectly indicates that the minor apical foramen has been reached (Suchde & Talim 1977). Another disadvantage of the DC current is that an electric shock can be felt by the patient (Kim & Lee 2004). To eliminate the disadvantages of DC current Suchde & Talim (1977) proposed using AC current to measure the resistance. However, they still used a simple electronic ohmmeter, a 'bridge circuit', to overcome the disadvantages of the simple resistance method. The advantages of AC current are that it causes less damage to the tissue and improves functionality in 'wet' conditions as the resistivity of the electrolytes experience better stability (Suchde & Talim 1977, Foster & Schwan 1989). However, the disadvantage is that the capacitive component of the canal, which is variable with many parameters, will have an additional effect on the circuit. Therefore, in wet conditions when the capacitive component is more dominant, these devices suffer from a lack of accuracy (O'Neill 1974, Suchde & Talim 1977, Meredith & Gulabivala 1997).

Low frequency oscillation ERCLMDs

As discussed earlier, in practical endodontic experiments, the structure of the endodontic instrument, canal and tissues have capacitive characteristics as well as resistive characteristics. Therefore, modelling the circuit with a simple resistive characteristic is not sufficient (Inoue 1973, McDonald & Hovland 1990, Meredith & Gulabivala 1997). Unfortunately, these capacitive characteristic are variable and can change with the shape of the canal, and other physical parameters such as the dielectric constant of the liquids inside the canal. Based on this view, Inoue (1972, 1973) developed a different ERCLMD that worked through the principle of electrical resistance but was modified by the addition of an audible 'marker tone'. The principle of measuring root canal length by this device is based on the assumption that the low frequency oscillation, as produced by the resistance and capacity between the oral mucous membrane and the gingival sulcus, is the same as the frequency between the periodontal ligament (at the canal terminus) and the oral mucous membrane (Inoue & Skinner 1985). When the file reaches the canal terminus, the oscillating tones produced by the gingival sulcus and the canal terminus are coincident. As the impedance between the two electrodes is included in the feedback loop of the oscillator circuit, it influences the oscillated frequency value. Therefore, the frequency of the measured current changes as the load varies.

In other words, the impedance of the root canal depends on many parameters and is not the same in different canals. However, it can be assumed that the impedance between the oral mucous membrane and the depth of the gingival sulcus closely resembles the impedance between the canal terminus and the oral mucous membrane. Based on this assumption Inoue's device, the SonoExplorer® (Hayashi Dental Supply, Tokyo, Japan), measures these two impedances and identifies the canal terminus when the readings approach each other. The frequency of this impedance is directed to a speaker that develops an auditory tone generated by means of low frequency oscillation.

The most important disadvantage of this device was the need for individual calibration. The device had to be calibrated at the periodontal sulcus in each tooth. The technique involved inserting a file with a silicon plastic-sheath into the gingival crevice of the tooth to be measured and the sound produced was named the '*gingival crevice sound*'. Then, the conventional endodontic file was inserted into the root canal and when the sound produced by this file became '*identical*' with the '*gingival crevice sound*', the rubber stop was aligned with the reference point, and the measurement taken.

High frequency devices (capacitance-based devices) ERCLMDs

The Endocater® (Hygenic Corp., Akron, OH, USA) was developed in 1979 by Hasegawa (Fouad & Krell 1989, Fouad *et al.* 1990, Pallares & Faus 1994) that used a high frequency (400 kHz) reference circuit (McDonald & Hovland 1990). To further decrease the influence of the variable capacitive characteristics on measurements insulated files were also used (Keller *et al.* 1991). As explained earlier (equation 3), the value of a capacitor is directly proportional to the area of its plates. Here, the insulator covers most of the surface of the file to decrease its capacitance value. Unfortunately, the coated file cannot be used in narrow canals, because the coating is easily abraded thus disturbing the measurement (Keller *et al.* 1991). In addition, Himel & Schott (1993) showed that the quality of the seal provided against electrical conductivity was decreased after autoclaving.

Capacitance and resistance ERCLMDs (look-up table)

In 2003, the Elements™ Diagnostic Unit (SybronEndo, Anaheim, CA, USA) was introduced. It measured the capacitance and resistance of the circuit separately (Gordon & Chandler 2004, Vera & Gutierrez 2004). As explained earlier, these values are variable with many parameters. However, experimental look-up tables were developed that included the statistics of the values at different positions (Serota *et al.* 2004). The device exploits a composite signal with two frequencies to measure the resistance and capacitance of the system and then compares the measured values with its look-up table to diagnose the position of the file. As a result of modern electronic digital circuits, the manufacturer claims that this device has more consistent readings than its predecessors (Serota *et al.* 2004). Nevertheless, the fundamental principle of all the ERCLMDs is the same, i.e. an electrical model is assumed and the characteristics of that model are measured to diagnose the clinical properties. Based on clinical observations, Vera & Gutierrez (2004) reported that when using the Elements™ Diagnostic Unit the file should be withdrawn to the 0.5 mm mark instead of the 0.0 mm mark to achieve the accurate identification of the apical constriction that they assumed should be 0.5 mm short of the external (major) foramen. Therefore, taking the file to the 0.0 mark on the display and then withdrawing it 0.5 mm appears to be the most accurate way to use this device. In an attempt to achieve better results Vera & Gutierrez (2004) also recommended the access cavity should be dried before introducing the file into the canal.

Voltage gradient ERCLMDs (difference in impedance with three nodes)

Several studies have been conducted to determine a constant electrical resistance or impedance in order to diagnose the position of the canal terminus, e.g. Sunada (1962) who determined $R = 6.5$ kΩ. However, Meredith & Gulabivala (1997) reported there is neither constant reference impedance nor constant resistance for all root canals. The reason that, for example, resistance-based devices work in a reasonable number of cases is that there is a substantial difference between the resistance (or the impedance) value at the pulp and periodontal junction compared with intracanal positions. Indeed, this is the property Custer (1918) described many years ago.

Based on this fact, Ushiyama (1983) proposed a method to measure the variation in impedance when a file was inserted into the root canal. Using bipolar electrodes and applying a 400-Hz alternating current, this device monitored variations in the impedance value. Ushiyama (1983) concluded that a sharp variation in the value, determined the position of the file at the apical constriction, the narrowest portion of the root canal system. Ushiyama (1983) also reported that in the presence of strong electrolytes the 'voltage gradient method' could accurately detect the apical constriction. However, use of a special bipolar electrode is one of the main disadvantages of this device, as the electrode will not fit into narrow canals. No commercial product of the experimental device developed by Ushiyama (1983) appears to be available.

Two frequencies, impedance difference ERCLMDs

Yamaoka (1984 – quoted in Saito & Yamashita 1990) developed a measurement device in which two frequencies were employed in the measurement. This device measures the impedance value at two different frequencies (f_H and f_L) and calculates the difference between the two values:

$$\mathrm{Diff} = Z(f_H) - Z(f_L) \tag{7}$$

In fact, the actual measured signal is the difference between the voltages in two frequencies that is obviously proportional to the difference in impedance values. In the coronal portion of the root canal system, the device must be calibrated to eliminate any effect of the dielectric material inside the canal.

According to equation 3, the magnitude of the capacitance of the model is proportional to the distance between the two nodes shown in Fig. 6. That means, when the file approaches the canal terminus, the value of the capacitance sharply increases probably because of change in the morphology of the apical portion of the root. On the other hand, the f_H frequency used in this device is five times the f_L value. Therefore, according to equation 4, the change in $Z(f_L)$ will be five times larger than $Z(f_H)$, i.e. the difference between two $Z(f_L)$ and $Z(f_H)$ impedances rapidly increases at the 'apical foramen'. This method has been used in the Apit® device (Osada, Tokyo, Japan).

According to Saito & Yamashita (1990) electrolytes, such as saline, 5% NaOCl, 14% EDTA and 3% H_2O_2 did not interfere with the detection of the apical terminus regardless of the size of the endodontic file or the size of 'apical foramen'. Frank & Torabinejad (1993) also confirmed that the location of the canal terminus could be detected under moist conditions, but due to the open electrical circuit the Apit® cannot accurately detect the canal terminus in a dry canal. However, this phenomenon could be useful for checking the dryness of the root canal system prior to canal filling (Dahlin 1979).

Two frequencies, impedance ratio (Quotient) ERCLMDs

In the impedance ratio-based ERCLMDs the AC source is again a two-frequency source, i.e. it comprises two sine waves with a high and a low frequency (f_H and f_L respectively). The impedance of the model is measured at each frequency and the position of the file is determined from the ratio between these two impedances:

$$\text{Ratio} = \frac{Z(f_H)}{Z(f_L)} \quad (8)$$

Kobayashi & Suda (1994) proved that the ratio had a definite value determined by the frequencies used and that the ratio indicates the location of the file tip in the canal. The quotient of the two impedances is nearly 1 when the tip of the file is some distance from the canal terminus. When the file is not at the minor apical foramen, the distance between the two plates of the model capacitance is high. Therefore, according to equation 3, the magnitude of the capacitance is negligible. Hence, the ratio of equation 8 will turn out to be a ratio of two equivalent resistance values which tends towards 1. At positions close to the canal terminus, however, the capacitive characteristic of the impedance starts to appear. The influence of the capacitance on the overall impedance is proportional to the frequency of the measurement as shown in equation 4. At high frequencies (f_H) the overall impedance value will be much lower than at low frequency (f_L). That means, at the apical constriction the ratio tends towards a small value (Kobayashi & Suda 1994), however, this phenomenon is related to the morphology of the constriction. Lack of a constriction because of open apices (Hülsmann & Pieper 1989, Goldberg *et al.* 2002) or an impenetrable canal (Rivera & Seraji 1993, Ibarrola *et al.* 1999) have been reported as an impediment to determine the position of the canal terminus (Oishi *et al.* 2002).

The ratio of equation 8 is independent of the electrolyte liquid inside the canal. This is because a change in the electrolyte material, which is a change in dielectric constant (ε of equation 3), will influence equally the numerator and denominator of equation 8, and hence the final ratio will still remain constant. This concept underpins the development of the Root ZX® (J. Morita Co., Kyoto, Japan), the first commercial ratio-based ERCLMD (Kobayashi 1995). This fundamental operating principle could explain why there was no statistically significant difference between their ability to determine the apical constriction in roots with vital pulps versus those with necrotic pulps (Dunlap *et al.* 1998) and/or various irrigants (Jenkins *et al.* 2001). Dunlap *et al.* (1998) reported that there was no statistical difference between the ability of the Root ZX® to determine the apical constriction in vital canals versus necrotic canals. Overall, the Root ZX® was 82.3% accurate to within 0.5 mm of the apical constriction. In addition, this could also explain why this device was not adversely affected by the presence of sodium hypochlorite in the root canal system (Kobayashi 1995, Meares & Steiman 2002). Ounsi & Naaman (1999) in an *ex vivo* study reported that the Root ZX® was not capable of detecting the apical constriction and should only be used to detect the major foramen. Hoer & Attin (2004) also showed that the use of impedance ratio electronic devices did not result in precise determination of the apical constriction, rather, under clinical conditions it was only possible to determine the region between the minor and major apical foramen. In their study, accurate determination of the apical constriction was only successful in 51–64.3% of canals, although the probability of determining the area between minor and major foramen was between 81 and 82.4% of cases. However, Shabahang *et al.* (1996) showed that when a potential error of ±0.5 mm from the 'foramen' was accepted as a clinically tolerable range, the Root ZX® was able to locate the 'foramen' in 96.2% of cases.

Multifrequency ERCLMDs

There have been efforts to further increase the accuracy of ERCLMDs. One concept was to measure the impedance characteristics using more than two frequencies. In the Endo Analyzer® 8005 (Analytic Endodontics, Sybron Dental, Orange, CA, USA) and AFA Apex Finder® 7005 (Analytic Endodontics) five different frequencies have been used and the device measures both components (phase and amplitude) of impedance at each frequency. These figures are then analysed in a procedure to determine the location of the minor diameter (constriction) (Welk *et al.* 2003). The principle behind this device, however, is similar to the impedance ratio-based ERCLMDs. It detects the canal terminus by determining a sudden change in the dominant characteristic (capacitive or resistive) of the impedance. Welk *et al.* (2003) compared the accuracy of an impedance ratio-based ERCLMD (Root ZX®) and the Endo Analyzer® and found that the mean distance between the electronically located canal terminus and minor diameter was 1.03 mm for the Endo Analyzer and 0.19 mm for the Root ZX®; the ability of the devices to locate the apical constriction was 34.4 and 90.7% of cases respectively. Pommer *et al.* (2002) evaluated the effect of pulp vitality on the accuracy of the AFA Apex Finder® 7005 and reported that the difference between measurements in canals with vital or necrotic pulps was significantly different and concluded that the AFA Apex Finder® was more accurate in vital cases.

Summary

There is a general consensus that root canal procedures should be limited within the confines of the root canal, with the logical end-point for preparation and filling being the narrowest part of the canal. It is not possible to predictably detect the position of the apical constriction clinically, indeed, the constriction is not uniformly present, or may be irregular. Equally, it is not logical to base the end-point of root canal procedures on an arbitrary distance from the radiographic apex as the position of the apical foramen is not related to the 'apex' of the root.

Electronic root canal length measuring devices offer a means of locating the most appropriate end-point for root canal procedures, albeit indirectly. The principle behind most ERCLMDs is that human tissues have certain characteristics that can be modelled by means of a combination of electrical components. Then, by measuring the electrical properties of the model (e.g. resistance, impedance) it should be possible to detect the canal terminus.

Thus, most modern ERCLMDs are capable of recording the point where the tissues of the periodontal ligament begin outside the root canal, and hence from this a formula can be applied to ensure that preparation is confined within the canal. Most reports suggest that 0.5 mm should be subtracted from the length of the file at the point when the device suggests that the file tip is in contact with the PDL (zero reading). This does not mean that the constriction is located; rather it means that the instrument is within the canal and close to the PDL. It is not appropriate to rely on any device reading 0.5 mm short of the foramen as this will often be inaccurate. The use of 'generation X' to describe and classify these devices is unhelpful, unscientific and perhaps best suited to marketing issues.

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