Accuracy of different generations of apex locators in determining working length; a systematic review and meta-analysis

Kaveh Nasiri a,*, Karl-Thomas Wrbas b,c

a Independent Researcher, Essen, Germany
b Department of Endodontics, Center for Operative Dentistry and Periodontology, University of Dental Medicine and Oral Health, Danube Private University (DPU), Krems, Austria
c Department of Operative Dentistry and Periodontology, Center for Dental Medicine, Oral and Maxillofacial Surgery, Medical Center, University of Freiburg, Freiburg i.Br., Germany

Received 18 August 2021; accepted 16 September 2021
Available online 25 September 2021

Abstract  Background and objective: The accurate determination of working length has a major influence on the prognosis of root canal treatment. Electronic Apex Locators (EALs) appear to be excellent tools for the determination of working length (WL). This study aimed to assess the accuracy of four generations of EALs.

Materials and methods: For the purpose of the present review study, articles on different generations of EALs were selected from the PubMed, Cochrane Library, Google Scholar, and ScienceDirect databases using the search term apex locators. In addition, eligibility criteria were set and used for the inclusion of articles.

Results: Fifteen studies satisfied the eligibility criteria and were included in this study. According to the results of four meta-analyses, the Cochran’s Q-values were 3.042, 4.569, 0.636, and 0.443. The I² value of four heterogeneity tests was zero (I² = 0). In addition, the effect sizes (risk ratios) of the four meta-analyses were 1.040, 0.997, 0.935, and 0.959.

Conclusion: Based on the findings of this study, all four generations of apex locators under review were found to be accurate in measuring working length. Hence, the generation of an apex locator does not play a significant role in how accurately electronic devices determine working length.
1. Introduction

Accurately determining working length (WL) in root canal therapy facilitates treatment prognosis (de Morais et al., 2016; Sadaf and Ahmad, 2015). Successful root canal therapy depends on meeting three main criteria: a proper access cavity, cleaning and shaping, and three-dimensional obturation of the root canal system. Except for the access cavity, the other two prerequisites can be accomplished only if the WL is determined precisely (Adams and Tomson, 2014; Golvankar et al., 2019).

Electronic apex locators (EALs) use the human body to produce an electrical circuit. They have two sides: one is connected to the endodontic file in the root canal, and the other is connected to the patient’s lip. The electrical circuit will be complete when the tip of the dental file reaches the periodontal tissue. These devices are particularly useful for patients with gag reflex problems or those who cannot tolerate radiography films or sensors. Because each generation of apex locators has a distinct display, they show different images of the apical region (Bahrololoomi et al., 2015; Khattak et al., 2014).

The idea of using electronic methods to detect the apex of the root canal was first proposed by Custer in 1918 and was then revisited by Suzuki in 1942. Suzuki discovered that the constant value is the result of electronic resistance between the periodontal ligament and the oral mucosa. Later, Sunada used Suzuki’s idea and developed an apex locator in 1962 (Gutmann, 2017; Puri et al., 2013). With the advancement of technology in dentistry, various generations of EALs have been developed to measure the WL with higher accuracy (Golvankar et al., 2019; Guise et al., 2010). Table 1 (Connert et al., 2018; Guise et al., 2010; Gurel et al., 2017; Saxena et al., 2017; Stoll et al., 2010; Vanitha and Sherwood, 2019) illustrates different generations of electronic apex locators.

This review study aimed to examine the accuracy of four different generations of apex locators in measuring working length through previous studies found via searches in electronic databases.

1.1. Apical terminus of root canal

Apical Constriction (AC): First extensively investigated by Kuttler (Kuttler, 1955), the AC or minor apical diameter is considered the ideal spot for canal preparation and obturation of root canals. The AC is the narrowest spot of the root canal and has the lowest diameter. The morphological location of the apical constriction can vary among roots. The AC is generally located 0.5–1.0 mm short of the apical foramen (Diwanji et al., 2014; Kuttler, 1955).

Apical Foramen (AF): The AF or major apical diameter varies in size and formation among roots. The AF can change from symmetrical to asymmetrical in different physiological and pathological conditions. The AF is open before maturation; however, with time and after maturation, it decreases and takes a funnel shape, which is due to hard tissue deposition. The AF is not always found at the anatomical apex (AA); the distance between the AF and AA is, in particular, higher in the posterior and older teeth than in the frontal and younger teeth (Gordon and Chandler, 2004; Martos et al., 2009).

Anatomical and radiographic apex: The anatomical apex or true apex is the tip of the root and is the root terminus. The anatomical apex is normally straight; however, it tends to curve distally with time (Kuttler, 1955). The radiographic apex is determined via radiography, and its position can be different because of the distortion of radiographic images (Orosco et al., 2012).
Cement-dentinal junction (CDJ): The CDJ is the region in the root canal at the interface between the cementum and dentin. Since the CDJ has a unique organic matrix, the mineralisation in this junction is higher than that of both the cementum and dentin (Sudhakar and Pratebha, 2015). This histological landmark has the best prognosis in root canal treatment when biomechanical instrumentation and obturation are limited in the CDJ. Although the exact location of the CDJ cannot be identified clinically or through radiography, the apical constriction (AC) is an appropriate and reliable location as an endpoint for root canal treatment (Mousavi et al., 2018). The locations of the CDJ and AC do not always coincide (Sharma and Arora, 2010). Fig. 1 illustrates the longitudinal section of a palatal root of an extracted first maxillary molar, photographed with a camera equipped to a stereomicroscope at 20× magnification (Bresser, Rhede, Germany), as well as its schematic representation of the apical area made via ImageJ (National Institutes of Health (NIH), Bethesda, MD, USA).

### Table 1 Detailed description of different apex locators.

| Device                  | Manufacturer                        | Generations       | Display AC* | Display AF* |
|-------------------------|-------------------------------------|-------------------|-------------|-------------|
| Apex ID                 | SybronEndo, Orange, CA, USA         | Third generation  | 0.5         | 0.0         |
| Elements Apex Locator   | SybronEndo, Orange, CA, USA         | Fourth generation | 0.5         | 0.0         |
| iPex                    | NSK, Tochigi, Japan                 | Fourth generation | 0.5         | 0.0         |
| iPex II                 | NSK, Tochigi, Japan                 | Fourth generation | 0.5         | 0.0         |
| Precision Apex Locator  | Brasseler USA, Savannah, GA, USA    | Fourth generation | 0.5         | 0.0         |
| Raypex 5                | VDW, Munich, Germany                | Fifth generation  | Third green line | Red bar     |
| Raypex 6                | VDW, Munich, Germany                | Sixth (modification of a fifth generation) | Third green line | Red bar     |
| ProPex Pixi             | Dentsply Sirona, Ballaiges, Switzerland | Fifth generation | 0.5         | 0.0         |
| ProPex II               | Dentsply Sirona, Ballaiges, Switzerland | Fifth generation | 0.5         | 0.0         |
| Root ZX (Dentaport ZX)/ Root ZX II | J. Morita MFG. CORP, Kyoto, Japan | Third generation | Middle of APEX and 1 mark (0.5) | 0.0         |
| Root ZX Mini            | J. Morita MFG. CORP, Kyoto, Japan   | Third generation | Middle of APEX and 1 mark | Last green bar |

AC*: Apical constriction, AF*: Apical foramen.
2. Materials and methods

2.1. Search strategy

In this review study, four databases, namely, PubMed, Cochrane Library, Google Scholar, and ScienceDirect, were used to search and find published papers on different generations of apex locators. The general term searched in all databases was apex locators. A publication year range from 2000 to 2021 was applied in all databases except for Google Scholar. Since the initial search in Google Scholar yielded more than 4810 articles, publications from the last three years were considered for the next stage of the screening process. The initial search in each database was imported and combined in Microsoft Word. Duplicate publications were identified via the navigation function in Microsoft Word and then removed. Data extraction was performed by two investigators.

2.2. Inclusion criteria

Inclusion criteria in this review study:

1. Language restriction: only English.
2. Original articles.
3. Type of study: in vitro or in vivo experiments.
4. Studies with at least 10 samples.
5. Studies that compare different generations of apex locators.
6. In studies in which two or more devices belong to one generation, only the device with the highest level of accuracy in determining working length should be selected. (This holds except for the situations in which the most accurate device of one generation has the same level of accuracy (number of events) as that of other generations. In this case, the device with lower accuracy should be selected to avoid entering the same data and thus to be able to run meta-analysis).

2.3. Exclusion criteria

The exclusion criteria for the selection of the articles were as follows:

1. Studies excluded: case reports and review studies.
2. Studies involving artificial teeth and teeth with root resorption.
3. Studies with insufficient data.
4. Studies comparing electronic methods and radiography or other methods.
5. Studies investigating the effect of different file sizes, variable irrigation solutions, and horizontal or vertical root fracture on the accuracy of apex locators.
6. Studies on endodontic rotary motors with integrated apex locators.

2.4. Structured question

Which one of the generations of apex locators is most effective at determining working length?

3. Results

The initial search in the four databases identified 2286 studies. After the removal of duplicates, the search strategy yielded 1990 studies, the titles of which were then examined. A total of 1851 articles were subsequently excluded because they did not contain a comparison of electronic apex locators, leaving a total of 139 articles. This process was followed by reviewing the abstracts of the remaining articles using the inclusion and exclusion criteria. As a result, a further 119 articles were removed, and only 20 articles remained, which were then assessed for eligibility. Full-text analysis led to the removal of another five articles for the following reasons: four of the articles either focused on a different outcome of interest rather than generations of EALs or data on the number of events in the articles were not available. The fifth one was removed due to the inaccuracy of some data on the generation of apex locators. Thus, at the end of the screening process, 15 articles were included in the quantitative synthesis of this study. Fig. 2 shows the flow diagram of the article screening in the review process. Statistical analysis was conducted via Comprehensive Meta-Analysis 2.0 (CMA).

The results of four meta-analyses of the 15 studies showed that the heterogeneity tests resulted in Q-values of 3.042, 4.569, 0.636, and 0.443 among the 3rd and 4th generations, 3rd and 5th generations, 4th and 5th generations, and 3rd and 6th generations, respectively. The $I^2$ value of four heterogeneity tests was zero, which revealed that there was no dispersion. As depicted in Fig. 3, the risk ratio was selected as the effect size. The overall effect sizes of the studies were 1.040, 0.997, 0.935, and 0.959, respectively, indicating that the risk of measurement error when using 3rd and 4th, 3rd and 5th, 4th and 5th, and 3rd and 6th generations of apex locators is the same. Table 2 (Betancourt et al., 2019; Guise et al., 2010; Gurel et al., 2017; Moscoso et al., 2014; Nasiri and Wrbas, 2019; Plotino et al., 2006; Puri et al., 2013; Serna-Pena et al., 2020; Somma et al., 2012; Stober et al., 2011; Swapna et al., 2015; Tselnik et al., 2005; Tufenkci and Kalayci, 2020; Vasconcelos et al., 2014; Wrbas et al., 2007) gives general information about the selected articles and their results. Fig. 4 presents the data of the selected studies within ±0.5 mm from working length except for one study. Since the data within ±0.5 mm of working length in the study by Tselnik et al. (Tselnik et al., 2005) provided the same accuracy between two generations, the data were selected within the −0.5 to 0.75 range so that the inclusion of the data in the meta-analysis would be possible.

3.1. Risk of bias assessment

1. This review study selected studies in which the comparison occurred only among generations of EALs. 2. The accuracy of EALs was considered within ±0.5 mm of the WL (except Tselnik et al.). 3. Seven studies were performed in vitro, and 8 studies were conducted in vivo; however, the final evaluation of these 8 studies was also performed in vitro. Thus, all selected studies were performed in the same way. 4. In this study, a comprehensive search was conducted in four databases to select studies on the generation of EALs. For this reason, the probability of an existing article on this topic is not zero but low. 5. Fifteen articles supported the quantitative results of the current study. Although new articles will be published in the future in this regard, they cannot affect the results of the current review study because of the high number of studies included. Hence, the risk of bias in this study is low.

4. Discussion

The use of electronic apex locators for the determination of working length has increased in popularity. Apex locators are classified according to their generations (Mull et al., 2014; Wrbas et al., 2007) gives general information about the selected articles and their results. Fig. 4 presents the data of the selected studies within ±0.5 mm from working length except for one study. Since the data within ±0.5 mm of working length in the study by Tselnik et al. (Tselnik et al., 2005) provided the same accuracy between two generations, the data were selected within the −0.5 to 0.75 range so that the inclusion of the data in the meta-analysis would be possible.
First-generation EALs or resistance apex locators use a direct current (resistance) to measure the apical area, which causes pain to the patient due to the high currents. Moreover, the EALs in this generation, such as Dentometer (Dahlin Electromedicine, Copenhagen, Denmark) and Endo Radar (Electronica Liarre, Imola, Italy), were found to be inaccurate.

Fig. 2 Flow chart of study selection.
Fig. 3  Forest plot of the meta-analysis: 3rd and 4th generations, 3rd and 5th generations, 4th and 5th generations, and 3rd and 6th generations.

Fig. 4  Data visualisation of the included studies.
| Authors and year of publication | Study type | Type of EALs | Type of generations | Main study result | Conclusion |
|-------------------------------|------------|--------------|---------------------|------------------|------------|
| Betancourt et al. 2019        | In vitro study | Pixi, Root ZX II, Propex II, Raypex 6 | Fifth, third, fifth, sixth | No significant difference | Root ZX II and Raypex 6 showed the best overall performance |
| Guise et al. 2010             | In vitro study | Root ZX II, Elements Apex Locator, Precision Apex Locator | Third, fourth, fourth | Significant difference | Root ZX II was the most accurate in locating the apical foramen |
| Gurel et al. 2017             | In vitro study | Raypex 5, Raypex 6, iPex, iPex II | Fifth, sixth, fourth, fourth | No significant difference | All devices showed the same accuracy |
| Moscoso et al. 2014           | In vivo study | Dentaport ZX, Raypex 6 | Third, sixth | No significant difference | Both devices were effective in determining working length |
| Nasiri and Wrbas 2019         | In vitro study | Root ZX and Raypex 6, Root ZX, Elements Diagnostic Unit, ProPex | Third, sixth, fourth, fifth | No significant difference | Both devices were capable of determining canal length, the majority of ProPex readings were long. |
| Puri et al. 2013              | In vitro study | DentaPort ZX, iPex, Root ZX Mini, Apex ID, Propex Pixi | Third, fourth | No significant difference | Both devices showed the same precision |
| Serna-Pena et al. 2020        | In vivo study | Dentaport ZX, Raypex 5, ProPex II | Third, fifth, fifth | No significant difference | All devices showed satisfactory precision |
| Somma et al. 2012             | In vivo study | Dentaport ZX, Raypex 6, ProPex II | Third, fourth | No significant difference | Both devices were equally effective |
| Stöber et al. 2011            | In vivo study | Root ZX, iPex | Third, fourth | No significant difference | Both devices were equally effective |
| Swapna et al. 2015            | In vivo study | Root ZX, Raypex 5 | Third, fifth | No significant difference | Both devices were equally effective |
| Tselnik et al. 2005           | In vivo study | Root ZX, Elements Diagnostic Unit, ProPex | Third, fourth, fifth | No significant difference | All devices had the same satisfactory accuracy |
| Tufenkci and Kalayci 2020     | In vitro study | Dentaport ZX, iPex II, Propex Pixi | Third, fifth | No significant difference | Both devices were capable of locating the apical foramen |
| Vasconcelos et al. 2014       | In vivo study | Root ZX, Propex II | Third, fifth | No significant difference | Both devices can accurately determine working length |
| Wrbas et al. 2007             | In vivo study | Root ZX, Raypex 5 | Third, fifth | No significant difference | Both devices can accurately determine working length |
particularl in comparison to radiography methods, in determining working length, which is considered to be a main drawback (Chopra et al., 2008; Gordon and Chandler, 2004; Mull et al., 2012). Thus, in second-generation EALs, also known as impedance-based apex locators, some modifications were made to improve first-generation apex locators. One improvement was using an alternating current (impedance) for the detection of the apex. Impedance has a sinusoidal amplitude trace and consists of resistance and capacitance. The main shortcomings of second-generation devices, such as Sonopax (Hayashi Dental Supply, Tokyo, Japan), were poor accuracy in the presence of electroconductive irrigations and tissue fluids and no digital read-out (Chopra et al., 2008; Gordon and Chandler, 2004; Mull et al., 2012).

With the advancement of science and technology in dentistry, new generations of EALs, the third, fourth, fifth, and sixth generations (modified fifth generation), with higher accuracy in measuring working length have been developed (Gurel et al., 2017; Jadhav et al., 2018). Third-generation apex locators, such as J. Morita MFG electronic devices, use a dual frequency, which is based on the "ratio method", to measure canal length with high accuracy in endodontic therapy. In the ratio method, the impedance values at two frequencies, i.e., high (8 kHz) and low (400 Hz), are simultaneously measured. Based on the result, a quotient of impedances is calculated, and the quotient value shows the location of the dental file in the canal. This generation is capable of locating the point or the narrowest part of the root canal (Chopra et al., 2008; Golvanak et al., 2019; Gordon and Chandler, 2004; Mull et al., 2012).

Unlike the third generation, the fourth generation is incapable of processing impedance values as a mathematical algorithm. This generation measures the capacitance and resistance of the circuit separately and compares them with a database to detect the narrowest part of the root. This generation can perform well in relatively dry canals (Gordon and Chandler, 2004; Mull et al., 2012). Fifth-generation EALs provide several benefits, including safety, reliability, clinician and patient friendliness, as well as an accurate detection of working length in cases where there are exudates or weeping in the canal (Chopra et al., 2008). The sixth generation, also called adaptive apex locators, is a modification of the fifth generation and shows the highest consistency for measurements in the case of root perforation or apical root resorption (Haupt and Hülsmann, 2018; Jadhav et al., 2018). Among the different generations of EALs, the first and second generations are obsolete and no longer manufactured and used in modern dentistry. Therefore, studies examining the efficacy of first- and second-generation EALs were not included in this study and thus are not presented in Table 1.

To develop search strategies in systematic reviews, the question is often formed by the "PICO" framework. The elements of PICO are problem/patient/population, intervention/indicator, comparison, and outcome (Neelakantan et al., 2020; Siddique and Niveditha, 2019). In this review study, four generations of apex locators were evaluated. Since the intervention factor in PICO could be any of the generations of devices in the subset, the question under review, in line with a previous study, was not formed according to the "PICO" framework (Hartmann et al., 2019). Instead, the question guiding the study was framed as follows: which one of the generations of apex locators is most effective in determining working length? In addition, since various studies reported different agreement and disagreement of accuracy among generations of EALs (Golvanak et al., 2019; Haupt and Hülsmann, 2018), meta-analysis was used to reach a comprehensive conclusion.

The four meta-analyses of the 15 studies among the 3rd and 4th generations, 3rd and 5th generations, 3rd and 6th generations, and 4th and 5th generations showed that there was no significant difference among the generations of EALs, which is consistent with the results of previous studies (Chaudhary et al., 2018; Golvanak et al., 2019). Therefore, the response to the structured question is that the third, fourth, fifth, and sixth generations of apex locators are not different in how accurately they determine working length.

Regarding the inclusion criteria, in the studies by Betancourt et al., Guise et al., and Somma et al. (Betancourt et al., 2019; Guise et al., 2010; Somma et al., 2012), as there were two devices of the same generation, data of the more accurate device were employed. However, in the studies by Gurel et al. and Serna-Pena et al. (Gurel et al., 2017; Serna-Pena et al., 2020), the device data with lower accuracy were selected. The reason, as mentioned earlier in the article, is using the same data of devices with the highest level of accuracy across generations of apex locators. Meta-analysis cannot be run using the same data; and consequently, comparison would not be feasible. By choosing the data of less accurate devices, this problem was addressed.

Moreover, since the accuracy of EALs decreases as the file size increases (Sadeghi and Abolghasemi, 2008), in the study by Tufenkci and Kalayci (Tufenkci and Kalayci, 2020), only the data from root canals before preparation were used, and the data during retreatment were excluded. Considering the aim of this study, in the last selected study (Nasiri and Wrbas, 2019), only the root canal measurement data were selected, and the perforation site data were excluded.

It also needs to be mentioned that while Dentaport ZX and Root ZX are similar, Dentaport ZX has the capability to attach an endomotor (Pascen et al., 2009; Puri et al., 2013). In the four selected studies examining the accuracy of Dentaport ZX along with other devices, Dentaport ZX was evaluated without endomotors (Moscoso et al., 2014; Puri et al., 2013; Somma et al., 2012; Tufenkci and Kalayci, 2020). Therefore, the exclusion factor (studies on endodontic rotary motors with integrated apex locators) was eliminated; and after the screening process, the four studies were included in the study. Finally, the limitation of this study was that the existing data on the four generations of EALs are insufficient; therefore, in order to use meta-analysis, four separate meta-analyses were performed.

5. Conclusions

The findings of this systematic review showed no significant difference in the determination of working length among the four generations of apex locators under review. Hence, it can be concluded that all generations can be equally useful and accurate in determining working length. It is suggested that more in vivo or in vitro studies, in which all generations of devices are examined and compared, be performed to obtain more precise and valid data on the accuracy of different generations of EALs.
Ethical statements

According to the German Ethics Council for research studies, only in vivo studies require ethical statements. This is a review study, in which we only summarized already existing data from various databases. Thus, an ethical statement is not required for the current study.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Adams, N., Tomson, P.L., 2014. Access cavity preparation. Br. Dent. J. 216 (6), 333–339.
Bahrololoomi, Z., Soleymani, A.A., Modaresi, J., Imanian, M., Lotfian, M., 2015. Accuracy of an electronic apex locator for working length determination in primary anterior teeth. J. Dent. (Tehran) 12, 243–248.
Betancourt, P., Matus, D., Muñoz, J., Navarro, P., Hernández, S., 2019. Accuracy of four electronic apex locators during root canal length determination. Int. J. Odontoostomat. 13 (3), 287–291.
Chaudhary, S., Gharti, A., Adhikari, B., 2018. An in vivo comparison of accuracy of two electronic apex locators in determining working length using stainless steel and nickel titanium files. Clin. Cosmet. Investig. Dent. 10, 75–82.
Chopra, V., Grover, S., Prasad, S.D., 2008. In vitro evaluation of the accuracy of two electronic apex locators. J. Conserv. Dent. 11 (2), 82. https://doi.org/10.4103/0972-0707.44056.
Connett, T., Judenhofer, M.S., Hülber-J, M., Schell, S., Mannheim, J. G., Pichler, B.J., Löti, C., ElAyouti, A., 2018. Evaluation of the accuracy of two electronic apex locators using Micro-CT. Int. Endod. J. 51 (6), 223–232.
de Morais, A.L., de Alencar, A.H., Estrela, C.R., Decurcio, D.A., Estrela, C., 2016. Working length determination using cone-beam computed tomography, periapical radiography and electronic apex locator in teeth with apical periodontitis: a clinical study. Iran Endod. J. 11, 164–168.
Diwanji, A., Rathore, A.S., Arora, R., Dhar, V., Madhussudan, A., Doshi, J., 2014. Working length determination of root canal of young permanent tooth: an in vitro study. Ann. Med. Health Sci. Res. 4 (4), 554. https://doi.org/10.4103/2141-9248.139314.
Golvankar, K., Kader, M.A., Latheef, A.A., Mohammed Ali, A.B., Abullais, S.S., Sibagathullah, M., 2019. Comparison of accuracy in determining the root canal working length by using two generations of apex locators - an in vitro study. Open Access Maced. J. Med. Sci. 7 (19), 3276–3280.
Gordon, M.P.J., Chandler, N.P., 2004. Electronic apex locators. Int. Endod. J. 37 (7), 425–437.
Guise, G.M., Goodell, G.G., Imamura, G.M., 2010. In vitro comparison of three electronic apex locators. J. Endod. 36 (2), 279–281.
Gurel, M.A., Helvacioglu Kivanc, B., Ekici, A., 2017. A comparative assessment of the accuracies of Raypex 5, Raypex 6, iPex and iPex II electronic apex locators: an in vitro study. J. Istanb. Univ. Fac. Dent. 51, 28–33.
Gutmann, J.L., 2017. Origins of the electronic apex locator - achieving success with strict adherence to business. J. Hist. Dent. 65, 2–6.
Hartmann, R.C., Fensterseifer, M., Peters, O.A., de Figueiredo, J.A.P., Gomes, M.S., Rossi-Fedele, G., 2019. Methods for measurement of root canal curvature: a systematic and critical review. Int. Endod. J. 52 (2), 169–180.
Haupt, F., Hülsmann, M., 2018. Consistency of electronic measurements of endodontic working length when using multiple devices from the same manufacturer-an in vitro study. Clin. Oral Investig. 22 (9), 3107–3112.
Jadhav, G.R., Mittal, P., Patil, V., Kandekar, P., Kulkarni, A., Shinde, S., Syed, S., Elahi, S., 2018. Accuracy of different apex locators in teeth with simulated apical root resorption: an in vitro study. Folia Med. (Plovdiv) 60, 624–631.
Khattak, O., Raudullah, E., Francis, M.L., 2014. A comparative assessment of the accuracy of electronic apex locator (Root ZX) in the presence of commonly used irrigating solutions. J. Clin. Exp. Dent. 6, e41–e46.
Kullter, Y., 1955. Microscopic investigation of root apexes. J. Am. Dent. Assoc. 50 (5), 544–552.
Martos, J., Ferrer-Luque, C.M., González-Rodríguez, M.P., Castro, L.A., 2009. Topographical evaluation of the major apical foramen in permanent human teeth. Int. Endod. J. 42, 329–334.
Moscoso, S., Pineda, K., Basilio, J., Alvarado, C., Roig, M., Duran-Sindreu, F., 2014. Evaluation of Dentaport ZX and Raypex 6 electronic apex locators: an in vivo study. Med. Oral Patol. Oral Cir. Bucal. 19, e202–e205.
Mouravi, S.A., Farhad, A., Shahnaseri, S., Basiri, A., Kolahdouzan, E., 2018. Comparative evaluation of apical constriction position in incisor and molar teeth: an in vitro study. Eur. J. Dent. 12 (02), 237–241.
Mull, J.Paras, Manjunath, V., Manjunath, M.K., 2012. Comparison of accuracy of two electronic apex locators in the presence of various irrigants: an in vitro study. J. Conserv. Dent. 15 (2), 178. https://doi.org/10.4103/0972-0707.94585.
Nasiri, K., Wirbas, K.T., 2019. Comparing the accuracy of two electronic apex locators in the determination of working length and the detection of root perforations: an in vitro study. Dent. Oral Craniofac. Res. 5, 1–5.
Neelakantan, P., Liu, P., Dummer, P.M.H., McGrath, C., 2020. Oral health-related quality of life (OHRQoL) before and after endodontic treatment: a systematic review. Clin. Oral Investig. 24 (1), 25–36.
Orosco, F.A., Bernardinelli, N., Garcia, R.B., Bramante, C.M., Duarte, M.A.H., Moraes, I.G.d., 2012. In vivo accuracy of conventional and digital radiographic methods in confirming root canal working length determination by Root ZX. J. Appl. Oral Sci. 20 (5), 522–525.
Pascone, E.A., Marrelli, M., Congi, O., Ciancio, R., Miceli, F., Versiani, M.A., 2009. An in vivo comparison of working length determination of two frequency-based electronic apex locators. Int. Endod. J. 42, 1026–1031.
Plotino, G., Grande, N.M., Brigante, L., Lesti, B., Somma, F., 2006. Ex vivo accuracy of three electronic apex locators: root ZX, elements diagnostic unit and apex locator and ProPex. Int Endod. J. 39 (5), 408–414.
Puri, N., Chadha, R., Kumar, P., Puri, K., 2013. An in vitro comparison of root canal length determination by DentaPort ZX and iPex apex locators. J. Conserv. Dent. 16 (6), 555. https://doi.org/10.4103/0972-0707.120953.
Sadaf, D., Ahmad, M.Z., 2015. Accurate measurement of canal length during root canal treatment: an in vivo study. J. Int. Biomed. Sci. 11, 42–47.
Sadeghi, S., Abolghasemi, M., 2008. The effect of file size on the accuracy of the raypex 5 apex locator: an in vitro study. J. Endod. Res. Dent. Clin. Dent. Prospects. 2, 24–27.
Saxena, D., Saha, S.G., Bharadwaj, A., Vijaywargiya, N., Dubey, S., Kala, S., 2017. A comparative evaluation of accuracy of three electronic apex locators using histological section as gold standard: an in vivo study. J. Conserv. Dent. 20 (4), 251. https://doi.org/10.4103/0972-0707.120953.
Serna-Peña, G., Gomes-Azevedo, S., Flores-Treviño, J., Madla-Cruz, E., Rodríguez-Delgado, I., Martínez-González, G., 2020. In vivo evaluation of 3 electronic apex locators: root ZX mini, apex ID, and Propex Pixi. J. Endod. 46 (2), 158–161.
Sharma, M.C., Arora, V., 2010. Determination of working length of root canal. Med. J. Armed Forces India. 66 (3), 231–234.
Siddique, R., Niveditha, M.S., 2019. Effectiveness of rotary and reciprocating systems on microbial reduction: a systematic review. J. Conserv. Dent. 22 (2), 114. https://doi.org/10.4103/JCD.JCD_523_18.
Somma, F., Castagnola, R., Lajolo, C., Paternò Holtzman, L., Marigo, L., 2012. In vivo accuracy of three electronic root canal length measurement devices: Dentaport ZX, Raypex 5 and ProPex II. Int. Endod. J. 45, 552–556.
Stoll, R., Urban-Klein, B., Roggendorf, M.J., Jablonski-Momeni, A., Strauch, K., Frankenberger, R., 2010. Effectiveness of four electronic apex locators to determine distance from the apical foramen. Int. Endod. J. 43, 808–817.
Stöber, E.K., Duran-Sindreu, F., Mercadè, M., Vera, J., Bueno, R., Roig, M., 2011. An evaluation of root ZX and iPex apex locators: an in vivo study. J. Endod. 37, 608–610.
Sudhakar, R., Pratebha, B., 2015. Fibrous architecture of cemento-dentinal junction in disease: a scanning electron microscopic study. J. Oral Maxillofac. Pathol. 19 (3), 325. https://doi.org/10.4103/0973-029X.174623.
Swapna, D.V., Krishna, A., Patil, A.C., Rashmi, K., Pai, V.S., Ranjini, M.A., 2015. Comparison of third generation versus fourth generation electronic apex locators in detecting apical constriction: an in vivo study. J. Conserv. Dent. 18 (4), 288. https://doi.org/10.4103/0972-0707.159726.
Tselnik, M., Baumgartner, J., Marshall, J., 2005. An evaluation of root ZX and elements diagnostic apex locators. J. Endod. 31 (7), 507–509.
Tufenkci, P., Kalayci, A., 2020. Evaluation of the accuracy of different apex locators in determining the working length during root canal retreatment. J. Dent. Res. Dent. Clin. Dent. Prospects. 14 (2), 125–129.
Vanitha, S., Sherwood, I.A., 2019. Comparison of three different apex locators in determining the working length of mandibular first molar teeth with irreversible pulpitis compared with an intraoral periapical radiograph: a block randomized, controlled, clinical trial. J. Investig. Clin. Dent. 10 (3). https://doi.org/10.1111/jicd.v10.310.1111.jicd.12408.
Vasconcelos, B.C.d., Araújo, R.B.R., Silva, F.C.F.A.e., Luna-Cruz, S. M., Duarte, M.A.H., Fernandes, C.A.d.O., 2014. In vivo accuracy of two electronic foramen locators based on different operation systems. Braz. Dent. J. 25 (1), 12–16.
Wrbas, K.T., Ziegler, A.A., Altenburger, M.J., Schirrmeister, J.F., 2007. In vivo comparison of working length determination with two electronic apex locators. Int. Endod. J. 40 (2), 133–138.