International Journal of Chemical, Materials and Biomolecular Sciences
ISSN: 2415-6620
Vol:12, No:11, 2018

The System for Root Canal Length Measurement Based on Multifrequency Impedance Method

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***Abstract*—Electronic apex locators (EAL) has been widely used clinically for measuring root canal working length with high accuracy, which is crucial for successful endodontic treatment. In order to maintain high accuracy in different measurement environments, this study presented a system for root canal length measurement based on multifrequency impedance method. This measuring system can generate a sweep current with frequencies from 100 Hz to 1 MHz through a direct digital synthesizer. Multiple impedance ratios with different combinations of frequencies were obtained and transmitted by an analog-to-digital converter and several of them with representatives will be selected after data process. The system analyzed the functional relationship between these impedance ratios and the distance between the file and the apex with statistics by measuring plenty of teeth. The position of the apical foramen can be determined by the statistical model using these impedance ratios. The experimental results revealed that the accuracy of the system based on multifrequency impedance ratios method to determine the position of the apical foramen was higher than the dual-frequency impedance ratio method. Besides that, for more complex measurement environments, the performance of the system was more stable.

***Keywords*—Root canal length, apex locator, multifrequency impedance, sweep frequency.

I. INTRODUCTION

ORAL health is regarded as one of the ten standards of human health by World Health Organization, which is also regarded as a mirror reflecting the health of life. Root canal therapy is the most fundamental and effective method for the treatment of pulp and periapical diseases. The prerequisite and guarantee for the successful completion of root canal therapy is to accurately measure the working length of the root canal [1].

Two mainly methods exist for measurement of root canal length: radiographic determination and the use of an electronic apex locator (EAL).

A. Radiograph

Radiographic determination of working length has been used for many years [2]. It is generally believed that the actual position of the apical foramen is 0.5 - 1.0mm shorter than that of the imaging apical position [3]. In endodontics, the preoperative radiograph for root canal treatment is essential to determine theanatomy of the root canal system, the number and curvature of the root canal, and the presence or absence of disease. It can act as the initial guidance for measuring the working length of root canal as well [4].

Although radiograph is an extremely important part of root canal therapy, there are still unavoidable hazards of radiation [3]. In addition, radiograph provides two-dimensional images of three-dimensional structures that is technically sensitive to exposure and interpretation [5]. Therefore, it is often used as an auxiliary method for determining the position of the apical foramen in modern clinical practice, and combined with an electronic apex locator (EAL) to better control the measurement accuracy [4].

B. Electronic Apex Locators

The EAL approach is the most commonly used method for measuring root canal length in a clinical setting [6]. The EAL method has been developed over a long period. In 1962, Sunada [7], a scholar from Japan, found that although the ages of patients, types of tooth, and shapes of root canals differ widely, the direct current resistance between the apical foramen and oral mucosa is almost constant at approximately 6.5 $k\Omega$. The first-generation EAL is invented by Sunada based on this priciple; however, its performance was extremely unsatisfactory after it was separated from a dry measuring environment [8]. The second-generation EAL was developed based on the principle of the voltage gradient method [9]; it seemed to be more accurate than the first-generation EAL, but its dependence on the measuring environment still led to unsatisfactory stability of measurement results [10]. In the 1990s, Kobayashi [11] proposed a new measurement method based on impedance ratios. The method provided theoretical support for the third-generation EAL. The Root ZX (Morita, Japan), the most widely used EAL and the industry benchmark, was the earliest development and is representative of third-generation EALs. Its clinical performance was exceptional, with reports of accuracy up to 84% [12], [13] and 100% [14] as well as considerable stability [15]. The principle of the fourth-generation EAL was based on multifrequency impedance ratios, which are similar to dual-frequency impedance ratios [1]. At present, several types of fourth-generation EALs can be found on the market, such as iPex (NSK, Tochigi, Japan) and Endo Analyzer 8005 (Analytic Endodontics, Sybron Dental, Orange, CA, USA). Although the fourth generation of products has improved in clinical trials, compared to the best in the third generation, like

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Root ZX, it does not have superior performance under some conditions based on the results of comparative experiments using various types of EALs [16], [17].

The use of the length measuring instrument is the most widely used and accurate method in modern clinical practice but with a high price. Besides that, due to the complexity of the measurement environment, including the shape of the root canal, the size of the apical foramen and the residual vein in the root canal, the accuracy of the measurement is greatly affected. Therefore, this article proposes a measurement system for precisely locating the position of the apical foramen based on multifrequency impedance ratios.

II. Method

Fig. 1 presents the diagram of the measuring process. The measuring apparatus was designed and prepared to meet the research requirements. This apparatus is mainly composed of the power supply, a CPU, a programmable digital frequency synthesizer, an analog-to-digital converter and a LCD. A sweep signal varied from 100 Hz to 1 MHz was generated by this direct digital synthesizer (DDS). The impedances at different frequencies of the root canal soaked in the saline were measured by two electrodes and collected using the analog-to-digital converter (ADC) to upper computer. The impedance ratios of different frequency combinations were obtained through data processing. There were fourteen extracted teeth that had been treated and cleaned and for each tooth, the file distance from the root tip was changed from $+5$ mm to -1 mm ($+$ means that the file does not reach the apical foramen, and $-$ means the file exceeds the apical foramen). A precise translation table was used to strictly control the change of distance by increments of 0.5 mm. The LCD is responsible for displaying some important information. Two theoretical tests were verified using this approach: the impedance decreased with increasing frequencies when the file was in the same position; the closer the file was to the apical foramen, the smaller the impedance ratio, and the larger the frequency difference, the smaller the ratio. Moreover, the reliability of the measuring instruments and data processing methods used in this study was verified.

The dual-frequency ratio method selects the impedance ratio of one high frequency and one low frequency as the standard to determine the position of the apical foramen. On this basis, this paper proposed a multifrequency impedance ratios method that selects several sets of impedance ratios with characteristics, that is the features, and then uses statistical knowledge to analyze the relationship between impedance ratios and the distance from the file to the apical foramen. The position of the apical foramen can be determined by the mathematical relationship.

To select the features, generally, the following two aspects need to be considered [18].

- Divergence: if a feature does not diverge (for example, if the variance is close to 0), which means that samples are basically the same in the feature, then this feature is not useful for distinguishing the samples;
- Correlation between features and goals: features highly correlated with goals should be selected preferentially.

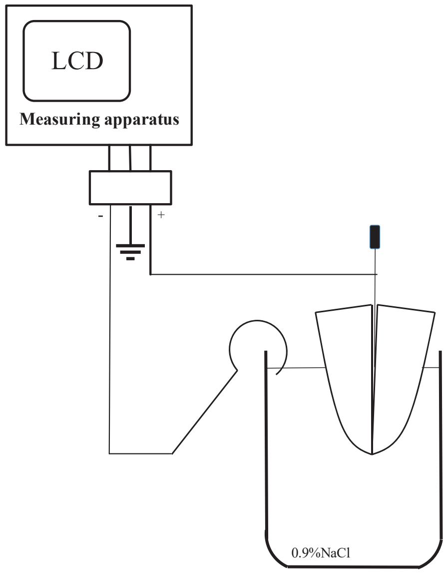

Fig. 1 Diagram of the measuring process

Filter is one of the most commonly used methods of feature selection. The basic task of Filter method is to develop a rule to measure each feature and set the threshold or sort all features by their importance to the target attribute which is the position of the apical foramen in this measurement. Common measurement criteria include variance, correlation coefficient, mutual information, and information gain.

In this paper, the first step was to calculate the variance of each feature, and features with variance below the threshold were deleted. The formula for calculating the variance is shown in (1), where x_n represents the impedance ratios of the same combination of frequencies and $\bar{x}$ represents the mean value of the ratios.

$$var = \frac{(x_1 - \bar{x}) + (x_2 - \bar{x}) + (x_2 - \bar{x}) + \cdots + (x_n - \bar{x})}{n} \quad (1)$$

The next step was univariate feature selection with the principle that separately calculate a certain statistical indicator of each variable, and judge which features are important according to the indicator, and eliminate those features that are not important. Pearson correlation coefficient is the simplest way to understand the relationship between features and response variables. For continuous variables X and Y, the Pearson correlation coefficient was calculated by (2).

$$r = \frac{\sum_{n=1}^{N}(x_n - \bar{x})(y_n - \bar{y})}{(N-1)\sqrt{s_x^2 s_y^2}} \quad (2)$$

In (2), $\bar{x}, \bar{y}$ represents the mean value and s_x^2, s_y^2 represents the variance. The result ranges from -1 to 1, while $-1(1)$ represents completely negative (positive) correlation and 0 represents no linear correlation. With these selected impedance ratios, the position of the apical foramen can be determined by the mathematical relationship analyzed next.

In statistics, linear regression is a regression analysis of the relationship between one or more independent variables and dependent variables using a least squares function. This function is a linear combination of one or more model parameters called regression coefficients. Linear regression models are often fitted with least squares approximation. The function of the impedance ratios and the distance between the file and the apical foramen can be expressed as (3)

$$\begin{pmatrix} 1 & r_{11} & \cdots & r_{1j} & \cdots & r_{1m} \\ \vdots & & & & & \\ 1 & r_{i1} & \cdots & r_{ij} & \cdots & r_{im} \\ \vdots & & & & & \\ 1 & r_{n1} & \cdots & r_{nj} & \cdots & r_{nm} \end{pmatrix} \cdot \begin{pmatrix} a_0 \\ a_1 \\ \vdots \\ a_j \\ \vdots \\ a_m \end{pmatrix} = \begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_i \\ \vdots \\ y_n \end{pmatrix} \tag{3}$$

Equation (3) can also be expressed as $\boldsymbol{X}\vec{b} = \vec{y}$. Usually the impedance ratios r_{ij} are referred to as the data matrix $\boldsymbol{X}$, parameters a_j are referred to asthe parameter vector $\vec{b}$ and the position of the apical foramen y_i are referred to as $\vec{y}$. A series of mathematical derivations can be used to obtain a standard equation of $\vec{b}$ shown as (4).

$$\vec{b} = (\boldsymbol{X}^T\boldsymbol{X})^{-1}\boldsymbol{X}^T\vec{y} \tag{4}$$

Finally, the position of the apical foramen can be determined by (3) with parameter vector $\vec{b}$.

III. Result

For different teeth at ages and types, the impedance decreases as the frequency increases as shown in Fig. 2. Analogously, Fig. 3 presents two phenomena: 1) regardless of the distance between the file and apical foramen, the impedance decreases as the frequency increases, 2) and at the same frequency, the impedance increases as the distance between the file and apical foramen increases. These phenomena verify the correctness of the principles of the second and third generations of EALs, as well as the reliability of the originally designed measurement system.

In Fig. 3, when the frequency increased to approximately 10 kHz, the impedance almost stopped increasing, as illustrated in Fig. 3. Therefore, when we calculated the impedance ratios of different frequency combinations (Fig. 5), the highest frequency was 20 kHz, which barely affected the subsequent analysis of experimental results.

Fig. 4 presents the impedance ratios at 10 kHz/ 0.5 kHz of different teeth at vary with the distance between the file and apical foramen. The similiar tendency of curves is also shown in Fig. 5 that the impedance ratio does not change significantly when the file is far from the apical foramen. When it is close to the apical foramen, especially when the distance is less than 1 mm, the impedance ratio drops rapidly, and the gradient is steepest at the apical foramen. Moreover, the larger the difference between high and low frequencies, the more significantly the impedance decreases when the file is close to the apical foramen; by contrast, it is not beneficial to determine the position of the file. The data for Fig. 5

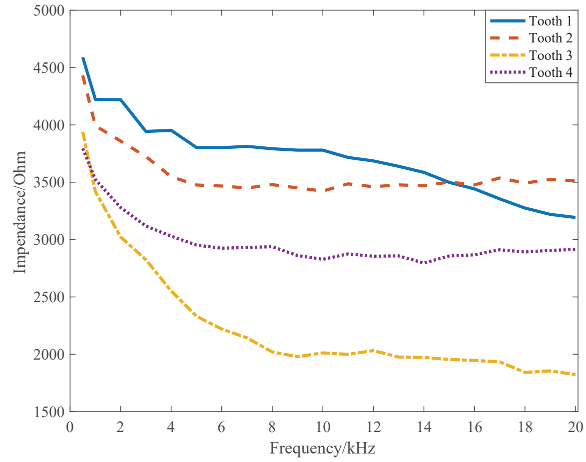

Fig. 2 Impedance curve of the file with different teeth varies with frequency

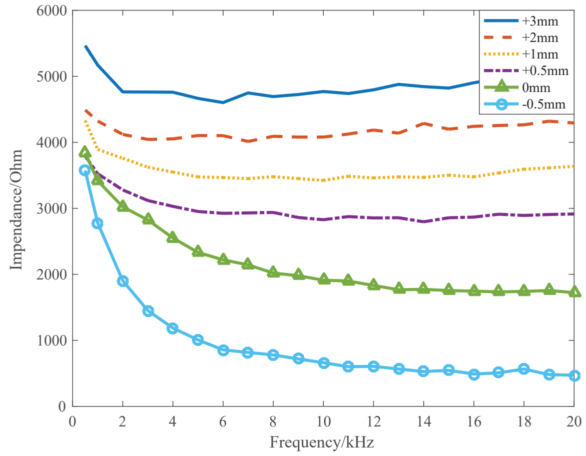

Fig. 3 The average of impedances curve of the file at various positions from the apical foramen varies with frequency

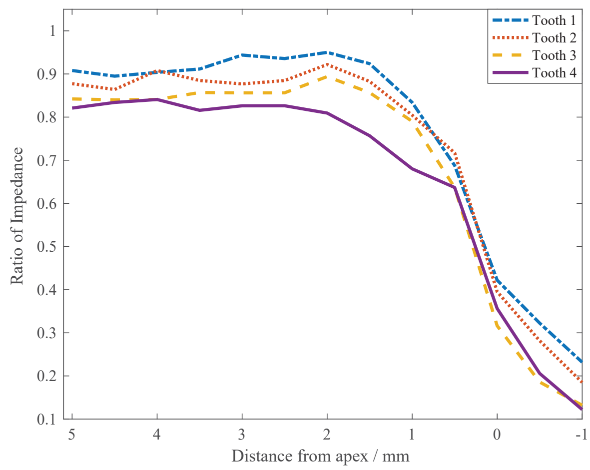

Fig. 4 Impedance ratios (10 kHz/ 0.5 kHz) of different teeth at vary with the distance between the file and apical foramen

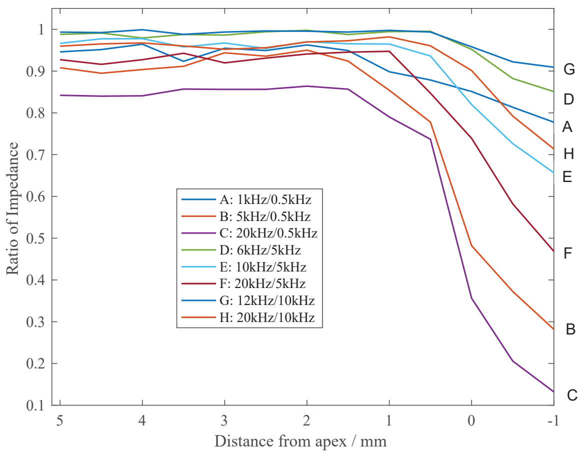

Fig. 5 The average of impedance ratios of nine groups of frequency combination vary with the distance between the file and apical foramen

were obtained under the conditions of a molar tooth type and file #25; the curve trend was similar for other conditions. The multifrequency impedance ratio method can determine the position of the apical foramen, accually it will calculate the distance between the file and the apex. The measurement system will generate a warning signal when the distance is 0.5mm, and a alarm signal when the result is 0mm. In clinical practice, the allowable measurement error is $\pm 0.5mm$, thus in order to facilitate statistical results, a set of measurements for one tooth is considered correct only if all the following conditions are met:

1) The results are greater than 0.5 mm when the actual distance is above 0.5 mm;
2) The results are no less than 0.5 mm and no bigger than 0.6 mm when the actual distance is equal to 0.5 mm;
3) The result is no bigger than 0 when theactual distance is equal to 0 mm;
4) The results are less than 0 when the file is beyond the apical foramen.

The fourteen teeth were divided into three groups according to the types and ages of tooth: I: molar, younger teeth; II: molar, older teeth. Table I presents a comparison of the performance of the impedance ratio method and multifrequency method in this measurement system. There are five pairs of frequencies selected for the impedance ratio method: 5 kHz/0.5 kHz, 5 kHz/1kHz, 10 kHz/0.5 kHz, 10 kHz/1 kHz, and 20 kHz/1 kHz. As shown in Table I, the performance of the impedance ratio method to determine the apical foramen was not appropriate for Group I. This was because only using the average of the impedance ratios as the criterion was with poor repeatability and susceptibility to measurement conditions. By contrast, the multifrequency method could Overcome this shortcoming, had a high accuracy rate, was less affected by changes in measurement conditions, and exhibited decent robustness.

TABLE I
PERFORMANCES OF THE IMPEDANCE RATIO METHOD AND MULTIFREQUENCY METHOD IN THE MEASUREMENT SYSTEM

Method	Group I	Group II	Total
5kHz / 0.5kHz	66.67 %	75.00 %	71.43 %
5kHz / 1kHz	50.00 %	62.50 %	57.14 %
10kHz / 0.5kHz	83.33 %	75.00 %	78.57 %
10kHz / 1kHz	66.67 %	75.00 %	71.43 %
20kHz / 1kHz	83.33 %	87.50 %	85.71 %
Multifrequency	83.33 %	100.00 %	92.86 %

IV. DISCUSSION

The development of EALs is a long and continual process, but compared with the rapid development of modern medical technology, it seems to lag behind. After the first third-generation EAL based on the impedance ratio method was established, until now, it has been unchallenged in the field of root canal length measurement. After entering the 21st century, from the so-called fourth-generation EAL, there are many fourth-generation products today. Although the measurements of fourth-generation EALs seem to be more accurate, the machines' actual performance does not present a great improvement compared with the benchmark of the third-generation product, Root ZX, according to product comparison experiments [19], [20]. In addition, in actual surveys, many dentists have provided feedback that they are more inclined to use third-generation products such as Root ZX, because in clinical settings, the third- and fourth-generation EALs differ little in accuracy, and furthermore, the old models are more stable and cheaper. Root ZX is an excellent product, but it is not perfect; doctors often must use radiography as an aid to obtain accurate results when employing Root ZX [21].

Obviously, much space still exists for improvement in the development of EALs. In the measurement system proposed in this paper, the impedance ratios of different frequency combinations were sampled by ADC and calculated through data process, after the sweep signal generated by the DDS. Applied statistics, the position of the apical foramen can be determined by the functional relationship between the impedance ratios and the distance from the file to the apex. The experimental results indicated that the proposed measurement system was relatively robust and improved the effects of measuring factors on the results. The system in this study might not have been perfect. Further improvements in accuracy can be considered based on a more appropriate statistical model.

V. CONCLUSION

This paper proposed a root canal length measurement system based on the multifrequency impedance ratios method. Compared with the traditional dual-frequency impedance ratio method, the proposed approach can reduce the influence of measuring conditions on the accuracy, enhance robustness and has a lower cost compared with the existing commercial products.

ACKNOWLEDGMENT

This study was supported by the Science and Technology Commission of Shanghai Municipality (No. 17JC1400804).

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