# Application of Micro-computed Tomography to Compare the Accuracy of Two Clinical Methods in Length Determination

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**Abstract**

This study used a 3-dimensional micro-computed tomography (MCT) imaging to ascertain the accuracy of radiovisiography (RVG) and electronic apex locator (EAL) in working length (WL) determination of single-rooted teeth. Anatomic location of the apical constriction (AC) and apical constriction to apical foramen (AF) distance were also analysed. The WL of 40 extracted maxillary incisors were measured using 3 methods; MCT, RVG and EAL. AC diameter and the distance from the AC to the AF were also analysed with MCT.

Data were collected and analysed using descriptive analysis and Repeated ANOVA. P value was set at 0.05. The mean WL for MCT, RVG, and EAL were 13.443mm, 13.440mm, and 13.280mm respectively.

There was a statistically significant difference between EAL and MCT (P= .031). No significant difference was recorded between the RVG and the MCT (P> .05). The mean diameter of the AC is 0.38±0.11mm and the mean distance from the AC to the AF was 0.6±0.3mm. RVG was more precise in locating the 0.5mm mark from the AF compared to EAL.

The first bind file (FBF) suggested was at size #40. MCT is a reliable method to be used in determining the working length in a straight, single-rooted teeth.

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## Introduction

The presence of microorganisms in the root canal system is generally accepted as the main cause of root canal treatment failure.[1] A systematic review has shown that the success rates of treatments completed at least 1 year previously, ranged between 68% and 85%.[2] The success rate of conventional root canal treatment has been strongly related to the length of the final root filling.[3] Both overfilling and underfilling has been showed to decrease the overall success rate of endodontic treatment.[4] One crucial step in determining endodontic treatment is working length (WL) determination. WL determination is defined as the distance from a coronal reference point to the point at which canal preparation and obturation should terminate.[5]

The term apical constriction (AC) has been recommended as the ideal apical limit of working length [6] because it corresponds to the narrowest diameter of the root canal [7] and also demarcates the creation of an apical stop.[7]

Various techniques have been introduced in achieving ideal and close to accurate WL. It has been set based on the examination of tactile sensation, knowledge of root canal lengths and anatomy, pre-determined normal tooth length or conventional intraoral radiographs.[8] Nevertheless, it has many limitations, such as the anatomical variations in location, size, tooth type, age and sclerosed or the constriction has been destroyed by inflammatory resorption.

Ever since the market has enlarged and a variety of digital imaging systems are available from a range of dental X-ray machine manufacturers[9] and digital enhancement

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techniques.[10] A digital imaging dental radiographic system, Radiovisiography (RVG) has a 77% reduction in radiation dose as compared to conventional intraoral radiograph and also capable to amend the image produced in order to improve the recognition of details.[11] X-Mind AC/DC by Acteon is one of the leading brands of intraoral x-rays available and able to produce better protection due to a high focus-to-skin distance.

Micro-computed tomography (MCT) imaging is one of the greatest advances in endodontic research. A three-dimensional (3-D) image is produced based on multi-slice X-ray images that are digitally grouped. It is a non-destructive research tool which has the advantage of providing 3-dimensional reconstructions without the requirement of sectioning the samples. MCT can be used to evaluate volume and/or area using scanning pre- and post-endodontic treatment.[12] One of the high performances in vivo MCT scanner for preclinical research is the SKYSCAN 1176 by Bruker (Bruker microCT, Kontich, Belgium). Recently, MCT's importance in the study of hard tissues in endodontics has escalated significantly.[13,14] Not only the usage of MCT is non-destructive to the specimen but it also provides a 3-D reproducible. It produces numbers of serial cross sections in which it can be efficiently analyzed. The high resolution of MCT portrays the apical anatomy in detail and offers accurate measurements and location of the constriction and foramen without destruction of the tooth.[15]

RVG and EAL has been described as modern technology methods with a more reliable alternative.[16] RVG is an intraoral, direct digital and radiographic imaging system. It is a method of reproducing a radiographic image using a technology sensor of solid-state, which are broken into electronic pieces, and presented and stored as an image using a computer.[17] Several studies have been conducted to compare the best method to achieve the accurate WL measurement.[18] compared the accuracy of conventional and digital radiographies reported both techniques to have similar accuracies in the determination of WL. However, the use of digital radiography has advantages, such as the reduced patient exposure, eliminating the time-consuming processing stages, and producing fast images.[19]

EAL is considered as a more reliable instrument for detecting the apical constriction and determining working length with accuracy 80-100%.[20, 21] Even though the first two generations of EAL were sensitive to the content of the canal and irrigants used during endodontic treatment, but with the advanced technology, its latest generation has displayed the ability to produce an accurate reading in the presence of various intracanal contents and irrigants.[17] EAL also has several advantages over radiographic methods such as easier, faster, and can be indefinitely repeated without exposure to radiation.[22] However, it has also been reported to be influenced by some anatomic variations such as the foramen's area, diameter, shape, and position of the apical region.[23-25] Root ZX apex locator is considered to be the gold standard against other EALs in the market.[26] Dentaport ZX (J. Morita Corp, Tokyo, Japan) is the latest version of Root ZX measures the quotient between the impedances of 2 frequencies (0.4 and 8 kHz) and it works with the same principle as the original Root ZX does.[27] The Dentaport ZX claims to offer an accuracy 82.35% of the time to ± 0.5 mm and 97.05% of the time to ± 1 mm[28] and not adversely affected by the presence of 0.5% or 2.5% sodium hypochlorite (NaOCl) and ethylenediaminetetraacetic acid (EDTA).[17]

The use of EAL alone is not recommended practice due to the large variations in tooth morphology. A combination of digital radiography and EAL can be considered as safe, reliable and precise.[29] A study attempted to compare the accuracy in determining WL using cone beam computed tomographic (CBCT) with conventional radiographic. It was found that root canal length measurements of posterior maxillary teeth were more accurate when assessed with CBCT.[30]

Few studies have been conducted using MCT to determine the location and dimensions of the AC in maxillary and mandibular molars,[31] the accuracy between 2 electronic apex locators.[32] Apart from that, the MCT imaging is used to analyse the AC diameter as well as the distance between the apical constriction (AC) and the apical foramen (AF) in premolar teeth.[32] The previous study has shown that the mean size of AC in molars was instrument size 30.[31] However, no study has been conducted to determine the mean size AC for maxillary incisors teeth. Due to MCT's high accuracy, it has also been used as a baseline for various studies to compare different

methods and endodontic anatomical research.[33]

No study has been conducted to compare the accuracy of WL measurement between MCT, EAL, and RVG in single-rooted teeth. Therefore, this study aimed to evaluate micro-computed tomography (MCT) as a baseline method to compare the accuracy of two clinical methods: RVG and EAL in WL determination of straight, single-rooted teeth and also to analyse its anatomic location of apical constriction (AC).

## Materials and methods

This is a laboratory-based experimental study evaluating the accuracy of MCT, RVG, and EAL in working length determination of straight, single-rooted teeth. This in-vitro study was approved by the ethical committee of Universiti Teknologi MARA, Malaysia [Reference no.: 600-IRMI (5/1/16)].

Forty extracted straight, single-rooted permanent maxillary central incisors (n=40) were used in this study. The determination of sample size was based on the previous study, as advised by biostatistician, by setting type 1 error at 0.05 and type II error at 0.20 (80% power). All the teeth were immersed in 10% formalin and cleaned with an ultrasonic scaler, numbered and kept in 5.25% NaOCl for 2 hours and then stored in sterile 0.9% saline solution. The exclusion criteria included root caries, open apices, resorptive defects, sclerosed canals, pulp calcifications, metal restorations, prosthetic crowns, lateral foramen opening or previous endodontic treatment while the inclusion criteria were straight, single-rooted teeth, roots with no cracks and immature apices. All inspection of the suitable teeth was done by using x 3.0 Galilean dental surgical loupes (Univet Optical Technologies North America Inc., Markham, Canada) and using digital radiograph for preoperative assessment of the root canal morphology followed the method describe by Schneider.

The teeth were decoronated with diamond discs at a cementoenamel junction to establish a stable reference point. Access cavity was gained using diamond burs in air-rotor and long neck burs in micromotor. A #10 K-file (Dentsply Maillefer, Ballaigues, Switzerland) was used to check the patency of each sample. The canals were irrigated with 2.5% NaOCl. The working length of each sample was then measured using three different methods: Micro-computed tomography imaging (MCT), electronic apex locator (EAL) and radiovisiography (RVG).

Each sample was laid flat (horizontally) inside the styrofoam holder of the micro-computed tomographic machine (SkyScan 1176 by Bruker) and scanned at a resolution of 18.00 µm (voxel size) while maintaining the minimum transmission at a range of 25-35%.

Using a proprietary software (NRecon version 1.6.3.3, SkyScan N.V, Belgium), two-dimensional images of the cross-sections were reconstructed from the differential radiodensity of the raw (axial, rotational) images, producing approximately 700-900 images per sample. Three-dimensional (3-D) volume rendering of each specimen was reconstructed using CTVol (Version) and MeVIsLab (Version) (Figure 1).

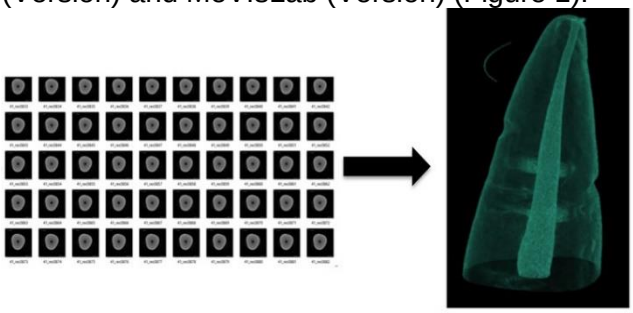


**Figure 1**. Three dimensional (3-D) volume reconstruction of a sample from two dimensional(2-D) cross sectional images.

The internal (root canal) configuration was visualized by changing the opacity and the color of the dentine and cementum in the software. Some of the images were re-orientated to show the exact inclination of the apical foramen (AF) and also to ensure the correct presentation of apical foramen before measuring its diameter. This is due to if the AF deviated from the long axis of the root. The 3-D reconstruction of the tooth helped determine the apical constriction of the canal, which is the point at which working length determination should stop.[32]

The actual working length was measured by determining the coronal reference slice to the most apical slice that showed the apical constriction at a 0.025mm precision. The result is then used as a baseline to compare the accuracy of electronic apex locator and radiovisiography in working length determination. One calibrated operator was involved in visualizing all scans. The internal anatomy of the apical third was analysed, and the following were evaluated

(Figure 2), a diameter of apical constriction (AC) and distance from major foramen to minor foramen.

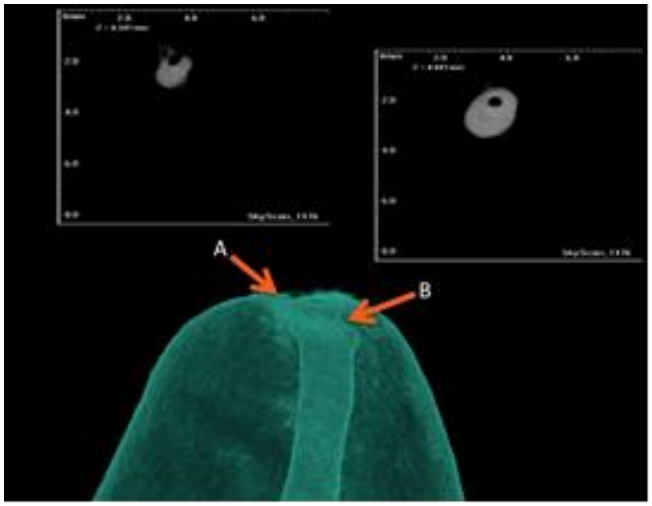



**Figure 2.** 3-D reconstruction of a sample showing the exact slice and measurement of the apical foramen (AF) and the apical constriction (AC).

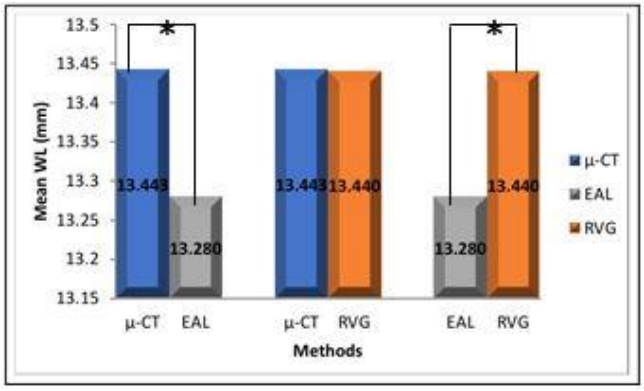
Dentaport ZX (J. Morita, Japan) the third generation of Root ZX apex locator was used in this study. All samples were mounted in an alginate mold that was kept moist in 0.9% normal saline, which acted as a conducting medium.[34] A #15 K-file with a rubber stopper was inserted gently into the canal attached with the file holder of the electronic apex locator.[35] The file is advanced inside the canal until the "APEX/0.0" mark displayed, then the file is withdrawn until the "0.5' mark showed according to the manufacturer's instruction and the beeping sound stayed constant for 3 seconds. The file was then taken out and measured with a digital caliper that was set to zero. Only one operator handled the electronic apex locator and a digital caliper. An intra-examiner reliability was conducted prior to the measurements with EAL monitored by one senior endodontist. Three readings were taken for each sample and the mean value was recorded.

The tooth was mounted on a compound that was placed on the digital sensor. The digital sensor was stabilized with a holder constructed from putty. A pre-operative radiograph of the sample was taken with the tube head being placed perpendicularly 8cm away from the sample.[7] The technique applied was the paralleling technique. The image was zoomed at 100% magnification and the average tooth length was measured using the measurement tool in the software (EasyDent V4 Viewer Version 4.1.4.5, VATECH, Korea).[35] The working length was then calculated by deducting 0.5mm from the estimated tooth length. A size #15 K-file was measured to the estimated working length with a digital caliper which was operated by a single operator. Without moving the sample's position, a size #15 K-file with a rubber stopper was inserted into the canal to the length obtained from the calculation. Another radiograph was taken with the same parameters. The distance from the end of the K-file to the apex was measured and the corrected working length was calculated accordingly.

Descriptive statistics including means, standard deviations, and frequency distribution were calculated for each group, compared and analysed using repeated analysis of variance (ANOVA). A statistically significant difference was determined at a 95% confidence level. The analyses were carried out with SPSS (IBM SPSS Statistics for Macintosh, Version 23.0, IBM Corp., Armonk, NY).

## Results

Table 1 shows the mean and standard deviation of working length for MCT, EAL, and RVG methods. Table 2 shows a significant difference with a repeated ANOVA test. Statistical analysis exhibited significant differences among all groups ($p < .05$). However, there was no statistically significant difference between the mean measurements of the RVG method and MCT method ($p$=1.000). A statistically significant difference was observed between the mean WL measurements acquired by the RVG and the EAL ($p$= .020), and the MCT to the EAL ($p$= .031) as a marked by the asterisk (*) (Graph 1). The percentage difference of the mean WL between MCT vs EAL, MCT vs RVG, and EAL vs RVG was 1.21%, 0.02%, and 1.19% respectively.




μ-CT: micro computed tomography; EAL: electronic apex locator; RVG: radiovisiography

**Graph 1.** Comparison mean working length with different measurement methods.

Table 3 displayed the mean and standard deviation of the diameter of AC for all samples using 3-D reconstruction. The mean diameter of AC was 0.4mm, ranging from 0.29mm to 0.51mm and the mean distance between AC and AF was 0.6mm, ranging from 0.3 to 0.9mm.

## Discussion

In this study, the latest technology in EAL, Dentaport ZX and digital radiography, RVG a and in comparison with the most advanced 3-D measurement technology, MCT were selected. Several methods have been used as a baseline to compare with the clinical methods used such as visual methods, histological examination, confocal microscopy, stereomicroscope, scanning electron microscope and micro-computed tomography.[33] To quantify the measurement error, three repeated readings of WL were taken for each method by one operator.

Although radiography is among the most familiar and often used method for determination of root canal length, its result may be misleading especially in cases with resorption and apical constriction[36] even though the doses derived from both examinations did not exceed the prescribed levels.[37] Furthermore, in the endodontic imaging, the highest repeat rate was from WL estimation (51.9%) followed by trial gutta-percha (48.5%), obturation (42.2%), and removal of gutta-percha (35.6%) as reported by.[38]

Studies over an extensive period of time have validated the reliability of EAL as this method is beneficial in overcoming shortcomings such as cooperation, invisible minor degrees of resorption and overlapping by adjacent anatomical structures that are experienced when using radiography.[39] Martins et. al (2014) reported electronic apex locators (EALs) are more precise and reliable in WL determination.[40]

| Measurement method | Working Length | | |
|---|---|---|---|
| | N | Mean | SD |
| MCT | 40 | 13.443 | 1.012 |
| EAL | 40 | 13.280 | 1.016 |
| RVG | 40 | 13.440 | 1.052 |

MCT: micro-computed tomography; EAL: electronic apex locator; RVG: radiovisiography

**Table 1.** Mean ± standard deviation (SD) (mm) for the working length using different measurement methods.

Therefore, in consideration of the foregoing, the study will discover whether the need to eliminate radiography at working length stage. There was a significant difference between the WL obtained by the EAL method and the RVG method ($p$= .020) with the RVG method being closer to the baseline ($p$= 1.000). There was a statistically significant difference between the EAL and the MCT methods ($p$= .031) (Table 2).

| Group | | Mean Difference (A-B) | Standard Deviation | p-value |
|---|---|---|---|---|
| Group A | Group B | | | |
| MCT | EAL | .162* | .060 | .031 |
| MCT | RVG | .002 | .071 | 1.000 |
| RVG | EAL | .160* | .056 | .020 |

*The mean difference is significant.

b. Adjustment for multiple comparisons: Bonferroni

**Table 2.** Repeated analysis of variance (ANOVA) tests for different measurement methods.

It can be concluded that RVG is a more superior method than EAL in determining the WL being 0.5mm from the AF. These findings were also in agreement with the study done by[35] reported that EAL remains to act as an adjunct to radiography even though it is able to get the WL without the need to irradiate the patient.[35] It has been reported that the precision of EAL in locating the apical foramen was 67.8%[3] or an even higher values, in the range of 85-96%.[8]

Therefore, it could be suggested that EAL cannot be used solely instead should only act as an adjunct to RVG. This is further supported by the percentage difference of the mean WL between MCT vs EAL, MCT vs RVG, and EAL vs RVG was 1.21%, 0.02%, and 1.19% respectively.

No significant difference was found between MCT and RVG methods (p=1.000) suggesting that RVG can be solely employed during WL determination in straight, single-rooted teeth. This result is comparable to the study done by[41] whereby they found MCT and RVG does not show a significant difference in WL measurement.

The MCT imaging was also used to obtain the mean diameter of the AC and the mean distance from the AC to the AF. The result of this study showed the mean diameter of AC in the maxillary upper central incisor was 0.40mm ranging from 0.29mm to 0.51mm (Table 3), which is within the similar range on mandibular canines in the study done by.[13] With this, a firm suggestion that the mean first bind file being size #40 can be made.

| | N | Mean | SD |
|---|---|---|---|
| Diameter | 40 | .380 | .114 |
| Distance | 40 | .588 | .287 |

N: number of sample, AC: apical constriction.

**Table 3.** Descriptive analysis of mean and standard deviation (SD) distance from major foramen to minor foramen and mean diameter of AC.

The mean distance from the AC to the AF obtained was 0.6mm ranging from 0.3mm to 0.9mm (Table 3), which is similar to other studies on mandibular canines.[13,42] Hence, the 0.5mm mark can be used with confidence to determine the working length with high precision. Nonetheless, some anatomic variations may influence the accuracy of EAL.[32]

The limitation experienced in this study includes the electronic digital caliper used. It is suggested to use an electronic digital caliper to obtain a precise measurement specifically for endodontic purposes. However, in order to ensure accuracy, the handling and reading of the electronic digital caliper for all methods were taken 3 times by the same operator and the mean value was obtained. The operation of MCT machine and its software (CTVol, CTAn, CTVox) need to be operated by a highly skilled technician or a researcher who has undergone a rigorous course in this field to ensure the accurateness of the result obtained. The usage of apex locator would also require good technical skills and be supervised by a lecturer to hinder any kind of inaccuracy throughout the process.

It could also be beneficial in future research could distinguish how similar or different working length measurements by using MCT method is in comparison with the clinical cone beam computed tomography (CBCT) in various canal configurations.

## Conclusions

MCT is a reliable method to be used in determining the working length in a root canal treatment of straight, single-rooted teeth, precisely in locating the 0.5mm mark from the AF. Clinically, RVG is a more superior method than EAL. This study also suggested the 0.5mm mark can be used with confidence to determine the working length with high precision. Based on the AC diameter analysis, the mean diameter of AC is 0.4mm, therefore, the minimum size recommended for first bind file in straight, single-rooted maxillary incisor teeth is size #40.

## Declaration of Interest

None declared.

## Ethical statement

The authors confirm that this study has been conducted with the ethical approval of all relevant bodies and approvals are acknowledged within the manuscript.

## Conflict of interest

The authors report no conflict of interest.

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## References


1. Lin LM, Skribner JE, Gaengler P. Factors associated with endodontic treatment failures. J Endod 1992;18(12):625-27.
2. Ng YL, Mann V, Rahbaran S, Lewsey J, Gulabivala K. Outcome of primary root canal treatment: systematic review of the literature–part 1. Effects of study characteristics on probability of success. Int Endod J 2007;40(12):921-39.
3. Martínez-Lozano M, Forner-Navarro L, Sánchez-Cortés J, Llena-Puy C. Methodological considerations in the determination of working length. Int Endod J 2001;34(5):371-76.
4. Seltzer S, Bender I, Turkenkopf S. Factors affecting successful repair after root canal therapy. JADA 1963;67(5):651-62.
5. Glickman GN. AAE Consensus Conference on Diagnostic Terminology: background and perspectives. J Endod 2009;35(12):1619-20.
6. Kuttler Y. Microscopic investigation of root apexes. JADA 1955;50(5):544-52.
7. Kishor K. Comparison of working length determination using apex locator, conventional radiography and radiovisiography: An in vitro study. J Contemp Dent Pract 2012;13(4):550-3.
8. Frank AL, Torabinejad M. An in vivo evaluation of Endex electronic apex locator. J Endod 1993;19(4):177-79.
9. Parks ET, Williamson GF. Digital radiography: an overview. J Contemp Dent Pract 2002;3(4):23-39.
10. Ahmad SA, Taib MN, Khalid N, Ahmad R, Taib H. A comparison of image enhancement techniques for dental x-ray image interpretation. Paper presented at: 2010 International Conference on Computer and Computational Intelligence (ICCCI), 2011.
11. Mandlik J, Shah N, Pawar K, et al. An in vivo evaluation of different methods of working length determination. J Contemp Dent Pract 2013;14(4):644.
12. Marciano M, Duarte M, Ordinola-Zapata R, et al. Applications of micro-computed tomography in endodontic research. Current microscopy contributions to advances in science and technology. Badajoz, Spain: Formatex research center 2012:p782-88.
13. Versiani M, Pécora J, Sousa-Neto M. Microcomputed tomography analysis of the root canal morphology of single-rooted mandibular canines. Int Endod J 2013;46(9):800-07.
14. Versiani MA, Pécora JD, de Sousa-Neto MD. Root and root canal morphology of four-rooted maxillary second molars: a micro–computed tomography study. J Endod 2012;38(7):977-82.
15. Kierklo A, Tabor Z, Petryniak R, Dohnalik M, Jaworska M. Application of microcomputed tomography for quantitative analysis of dental root canal obturations. Advances in Hygiene & Experimental Medicine/Postepy Higieny i Medycyny Doswiadczalnej 2014;68.
16. Neena I, Ananthraj A, Praveen P, Karthik V, Rani P. Comparison of digital radiography and apex locator with the conventional method in root length determination of primary teeth. J Indian Soc Pedod Prev Dent 2011;29(4):300.
17. Ebrahim A, Wadachi R, Suda H. An in vitro evaluation of the accuracy of Dentaport ZX apex locator in enlarged root canals. Aust Dent J 2007;52(3):193-97.
18. Esmaeili F, Akbari F. Comparison of accuracy of digital and conventional radiographies in determining endodontic working length. SADJ 2016;71(9):395-97.
19. Salemi F, Saati S, Falah-Kooshki S. A comparative study of the conventional and digital intraoral radiography methods for root canal length measurement. Braz Dent Sci 2014;17(4):34-39.
20. Fouad AF, Krell KV, McKendry DJ, Koorbusch GF, Olson RA. A clinical evaluation of five electronic root canal length measuring instruments. J Endod 1990;16(9):446-49.
21. McDonald N, Hovland EJ. An evaluation of the apex locator Endocater. J Endod1990;16(1):5-8.
22. Christensen GJ. What is a veneer?: Resolving the confusion. JADA 2004;135(11):1574-76.
23. Pagavino G, Pace R, Baccetti T. A SEM study of in vivo accuracy of the Root ZX electronic apex locator. J Endod 1998;24(6):438-41.
24. ElAyouti A, Kimionis I, Chu AL, Löst C. Determining the apical terminus of root-end resected teeth using three modern apex locators: a comparative ex vivo study. Int Endod J 2005;38(11):827-33.
25. Ding J, Gutmann JL, Fan B, Lu Y, Chen H. Investigation of apex locators and related morphological factors. J Endod 2010;36(8):1399-403.
26. de Vasconcelos BC, do Vale TM, de Menezes AST, et al. An ex vivo comparison of root canal length determination by three electronic apex locators at positions short of the apical foramen. Oral Surg Oral Med Oral Pathol Oral Radio Endod 2010;110(2):e57-e61.
27. Pascon E, Marrelli M, Congi O, et al. An in vivo comparison of working length determination of two frequency-based electronic apex locators. Int Endod J 2009;42(11):1026-31.
28. Moscoso S, Pineda K, Basilio J, et al. Evaluation of Dentaport ZX and Raypex 6 electronic apex locators: an in vivo study. Med Oral Patol Oral Cir Bucal 2014;19(2):e202.
29. Saeed MH, Luke A, Abtahi N, Pradeep A. An in vitro comparison of root canal measurement in permanent teeth by electronic apex locator, conventional and digital radiography. World Journal of Dentistry 2011;2(4):312-15.
30. Metska ME, Liem VML, Parsa A, et al. Cone-beam computed tomographic scans in comparison with periapical radiographs for root canal length measurement: an in situ study. J Endod 2014;40(8):1206-09.
31. ElAyouti A, Hülber-j M, Judenhofer MS, et al. Apical constriction: location and dimensions in molars—a micro–computed tomography study. J Endod 2014;40(8):1095-99.
32. Piasecki L, Carneiro E, da Silva Neto UX, et al. The use of micro–computed tomography to determine the accuracy of 2 electronic apex locators and anatomic variations affecting their precision. J Endod 2016;42(8):1263-67.
33. Peters OA, Laib A, Göhring TN, Barbakow F. Changes in root canal geometry after preparation assessed by high-resolution computed tomography. J Endod 2001;27(1):1-6.
34. Czerw RJ, Fulkerson MS, Donnelly JC. An in vitro test of a simplified model to demonstrate the operation of electronic root canal measuring devices. J Endod 1994;20(12):605-06.
35. Malik A, Kaul R, Kaul V. Comparison of conventional radiography, radiovisiography and root zx apex locator in working length determination-an in vitro study. Int J Sci Res 2015;2(12):12-17.
36. Bahrololoomi Z, Soleymani AA, Modaresi J, Imanian M, Lotfian M. Accuracy of an electronic apex locator for working length determination in primary anterior teeth. J Dent (Tehran, Iran) 2015;12(4):243.
37. Mohamed NC, Nawawi H, Yusof MYPM, Siong KK. Equivalent Dose Measurements from Digital Intra-and Extra-Oral Imaging Examinations. Pertanika J. Sci. 2017;25:251-62.
38. Yusof MYPM, Rahman NLA, Asri AAA, Othman NI, Wan Mokhtar I. Repeat analysis of intraoral digital imaging performed by undergraduate students using a complementary metal oxide semiconductor sensor: An institutional case study. Imaging Sci Dent 2017;47(4):233-39.
39. Subramaniam P, Konde S, Mandanna D. An in vitro comparison of root canal measurement in primary teeth. J Indian Soc Pedod Prev Dent 2005;23(3):124.
40. Martins JN, Marques D, Mata A, Caramês J. Clinical efficacy of electronic apex locators: systematic review. J Endod 2014;40(6):759-77.
41. Dutta K, Desai PD, Das UK, Sarkar S. Comparative evaluation of three methods to measure working length-Manual tactile sensation, digital radiograph, and multidetector computed tomography: An in vitro study. J Conserv Dent 2017;20(2):76.
42. Spangberg L. Instruments materials and devices. In: Cohen S, Burns RC, eds. Pathways of the Pulp, 8 th ed. St Louis MO, USA: Mosby Inc. (2002). 521-72.