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Evaluation of electrical impedance ratio measurements in accuracy of electronic apex locators

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Objectives: The aim of this paper was evaluating the ratios of electrical impedance measurements reported in previous studies through a correlation analysis in order to explicit it as the contributing factor to the accuracy of electronic apex locator (EAL). **Materials and Methods:** The literature regarding electrical property measurements of EALs was screened using Medline and Embase. All data acquired were plotted to identify correlations between impedance and log-scaled frequency. The accuracy of the impedance ratio method used to detect the apical constriction (APC) in most EALs was evaluated using linear ramp function fitting. Changes of impedance ratios for various frequencies were evaluated for a variety of file positions. **Results:** Among the ten papers selected in the search process, the first-order equations between log-scaled frequency and impedance were in the negative direction. When the model for the ratios was assumed to be a linear ramp function, the ratio values decreased if the file went deeper and the average ratio values of the left and right horizontal zones were significantly different in 8 out of 9 studies. The APC was located within the interval of linear relation between the left and right horizontal zones of the linear ramp model. **Conclusions:** Using the ratio method, the APC was located within a linear interval. Therefore, using the impedance ratio between electrical impedance measurements at different frequencies was a robust method for detection of the APC. (*Restor Dent Endod* 2015;40(2):113-122)

Key words: Canal length; Electrical impedance; Electronic apex locator; Endodontics; Impedance ratio

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Introduction

Determination of working length (WL) is a critical step for the success of root canal treatments. Over-filling and under-filling due to failure to determine accurate WL jeopardize the success of treatment.[1-3] The most common method to accurately determine WL involves the use of standardized radiographs. However, radiographic techniques have inherent drawbacks due to the projection of three-dimensional structures onto a two-dimensional plane. Three-dimensional structures of a tooth may overlap with important structures of the maxilla and mandible in the projection plane, and therefore make it difficult to detect the apical constriction (APC). Projection also distorts the visualization of the canal and affects estimation of the WL, especially for the molars and premolars.[4] Even though X-ray emissions in dental radiography are very low, they should be minimized for the safety of patients and clinicians. Electronic

apex locators (EALs) are some of the most innovative instruments available for determining WL. Practically, the development of EALs is a breakthrough that brings traditionally empirical endodontic practices into the electronic era.[5]

The EAL has a long history of development. Sunada first suggested using the resistance characteristics of root canals for WL determination.[6] Ohmmeters were used to measure the resistance of direct current (DC). Inoue and Skinner introduced a new EAL using low-frequency oscillating current, represented by the Sono-Explorer, which overcame the low specificity and poor accuracy of the ohmmeter.[7] Additional improvement came from the adoption of the ratio method by Kobayashi and Suda.[8] The ratio method represented by the Root ZX (J. Morita Mfg Corp., Kyoto, Japan) is known to be one of the most reliable methods for determining WL.

The principles of EAL can be explained by Ohm's law.[9] Ohm's law is expressed as voltage/current = resistance. Rather than DC, because alternating current (AC) is typically used in electrical measurements and expressed in sine wave form, Ohm's law is changed to voltage/current = impedance in AC. Impedance is expressed as the sum of resistance and reactance in a complex plane as $Z(f) = R(f) + j * X(f)$ (Z, impedance; R, resistance; X, reactance; j, the symbol of an imaginary number). Impedance values depend on the frequencies of AC. The observation that the ratio between two electrical impedances decreases as the file tip approaches the apical foramen led to the development of the ratio method for WL determination.[8]

Most previous studies evaluated EAL in the context of clinical results rather than electrical principles.[10-13] However, several studies analyzed frequency and impedance responses by applying AC on the basis of electrical principles.[9,14,15] In other studies, electrical circuit modeling was performed on the basis of the frequency response.[14-18] Among reports containing electrical property measurements, some provided these data in figures and tables. The data for most electrical models are highly reproducible and can be analyzed together, because similar measurements and easily convertible units were used. Therefore, to explicit

the characteristics of the impedance ratio measurements for EALs, a correlation analysis was performed for electrically measured values reported in previous studies, a model was suggested for the plots between the ratios of electrical impedance measurements and the distance of the file tip from the APC, and the electrical impedance ratio was evaluated as the contributing factor to the accuracy of EAL.

Materials and Methods

PubMed and Embase were searched for relevant studies from inception to February 6, 2013. Search words were selected in two categories, one for words related to 'canal' or 'tooth' and the other for words related to 'impedance'. The search terms used are presented in Table 1. We did not apply language restrictions.

A priori, the following inclusion criteria were established for paper selection.

1. The subject of the paper should include 'EAL' or 'electrical experiment'.
2. Data should be grouped according to the variables of the experiments, such as teeth and experimental materials.
3. Data should consist of output value, frequency, and distance.
4. Output should be paired values of resistance and reactance, absolute impedance values (Z_{abs}), or impedance ratios (Y_{ratio}) at different frequencies.
5. In one set of data, there must be more than 2 different frequency points.
6. In one set of data, there must be more than 2 different distance points.

Papers not meeting any of these criteria were excluded from abstract reading. The remaining papers were assessed through full text reading by two reviewers (KPJ and CBH). We also evaluated the references of all papers. Selection process for the articles evaluated in this study was shown in Figure 1. Ten papers selected for analyses of electrical property measurements of EALs are summarized in Table 2.

All possible data were extracted from the selected

Table 1. Search terms for electrical apex locator with electrical data used

| Search engine	Search term
Pubmed	((impedance[TIAB] or impedances[TIAB] or voltage[TIAB] or measure[TIAB] or measurement[TIAB] or 'electronic device'[TIAB]) and ((tooth[TIAB] or teeth[TIAB]) and 'root canal'[TIAB] or 'foramen locator'[TIAB] or 'root canal treatment'[TIAB] or 'apex locator'[TIAB]))
Embase	((impedance:ab,ti or impedances:ab,ti or voltage:ab,ti or measure:ab,ti or measurement:ab,ti or 'electronic device':ab,ti) and ((tooth:ab,ti or teeth:ab,ti) and 'root canal':ab,ti or 'foramen locator':ab,ti or 'root canal treatment':ab,ti or 'apex locator':ab,ti))
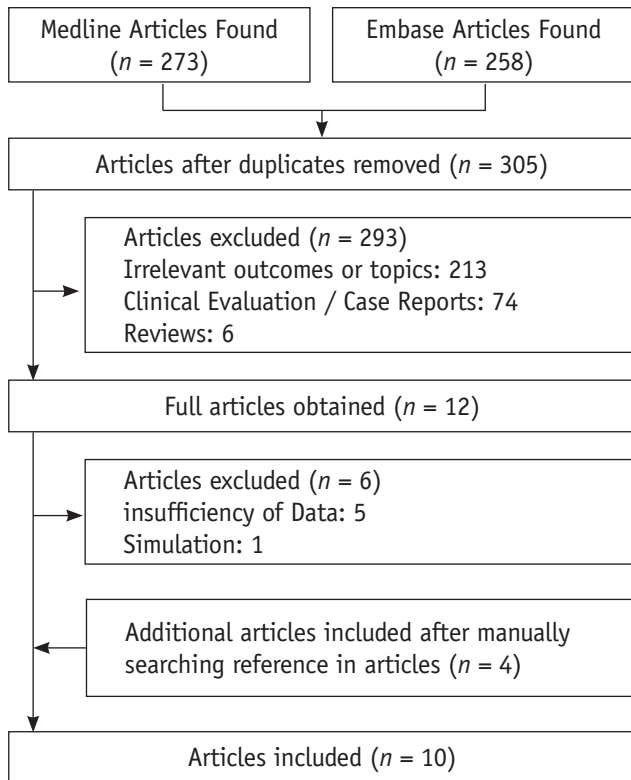
Figure 1. Selection process for the articles evaluated in this study.

papers. If data were presented in tables, the exact values were extracted directly. If data were shown as figures and no exact values were provided, data were extracted by measuring pixel positions using Adobe Photoshop CS6 (Adobe Systems, San Jose, CA, USA). Pixel positions were converted to numeric values by axial units. The data obtained were the sums of resistance and reactance, the Z_{abs}, or the Y_{ratio}. If data were the sums of resistance and reactance, the values were converted to the Z_{abs} in Ohms (Ω). The data obtained from the literature were plotted between the input data of the distance from the APC and frequency and the output data of the impedance values. As an example, the data extracted from Pilot and Pitts' paper were plotted three-dimensionally in Figure 2a.[19] We did not contact the authors of the studies to collect further information.

All data were organized in a table according to group number, output value, frequency, and distance from the APC. Based on the tables, the data sets and the grouped data sets were collected when the input data were the frequency or both frequency and distance from the APC (Table 2). All of the groups or papers were evaluated to determine whether they could be converted into a specific model. First and second order polynomials were estimated

Table 2. Summary of selected papers containing the electrical property measurements of electrical apex locator, and the number of data sets and grouped data sets when the input data were the frequency or both the frequency and the distance from the apical constriction

	In vivo	Output Format*	Data Set 1[†]	Data Set 2[‡]	Data Set 3[§]
Rambo et al. 2010[27]	Yes	Ratio	13	1	1
Jan and Krizaj 2009[28]	No	Value (50,000 Hz)	12	1	1
	No	Ratio			
Huang et al. 2008[18]	No	X + Yj	5	1	1
Rambo et al. 2007[26]	Yes	Ratio	4	1	1
Krizaj et al. 2004[15]	No	X + Yj	8	1	1
Oishi et al. 2002[21]	No	Ratio	47	47	0
Lee et al. 1997[22]	No	Value (no unit)	7	1	1
Pilot and Pitts 1997[19]	Yes	Value	36	7	7
Kobayashi and Suda 1994[8]	No	Ratio	23	5	3
Levinkind 1994[17]	No	X + Yj	3	1	1
Sum			158	66	17

*Ratio, the ratio between two electrical impedance values at two selected frequencies; Value, absolute impedance value; X + Yj, (Resistance) + j (Reactance).
[†]The number of data sets were counted when the frequency conditions of the input data were two or more.
[‡]The number of grouped data sets were counted when the frequency conditions were the input data. In each study, data were grouped according to experimental variables such as teeth and materials.
[§]The number of grouped data sets were counted when both the frequency conditions and the distance from the apical constriction were the input data. In each study, data were grouped according to experimental variables such as teeth and materials.
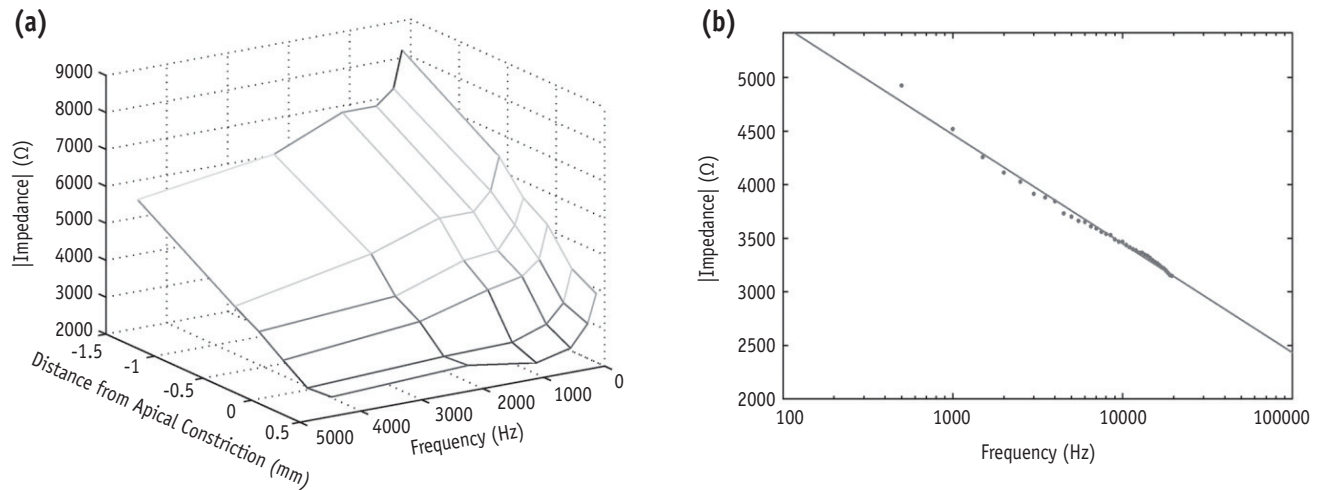
(a)

(b)

Figure 2. Sample plots for data obtained from the studies included in the correlation analysis. (a) Three-dimensional plot of a grouped data set from Pilot and Pitts, in which the inputs were the distance from the apical constriction and the frequency, and the outputs were the absolute impedance values (Z_{abs});[19] (b) Plot of the log-scaled frequency and the Z_{abs} from a sample data set from Krizaj *et al.*[15]

as candidates of the specific model using the least squares method. The least squares method was performed using a 'polyfit' function in Matlab R2012b (The MathWorks Inc., Natick, MA, USA). The independent and dependent variables of the model were frequency in a log scale and Z_{abs}, respectively. An example of the plot for the first order model between the log-scaled frequency and the Z_{abs} is presented in Figure 2b. Because a linear scale is impractical for expressing large frequency ranges, the log scale is commonly applied when employing the frequency responses of electronic circuits, as in Bode plots.[20] In the first and second order polynomial models, the numbers of the positive and negative coefficients of the highest order were examined.

The regression model between the log-converted frequency and Z_{abs} was determined as a first order polynomial (equation 1).

$$(Z_{abs}) = \alpha \times \log(f) + \beta \qquad \text{(Equation 1)}$$

where α, β and f were the slope, intercept and frequency of the first order regression curve, respectively (Figure 2b).

The regression model between the Y_{ratio} and the distance from the APC was derived from the same grouped data set that was collected according to the experimental variables, such as teeth and experimental materials. The Y_{ratio} values were obtained at two selected frequencies and then plotted against the distance data for the same group (Equation 2).

$$\hat{Y}_{ratio} = \frac{\log f_1 + \dfrac{(\beta)_{x=\bar{x}}}{(\alpha)_{x=\bar{x}}}}{\log f_2 + \dfrac{(\beta)_{x=\bar{x}}}{(\alpha)_{x=\bar{x}}}} \qquad \text{(Equation 2)}$$

where f_1 and f_2 were two different arbitrarily-selected frequencies, and $\bar{x}$ is the distance from the APC in millimeters. In each group, the $\hat{Y}_{ratio}$ was calculated and plotted in Figure 3a according to the inclusion criteria, when f_1 and f_2 were 8,000 Hz and 400 Hz, respectively.[8] If the plots from Pilot and Pitts are excluded, the model using the $\hat{Y}_{ratio}$ at two different frequencies fits as a linear ramp function (Figure 3b).[19] In the linear ramp function, the linear section and the two horizontal sections were discriminated using a searching algorithm as follows:

1. The points discriminating the two horizontal sections and a linear section in between them were assumed to be the last and the first points of the assuming left and right horizontal sections, respectively, in the $\hat{Y}_{ratio}$ data of each group (Figure 3c).
2. Move the discriminating points.
   a. In odd trials, the last point at the end of the left horizontal section was changed to the next right point (Figure 3d).
   b. In even trials, the first point at the start of the right horizontal section was changed to the next left point (Figure 3e).
3. In the linear interval and outer parallel horizontal areas, the linear ramp function was estimated using
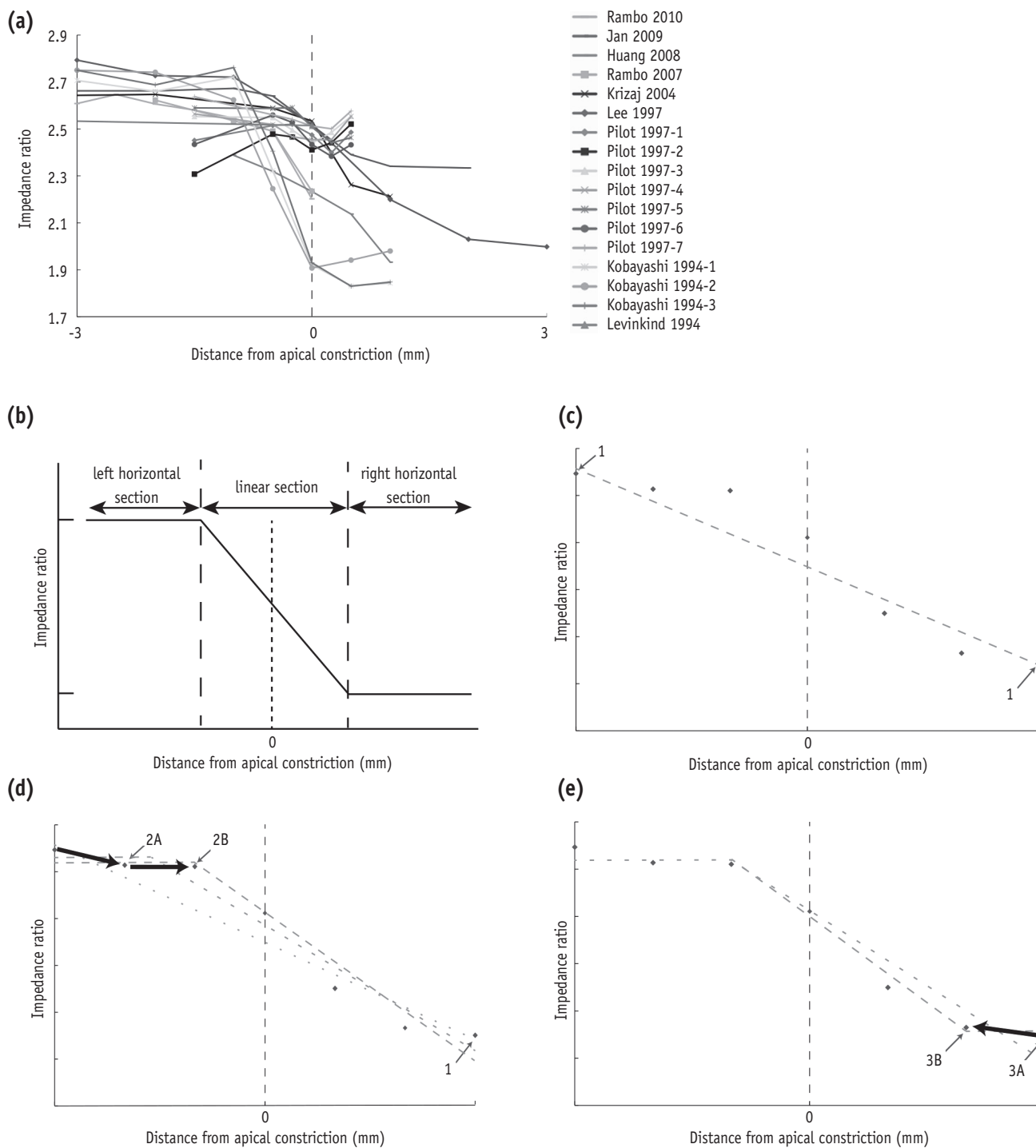
Figure 3. Plots of the distance from the apical constriction (APC) and the impedance ratio (Y_{ratio}), and the method used to find a simple linear ramp function model. (a) Plots of the distance from the APC and the Y_{ratio} between 400 and 8,000 Hz for all groups; (b) Model between the distance from the APC and the Y_{ratio} between 400 and 8,000 Hz; (c) - (e) Point selection algorithm for the simple linear ramp function model between the distance from the APC and the Y_{ratio} values. Move the discriminating points (1). (d) In odd trials, the last point at the end of the left horizontal section (2A) was changed to the next right point (2B); (e) In even trials, the first point at the start of the right horizontal section (3A) was changed to the next left point (3B).

the least squares method.

4. When the next trial was executed, if the previous least squares error was smaller than the current error, the point was reverted and the procedure was stopped.
    a. If no movement occurred between trials in the right-end last and left-end first points, the calculation was stopped and the points were selected as the final (polygonal) discriminating points.
    b. If there was any movement in the discriminating points, the next point was selected and the least squares error function was carried out to dictate the next trial.

The average values of the left and right horizontal sections of each group, and the values where the distance was 0 were compared using one-way repeated measures analysis of variance (ANOVA). If the output of each group was not Y_{ratio}, a regression analysis was performed for each group between β and the distance from the APC (Equation 3).

$$\beta = \chi \times x + \delta \qquad\qquad (Equation\ 3)$$

where β, χ, x and δ were the intercept, slope, distance from the APC, and interference of the regression curve, respectively. Numerical analysis was performed using Matlab R2012b (MathWorks Inc.). Statistical analyses were carried out using IBM SPSS 20.0 (IBM, Chicago, IL, USA).

Results

The data for ten selected papers, including three *in vivo* and seven *in vitro* experiments, are shown in Table 2. The output data were in Y_{ratio} in four_papers and in Z_{abs} in three papers. The remaining three papers were in Z_{abs}, which can be inferred from the resistance and reactance. The numbers of data sets and grouped data sets are also presented in Table 2 according to the input data, which were either the frequency or both frequency and distance from the APC. When the input and output data were frequency and Z_{abs}, respectively, 158 data sets could be extracted. The number of grouped data sets was 66, when data were grouped according to experimental variables. Among the 66 grouped data sets, 17 data sets could also be estimated when the inputs were both frequency and distance from the APC. Grouped data sets, in which the input data were the frequency and distance from the APC, could be extracted from nine papers except for Oishi *et al.*[21]

When the first-order equation was assumed as a model, the slope of the equations in all the models were in the negative direction (Figure 2b). However, the directions were not consistent in the models of the second order equation, especially in the grouped data. When the distances from the APC were different, both directions were possible and the distribution of directions, meaning the

numbers of coefficients with positive, negative, and both signs, did not have statistical differences in the grouped data sets or the data sets extracted from each paper. Therefore, the first order equation was selected.

After inspecting the first order plot, the model between the distance from the APC and $\hat{Y}_{ratio}$ in equation 2 was converted to a simple linear ramp function using the least squares method (Figure 3b). In eight cases, except for Pilot and Pitts, average $\hat{Y}_{ratio}$ values in the left horizontal zone were significantly higher than those in the right horizontal zone (Table 3).[19] In all cases, the APC was located within the interval of the linear relation between the left and right horizontal zones of the simple linear ramp model. The left-most positions of the linear interval were between -1.5 and 0, except for Levinkind, in which it was -14. The right-most positions of the linear intervals were between 0 and 2.[17]

Regarding the relationship between β and the distance from the APC, data sets could be extracted from 5 papers including Huang *et al.*, Krizaj *et al.*, Lee *et al.*, Pilot and Pitts, and Levinkind (Tables 2 and 4).[15,17,19,22] All slopes were negative (Table 4 and Figure 4). Regression analyses were performed for the data sets from all of the papers, and the linear coefficients of the data sets for each paper were statistically significant, except for Huang *et al.*[18]

Discussion

Kobayashi and Suda first introduced Root ZX based on the ratio method for measuring the WL.[8] The usefulness of this method was verified by many subsequent studies.[23] In the present study, all papers except for Pilot and Pitts reported that the interval of the linear relation had significantly higher average values in the left horizontal zone than in the right one ($p < 0.05$).[19] This indicates that the ratio method of determining impedance values can discriminate between the areas that are under-instrumented and those that are over-instrumented. The segregation we observed between the under-instrumented and over-instrumented areas provides the rationale for detecting apical constriction and avoiding failure in determination of WL. In all grouped data sets, the APC, designated as 'distance 0', was found within the linear interval, which indicates that the ratio method may be used for detecting the position of the APC. The $\hat{Y}_{ratio}$ values at the APCs showed no significant differences from those of the right horizontal zones (Table 3). This result supports the clinical protocol of Root ZX, which recommends a fitting procedure of initial passing and subsequent withdrawal of a file through the APC. The beep reading of Root ZX indicates the ratio value at the discriminating point between the right horizontal zone and the APC within the linear interval. Oishi *et al.* also noted a correlation between the distance from the APC and the Root ZX reading.[21] When data from Levinkind were excluded

Table 3. Impedance ratios ($\hat{Y}_{ratio}$) in the left and right horizontal zones and at the apical constriction within the linear interval and the positions of the left- and right-end points of the linear interval discriminating the horizontal sections, when a simple linear ramp model was estimated in each study

Studies	Average $\hat{Y}_{ratio}$ values in horizontal zones		$\hat{Y}_{ratio}$ Values at APC*[†§‖]	Position of linear relation	
	Left[†‡§]	Right[†‡‖]		Left	Right
Rambo et al. 2010[27]	2.60	2.20	2.24	-1	0
Jan and Krizaj 2009[28]	2.66	2.36	2.52	-0.5	0.5
Huang et al. 2008[18]	2.35	1.93	2.22	-0.5	1
Rambo et al. 2007[26]	2.58	2.23	2.27	-1	0
Krizaj et al. 2004[15]	2.62	2.24	2.46	-0.5	0.5
Lee et al. 1997[22]	2.75	2.01	2.49	-1	2
Pilot and Pitts 1997[19]	2.50	2.44	2.46	-0.25	0.25
	2.31	2.52	2.46	-1.5	0.5
	2.51	2.55	2.44	0	0.5
	2.56	2.50	2.46	-1.5	0.25
	2.59	2.45	2.51	-0.25	0.25
	2.50	2.41	2.45	-0.5	0.25
	2.64	2.54	2.52	-1.5	0.25
(Average of Pilot and Piits 1997)	2.52	2.49	2.47	-0.79	0.32
Kobayashi and Suda 1994[8]	2.70	1.87	1.92	-1	0
	2.71	1.94	1.90	-1	0
	2.73	1.87	1.95	-1	0
(Average of Kobayashi and Suda 1994)	2.71	1.89	1.92	-1	0
Levinkind 1994[17]	2.61	2.51	2.51	-14	0
Average by group	2.58 (0.12)	2.27 (0.25)	2.34 (0.22)	-1.59 (3.23)	0.37 (0.50)
Average by paper	2.58 (0.11)	2.23 (0.23)	2.33 (0.21)	-2.25 (4.69)	0.48 (0.36)

The numbers in parentheses are standard deviations.
*Values at APC meant the $\hat{Y}_{ratio}$ values when the distance from the apical contriction (APC) is 0 (zero).
[†]p-values of one-way repeated measures ANOVA were 0.005 and 0.011 when clustered by groups and papers, respectively.
[‡]p-values of Bonferroni corrected paired t-tests were 0.003 and 0.005 when clustered by groups and papers, respectively.
[§]p-values of Bonferroni corrected paired t-tests were 0.008 and 0.028 when clustered by groups and papers, respectively.
[‖]p-values of Bonferroni corrected paired t-tests were 0.183 and 0.114 when clustered by groups and papers, respectively.
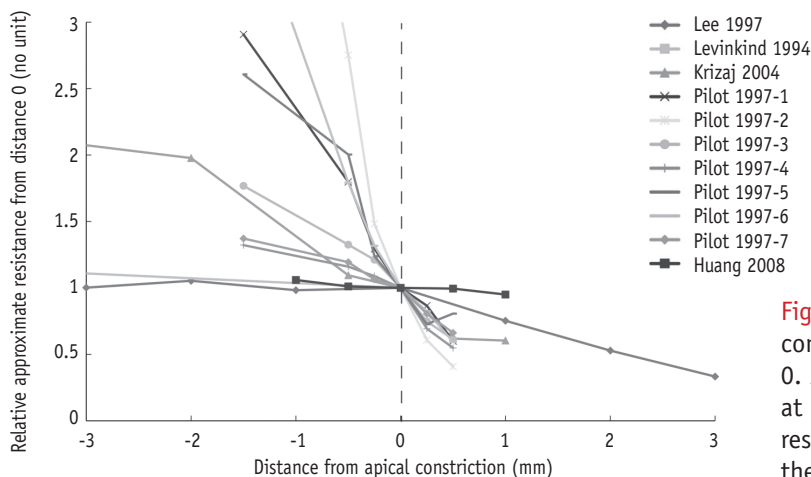

Figure 4. Plots of the distance from the apical constriction and the relative value from Distance 0. Approximate resistance values (β) obtained at 1 Hz from Equation 1 were substituted for the resistance at frequency f = 0 and calibrated using the approximate resistance value at point 0.

Table 4. Slope (ɣ) and interference (δ) values in the model, where the approximate resistances (β) in each group were plotted against the distance from the apical constriction

	Model (x10³ Ω/mm)		p value of slope	In vivo
	Slope (ɣ)	Interference (δ)		
Rambo *et al.* 2010[27]	-*	-	-	Yes
Jan and Krizaj 2009[28]	-	-	-	No
Huang *et al.* 2008[18]	-1.2	11.7	.322	No
Rambo *et al.* 2007[26]	-	-	-	Yes
Krizaj *et al.* 2004[15]	-1.7	6.8	.000	No
Oishi *et al.* 2002[21]	-	-	-	No
Lee *et al.* 1997[22]	-1.1	7.7	.005	No
Pilot and Pitts 1997[19]	-21.2	20.0	.000	Yes
	-97.7	38.0	.001	
	-7.7	12.8	.000	
	-5.5	13.0	.014	
	-17.3	19.4	.003	
	-33.9	22.4	.001	
	-3.3	8.9	.004	
(Average of Pilot and Pitts 1997)	-26.7	19.2		
Kobayashi and Suda 1994[8]	-	-	-	No
Levinkind 1994[17]	-9.4	265.3	.007	No
Average (SD) by group	-18.2 (28.3)†	38.7 (75.7)		
Average (SD) by paper	-8.0 (11.0)	62.2 (10.7)		

*'-' means 'value not available'.
†The numbers in the parentheses are standard deviations.

from Table 3, the linear interval was so narrow that it could be used to verify the relation between the $\hat{Y}_{ratio}$ value and the distance from the APC.[17] This finding supports the utility of the ratio method and the theoretical background underlying Root ZX.

There were negative correlations between frequency and impedance in the first order plot. If the equivalent circuit of root canal is resistance, impedance has a constant value. Negative slopes of impedance values in this study suggest that the equivalent circuit includes a capacitor element within the circuit (Figure 2b), that is, a pure capacitor or a constant phase element in the circuit of the root canal model.[15,24] The features of the second order models suggest the concavity or convexity of the model, but no directional tendencies were noted in this study. No tendencies of concavity or convexity were observed when the noise was higher than the original signal, when the model changed depending on distance, or when other electrical factors such as capacitance were induced by a long wire. Experiments for equivalent circuit modeling were performed

in many previous studies.[14-18] However, no common or interconvertible models exist. Studies discriminating the directional features of the second order model for root canals are needed.

In this analysis, we arbitrarily selected frequencies of 400 Hz and 8,000 Hz, as in Oishi *et al.*[21] When frequency changed, the ratio of impedance values also changed, but did not influence the final detection of WL, as shown in equation 2. This occurred because the slope (α) and interference (β) of the equations 1 and 2 were not changed by changes in frequency, and the log-scaled frequencies in equation 2 were determined by the selected experimental conditions. The selection of specific frequencies is very important to avoid the influence of frequencies caused by noise. In the human body, there are various low frequency electrical sources including the heart, muscle, and brainwaves. Separation of frequencies is critically important to avoid mutual interference. Because detecting very high frequencies in a small, portable electrical detector is challenging, it is very difficult to overcome internal noise

and errors generated by the electrical detector itself at very high frequencies. The frequencies found in cases of high signal-to-noise (SN) ratios are suitable for the detection and measurement of electrical properties. Therefore, it is practical to select suitable frequencies for the performance of electrical property measurements. The discovery that several pairs of frequencies can be used to obtain high SN ratios made the use of multi-frequency EAL possible.[25] Z_{abs} was chosen for the integration of the output values. If resistance and reactance are used as output data to achieve sufficiently high SN ratios, phase analysis may be used for locating the APC.[26]

Values of β were obtained from Equation 1 to substitute approximate resistance values at 1 Hz for resistance at a frequency f = 0, because the real resistance value (f = 0) cannot be obtained using this equation. The correlation between the approximate resistance and the distance from the APC was negative in the slopes (ɣ) of all papers, and the ɣ values were statistically significant in four papers not including Huang et al. (Table 4).[18] This suggests that the approximate resistance may also be used as a secondary source for detection of the APC. However, the values of ɣ and δ varied greatly between studies. In addition to various kinds of irrigants found in the canal, the complexity of dentin substrate composition, underlying tissues, or root canal shape may result in variation.[19] The variation may also be attributed to differences in experimental environments, such as sensitivity of sensors, calibration errors of devices, electrical noise, and the signal processing method used by the measuring instrument. While the major weakness of the ratio method is the narrow range of the detection distance beyond the linear interval, use of the approximate resistance alone is also inappropriate for detecting the WL and the APC. The accuracy of the ratio method, which is superior to the previous resistance and frequency methods for detecting the position of the APC, may also be supplemented by considering the approximate resistance, which offers the advantage of a wide range of detection sizes.

Conclusions

Through a correlation analysis of the data in previous studies, we found that the $\hat{Y}_{ratio}$ decreased when a file went deeper and deeper into the canal and the APC could be located within a narrow range of the linear interval of a simple linear ramp function model when an EAL was used to determine the WL by the ratio method. The average $\hat{Y}_{ratio}$ values of the left and right horizontal zones, which correspond to the under-instrumented and over-instrumented areas, respectively, were significantly different. Despite the limitations of this study, the impedance ratio method was found to be a robust method for detecting the APC from the perspective of electrical principles.

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