1991

Accuracy of an Electronic Apex Locator: A Clinical Evaluation in Maxillary Molar Teeth

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ACCURACY OF AN ELECTRONIC APEX LOCATOR: A CLINICAL EVALUATION IN MAXILLARY MOLAR TEETH

BY

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A Thesis Submitted to the Faculty of the Graduate School
of Loyola University of Chicago in Partial Fulfillment
of the Requirements for the Degree
of Master of Science

May

1991

DEDICATION

I dedicate this thesis to the memory of my father, Howard Hembrough, whose life lives on in my mind and serves as a constant example of hard work and dedication. I thank you, Dad, for enabling me to learn and succeed.

ACKNOWLEDGEMENTS

I am indebted to many individuals for their assistance during my studies at Loyola. I would like especially to thank my advisor and mentor, Dr. Franklin Weine, who offered freely his constant guidance, knowledge, and expertise in developing my clinical and scientific skills.

I extend my sincere gratitude to Dr. Jerome Pisano for his insights and assistance which made the completion of this thesis possible. For his assistance in the statistical analysis of the data collected in this investigation, I wish to thank Dr. Donald Doemling.

I exress my appreciation to my friends and colleagues, Dr. Salam Sakkal and Dr. Norman Eskoz, for their assistance and moral support throughout this endeavor.

My special thanks to my family for their love and encouragement, and especially to my wife, Karen, for her endless efforts throughout my residency. She is a constant source of love, support, and inspiration.

VITA

The author, Dr. Jeffrey H. Hembrough, was born in Jacksonville, Illinois on the fourteenth of December, 1959, the eldest of four sons of Howard and Harriet Hembrough.

In August of 1978, he entered Illinois State University in Normal, Illinois where he was a Dean's List student majoring in Chemistry.

He commenced his dental education at Loyola University School of Dentistry in September of 1982, and was graduated cum laude in May of 1986, receiving the degree of Doctor of Dental Surgery.

In July of 1987, he completed a general practice residency with the United States Air Force from which he was honored as a distinguished graduate.

In August of 1989, he entered Loyola University School of Dentistry and began a dual course of study leading to the degree of Master of Science in Oral Biology and a Certificate of Specialty Training in Endodontics.

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INTRODUCTION

The accurate determination of root canal length is a key factor in the success of endodontic therapy. It is widely accepted that canal preparation and filling should be terminated at the cementodentinal junction, which has been defined as the most apical site of the dental pulp (1, 2). The cementodentinal junction generally marks the location of apical root canal constriction and therefore provides a natural area of resistance against which endodontic filling materials may be packed (3). Kuttler (4) found this apical constriction, which he called the minor diameter, to be 0.524 to 0.659 mm from the opening of the apical foramen, known as the major diameter, onto the root surface.

Clinical radiographic techniques are employed commonly to determine endodontic working length using the radiographic root apex as a reference point (5). It is recommended by some for endodontic treatment to be terminated 1.0 mm short of this reference. However, the apical foramen has been shown to deviate from the root apex in 50 to 80 percent of the cases, according to studies by Kuttler (4), Coolidge (6), and Hess (7). Pineda and

Kuttler (8) and Green (9) found these deviations existed 2 to 3 mm from the apical vertex in certain teeth. Such variation can be misinterpreted on two-dimensional dental radiographs. Palmer, Weine, and Healey (10) demonstrated that, in cases where the apical foramen is eccentric to the root apex, radiographic methods are often inaccurate and result in overextension of endodontic preparation and filling procedures.

In 1969, Inoue (11) shocked the endodontic community with his presentation at the annual meeting of the American Association of Endodontists in Atlanta by demonstrating that an electronic measuring device could locate the apical constriction. Electronic apex locators provide a physiologic interpretation of a three-dimensional root canal system based on the electrical resistance theory of Suzuki (12) and Sunada (13). They were designed to reduce the subjectivity involved in radiographic interpretation and to decrease the potential for a high number of radiographs often needed in endodontic treatment. The accuracy of electronic apex locators has been clinically evaluated in several studies, with conflicting results. In 1975, Seidberg et al. (14) determined digital-tactile sense confirmed by radiographs to be superior to the Sono-Explorer electronic apex locator in the estimation of root canal length. Similarly, in 1980, Becker et al. (15)

found radiographic determination to be more accurate than that of an electronic measuring device when compared to the direct anatomical lengths of 24 extracted teeth. Conversely, in 1976, Busch et al. (16) reported the Sono-Explorer to be within 0.5 mm of the radiographic apex in 93.3 percent of the 72 single-rooted teeth studied. Plant and Newmann (17), also in 1976, found the Sono-Explorer to be superior to radiographic length determination in an investigation which made direct anatomical measurements of root canal length following tooth extraction. At present, results are inconclusive as to the ability of electronic apex locators to determine accurately root canal length in a clinical environment.

In contrast to previous studies, this investigation will focus solely on maxillary first and second molar teeth. Because of the multiple anatomic structures which overlap radiographs of maxillary molars, such as the malar process of the maxilla and the floor of the maxillary sinus, these teeth are the most difficult to interpret during endodontic therapy. Film placement and patient cooperation while radiographing these teeth may be problematic as well. In combination, these factors can make radiographic determination of root canal length in maxillary molar teeth less than ideal. Therefore, the ultimate success of endodontic therapy may be jeopardized in such instances.

No other study has specifically involved the maxillary molars, though Bramante and Berbert (5) included 22 maxillary molars in an investigation comprised of 224 teeth. Based upon the contradictory conclusions of previous investigations and a lack of data concerning the maxillary molar teeth, this thesis will evaluate the clinical accuracy of an electronic apex locator, the Sono-Explorer Mark III, in the determination of root canal length in the distobuccal and palatal canals of maxillary first and second molars.

REVIEW OF THE LITERATURE

The Position for Terminating Canal Preparation

The objective of endodontic therapy is the restoration of the pulpless tooth to proper health and function (10). In order to achieve successfully this objective, the root canal contents must be removed and the canal prepared in a manner which facilitates the placement of an inert filling material to obliterate the canal. This allows the root apex to be sealed from the surrounding structures and completes the final step in endodontic treatment (3). All of these procedures are based upon an endodontic principle of considerable importance: the location of the ideal position for terminating canal preparation and filling.

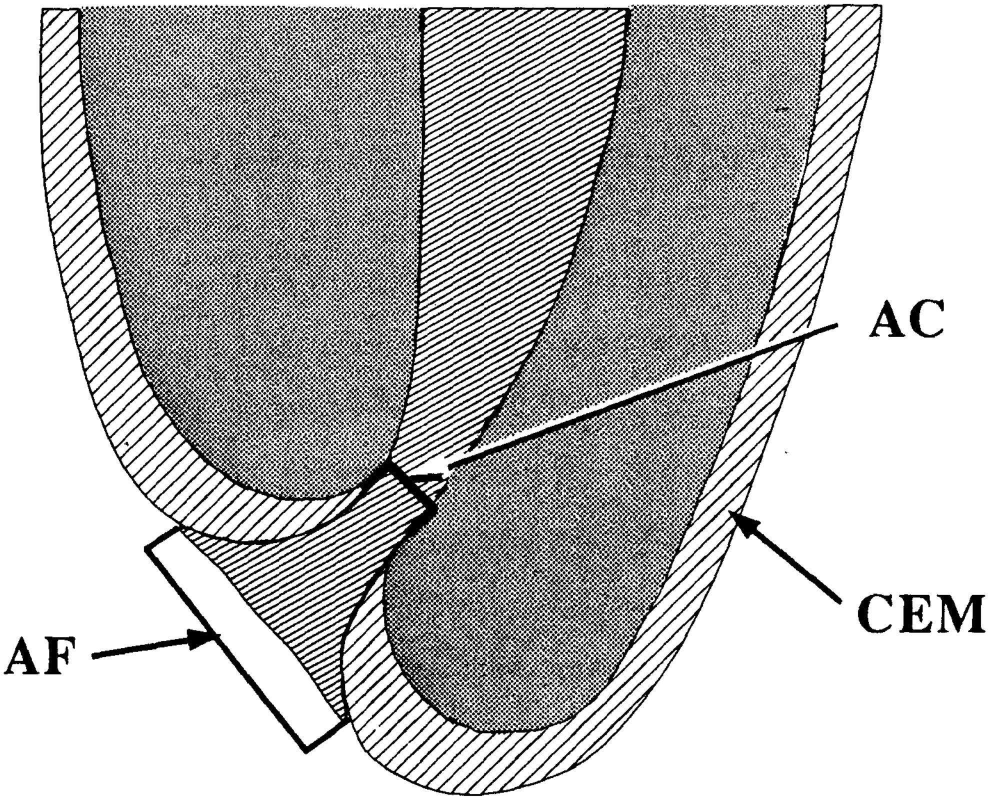
At the beginning of the twentieth century, techniques being employed in root canal therapy were considered faulty due to a misconception concerning the anatomy of the root apex (18). The concensus of opinion at the time was that the dental pulp extended through the apical foramen (19). In addition, for many years it was thought that the smallest diameter of the root canal was exactly at the site where the canal exits the tooth, at the extreme apex, which on an x-ray film would correspond to the radiographic apex. There were several reasons that fostered these views. At this point in the history of endodontic therapy, dental radiographs were not widely used in the determination of tooth length. In fact, Kells, in 1899, was the first to apply dental radiographs in a clinical setting (20). Additionally, there was a lack of understanding and appreciation for the need to establish a "critical point" at which root canal treatment should be terminated (21). Finally, studies on extracted teeth to define more clearly the anatomy of the root apex were just beginning.

In 1921, Grove (18) stated that it was impossible for pulp tissue to extend beyond the cementodentinal junction, because the unique cell to the pulp, the odontoblast, is not present beyond this point. Rather, cementoblasts are present, making the tissue in this region periodontal, not pulpal. Hatton (22) and Grove (23), after studying the root ends of teeth, concluded that instrumentation beyond the natural constriction of the cementodontinal junction would result in injury to the periapical tissues. Blayney (24), in 1924, stated that for some time it was believed to be best to instrument and fill root canals past the apical foramen; however, a review of his cases revealed that a canal filled to within

1 mm of the root end was preferable to an overfilled canal. Coolidge (6) agreed that the pulp should be amputated and the canal filled close to, but short of, the apical foramen. It appeared from these early reports that the ideal point for terminating canal preparation was short of the root apex and corresponded closely to the position of the cementodentinal junction (7).

Kuttler (4), in 1955, following a microscopic investigation of root apices, concluded that the narrowest diameter of the root canal occurs within the dentin, just prior to the initial layers of cementum. He referred to this position as the minor diameter, although others prefer to describe it as the apical constriction. The point at which the canal exits the tooth was found to have a diameter approximately twice that of the minor diameter and was hence termed the major diameter. The average distances between the major and minor diameters were 0.524 mm in teeth from the 18 to 25 year-old group and 0.659 mm in the 55 year-old and older age group. This evidence meant that those who viewed the canal as a tapering funnel to the tip of the root were incorrect. In fact, the canal funnel tapers to a distance short of the apex and then widens again (Fig. 1). Many authors have reported similar findings in relation to the complexities of the apical portion of the root canal (9, 25-28). The mean distance

Figure 1: Long-section diagram of root. Apical constriction (AC) lies within dentin just prior to the first layers of cementum (CEM), not at the tip of the root. The canal widens from the apical constriction as it approaches the site of exit on the root surface. This is referred to as the apical foramen (AF) or major diameter.


AC
CEM
AF

between the major and minor diameters did vary slightly in each of these investigations. However, the overall conclusion that an apical constriction exists in close association with the cementodentinal junction has been confirmed repeatedly.

The position at which the apical foramen (major diameter) opens onto the external root surface must be understood as well. Pineda and Kuttler (8) found that in 83 percent of the 4,183 teeth examined, the apical foramen was located to one side of the apical vertex, sometimes deviating 2 to 3 mm. Studies by Coolidge (6) and Hess (7) have confirmed that the root canal emerges slightly short of the root apex in 70 to 80 percent of cases. Green (9, 25), in stereomicroscopic studies of anterior and posterior root apices, showed that the major foramina routinely take eccentric positions which are located as far as 2 mm from the apex. In contrast, there is evidence which reveals that the minor diameter is found between 0.5 and 1.0 mm from the radiographic apex (26, 28).

An understanding of root canal apices had now been established through scientific research. The biologic aspects of endodontic therapy in relation to the termination of intracanal procedures now required investigation. Seltzer et al. (29) found that instrumentation beyond the apices of teeth with no previous evidence of apical pathosis produced more severe periapical reactions than instrumentation confined within the root canal. In the next study in their series of investigations, optimal healing was produced when canal preparation and obliteration were completed short of the apex (30). Davis, Joseph, and Bucher (31) examined healing following endodontic therapy in dogs. They found a high percentage of success in those teeth instrumented and filled 1 mm short of the radiographic apex. In contrast, the poorest results were demonstrated when endodontic preparation and filling procedures were terminated beyond the apex, leading to inflammation and degeneration of the periapical region. These investigations indicate that intracanal procedures completed short of the apex lead to a greater likelihood of endodontic success. With a few notable exceptions, most dental educators agree that canal preparation and filling should be terminated ideally at the cementodentinal junction, which has been defined as the most apical site of the dental pulp (1-3, 32).

Conventional Methods of Determining Tooth Length

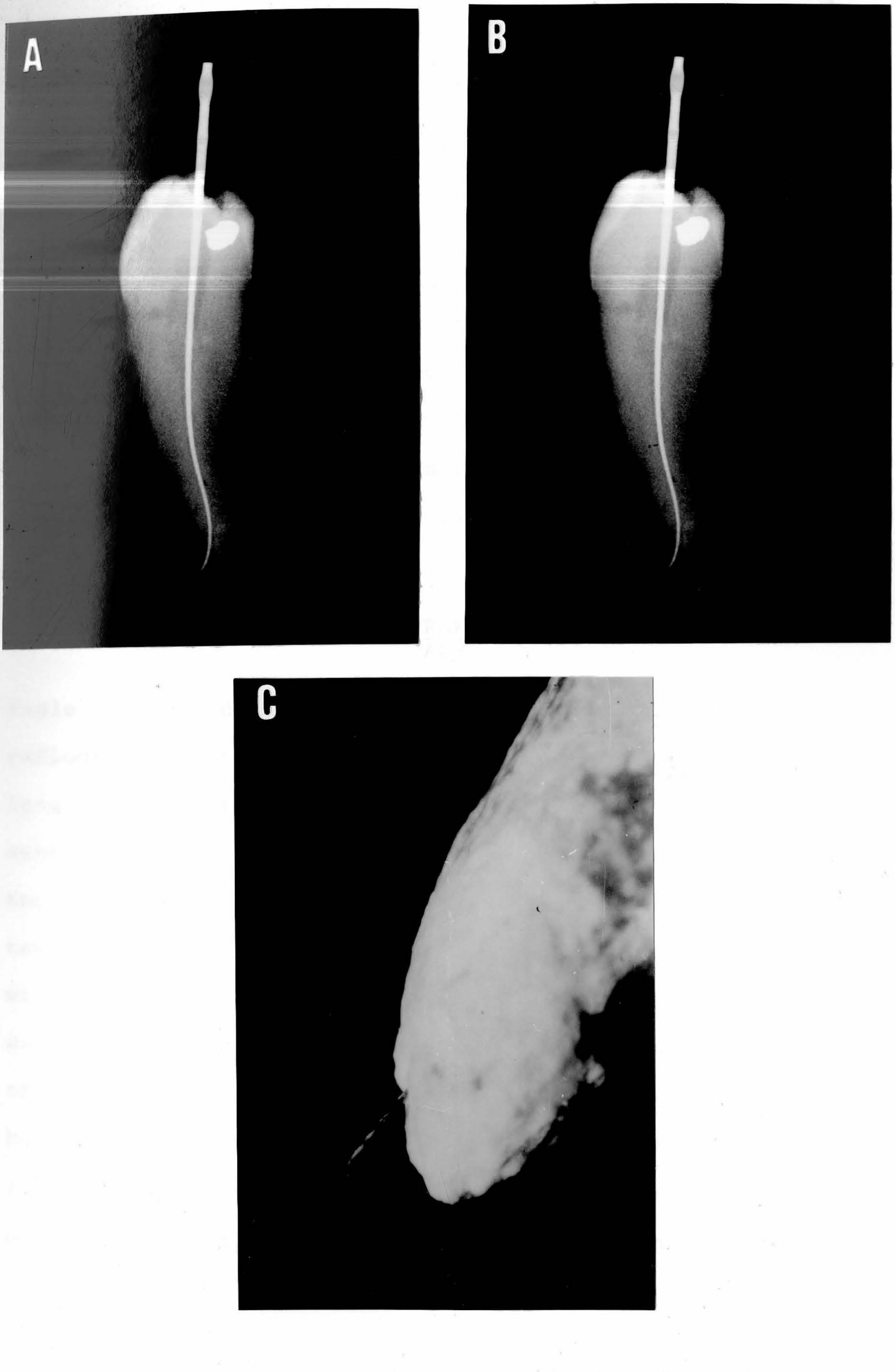
Several methods have been described for the determination of endodontic working length. Before the dental profession gained confidence in radiographic techniques, it was common to use patient response and digital-tactile sense to establish tooth length during endodontic treatment (33). In the first method, a diagnostic wire was inserted into the canal until the patient winced. This indicated the wire had either passed beyond the apical foramen or had encountered vital tissue remaining within the canal. In each of these situations, the patient was subjected to an unnecessarily painful experience. Additional disadvantages included periapical tissue damage through overinstrumentation and inaccurate length determination, especially when vital tissue remnants elicited a patient response. The technique involving the use of digital-tactile sense required the operator's thumb and index finger to act as the "eyes of the hand" in feeling for the apical constriction as the instrument neared the root apex (34). This technique relied too heavily upon the training, experience, and expertise of the dentist and therefore, rarely was the correct position identified within the canal. In combination with preoperative radiographs to estimate tooth length and intraoperative films to verify instrument position, both patient response and digital-tactile sense can be effective adjuncts in the determination of endodontic working length. However, when used alone, they are highly unreliable and of little value in modern endodontic therapy.

The first revolution in endodontics was centered around the discovery of dental radiographs. Rhein, in 1908, used a diagnostic wire in conjunction with x-rays to determine whether the apex had been reached (20). In 1920, McCormack (35) stated the need for a standardized paralleling radiographic technique based upon the principles used in medical radiography. Others, including LeMaster (36), Fitzgerald (37), and Updegrave (38-40), have suggested a variety of devices to minimize film-image distortion, including cotton roll backings, bite blocks, hemostats, and plastic film holders. Distortion is present in all radiographs, since the object being radiographed is three-dimensional and the radiographic image is depicted in only two dimensions (41). Size distortion results from different degrees of magnification due to the varying distances between the parts of the object and the film and anatomical structures restricting proper film alignment. Shape distortion is a product of improper placement of the film and tube in relation to the object being radiographed. It is recommended that a long source-film distance and a short object-film distance be employed to minimize distortion (42). In fact, a comparison of investigations (43-45) comfirms that an increase in the source-film distance (long cone vs. short cone) reduces image enlargement by 10 percent. Vande Voorde and Bjorndahl (42) concluded that paralleling radiographs are consistent enough to serve as reliable guides in predetermining and verifying tooth length, in accordance with the recommendations for diagnostic radiographs by Michanowicz (46) and Ingle (47).

A discussion of the radiographic determination of tooth length requires an understanding of the relationship between the anatomy of the root apex and the image it portrays on a dental radiograph. Langeland (48), describing the anatomical and histological location of the apical foramen, stated that the actual foramen is not necessarily distinguishable on a radiograph. Heuer (49), while commenting on the eventual end point of canal filling, pointed out that the apical constriction is usually 1-2 mm short of the radiographic apex. Similar to the findings reported by Grove, Green, and Kuttler, Levy and Glatt (50) demonstrated that the apical foramen deviates from the root tip in at least two thirds of all teeth. Furthermore, they stated that the deviation occurs toward the buccal or lingual aspect twice as often as it does toward the mesial or distal aspect of the root. This buccal or lingual exit would be indiscernible, since the routine radiograph shows only proximal deviation. This fact was demonstrated in a study by Palmer, Weine, and Healey (10) in which extracted teeth were selected at random, radiographed with an endodontic file in place to the radiographic apex, and then photographed. Of the forty teeth surveyed, half showed that the file extended over 1 mm beyond the apical foramen. These findings indicate that taking angled radiographs in addition to the normal file measurement view will give further important information. Relying strictly on the routine straight-on radiograph may cause a considerable error in determining the position of the apical foramen (Fig. 2).

Bramante and Berbert (5) discussed the following commonly employed radiographic methods for the determination of endodontic working length. Best (51) described the use of a 10 mm pin fixed with soft wax parallel to the long axis of the involved tooth. A radiograph is exposed and the film placed behind a B-W measurement scale. The B-W scale, in theory, allows for elongation and foreshortening of the portrayed image. Therefore, when the film is aligned in the appropriate position, based

Figure 2: Radiographic misinterpretation of endodontic working length. **A**, file in mandibular first premolar to the radiographic apex (straight-on view). **B**, proximal radiograph with the file in the identical position as shown in **A** revealing its extension into the periapex due to the early exit of the canal short of the root tip. **C**, photograph of the file protruding beyond the apical foramen.


A
B
C

upon the known length of the pin, the actual tooth length can be measured. Bregman (33) developed a second radiographic method based upon the mathematical relationship between real and apparent (radiographic) lengths. A stainless steel strip is threaded onto a 25 mm file at the 10 mm level, the file placed into the canal this distance, a radiograph exposed, and the actual tooth length determined by the application of a mathematical formula. The real tooth length (RLT) is equal to the real file length (RLW) divided by the apparent file length (ALW) times the apparent tooth length (ALT).

$$RLT = ALT \times \frac{RLW}{ALW}$$

Ingle (32, 47) describes the use of a preoperative radiograph in the determination of canal length. Tooth length is measured from the preoperative film, 2 mm subtracted to compensate for distortion and to avoid forcing the instrument through the apical foramen, and a radiograph taken with a file placed at this estimated length which will reveal the distance between the tip of the instrument and the canal terminus. The sum of this distance and that of the premeasured file gives the total canal length. However, 0.5 mm should be subtracted to give the working length at the ideal point for termination of endodontic procedures. Weine (3), describing a variation of Ingle's method, states that the apical foramen is usually found 0.5 to 1.0 mm from the radiographic apex and that therefore canal preparation must end no closer that 1 mm from this point. Furthermore, if the preoperative radiographs reveal that the canal exits definitely short of the radiographic apex, the distance involved must be added to the normal allowance of 1 mm. Radiographs with the file at the estimated length are taken from two directions, one straight-on and one from either a mesial or distal angulation depending on the tooth and the anticipated apical anatomy. The radiographs are processed and examined. If they show the file to be within 1 mm of the desired position, either short or long, the minor correction in length is made and the measurement recorded as the working length. If the films reveal the file to be more than 1 mm shorter or longer than desired, an interpolation is made and a new set of views taken to verify that the proper working length has been obtained.

The Advent of Electronic Apex Locators

Suzuki (12), in 1942, completed his experimental study on the ionophoresis of ammoniated silver nitrate in the teeth of dogs. He determined that the silver solution penetrated all parts of the root canal walls to almost equal depths, as viewed in cross-section. This occurred regardless of the position of the negative electrode which maintained contact with the oral mucous membranes. This fact indicated that the electrical resistances between the negative electrode (oral mucous membranes) and the periodontium were equal. It can then be concluded that the electrical resistance between the oral mucous membrane and the periodontal membrane would register a consistent reading when an endodontic instrument reached the periodontal membrane. Therefore, it would be possible to measure the length of a root canal by electrical resistance; though, Suzuki did not expand upon this particular endodontic application. In fact, 20 years passed before the potential to determine tooth length electronically was recognized and applied clinically. In 1962, Sunada (13), using a simple direct current ohmmeter, studied the electrical resistance between the periodontium and the oral mucous membranes in 124 human teeth. He found that when the tip of a reamer reached the apex, as confirmed by radiograph, the resistance value was consistently near 6.5 ohms. This value remained the same even when accidental perforation allowed the reamer to reach the periodontium. Furthermore, the resistance was found to be equal in every portion of the periodontium, regardless of the patient's age or the shape and type of canal. However, when the reamer remained within the root canal, the electrical resistance varied greatly. Suzuki (12) and Sunada's (13) investigations outlined the application of the principle of electrical resistance to the measurement of root canal length. They emphasized that (a) both the oral mucous membrane and the periodontium exhibit a consistent degree of conductivity, and (b) when the tip of the measurement reamer contacts the tissue of the apical foramen, the electrical resistance between the oral mucous membrane and the reamer is always consistent with the previously attained value. Inoue (11, 52, 53) attempted to put this relationship between the oral mucous membrane and the tooth into electrical terms, through the use of low-frequency oscillation. Two factors, resistance and capacity, may influence the audible output when using low-frequency oscillation. Since the resistance of the periodontium and mucous membrane were virtually identical in previous experiments (12, 13), the change in audible output between various persons can then be attributed to individual body capacity. To overcome this variance between individuals or between different teeth in the same individual, modifications were incorporated into the design of his apparatus (the Sono-Explorer). This allowed a gingival crevice sound to be established by placing the tip of the measurement reamer 0.5 mm into the gingival sulcus while adjusting the marker sound dial, thereby eliminating any error due to a change in capacity. Inoue (52) concluded that when the marker sound was adjusted for differences in individual capacity, the point at which the measurement reamer reached the radiographic apex and the experimental determination of length were identical in 91 percent of the 201 canals studied. In a similar study (53), he found that in 92.9 percent of the 84 teeth extracted, after the gingival crevice/marker sound concurred with the measurement reamer sound, the reamer tip had just reached the apical foramen. Inoue had apparently improved upon the electrical resistance theory of Suzuki and Sunada by accounting for differences in individual body capacity. Additionally, he used a transistor equalizer-amplifier to produce an audible output which allowed the eyes of the operator to remain on the tooth being treated.

Some authors have shared views in opposition to the electrical resistance theory in regard to the principle of electronic root canal measurement devices, though none come to a conclusion (54, 55). Previous studies (45-49) have suggested that the electrical resistance between the mucous membrane and periodontium can be considered a constant relationship. Huang (56) felt this constant value of resistance had a biologic basis and referred to it as the theory of biologic characteristics. He suggested that the principle of electronic root canal measurement could be explained by the principles of electrical physics, rather than the biologic characteristics of the tissue. His claim proposed electrical continuity was resultant of a constant surface contact between the electrode and the oral tissue. This theory, however, is not strongly supported by experimental evidence and lacks widespread acceptance.

Dahlin (57), in a 1979 article, grouped contemporary electronic apex locators into two categories: (a) analog-indicating devices, and (b) audio-indicating devices. The analog-indicating units contain an a.c. generator with a variable output, a built-in reference resistance equivalent to the resistance between the oral electrode and the apical foramen, and a meter-type indicator. When the meter indicator reading is equal to the built-in resistance value, the root canal instrument should be in contact with the periodontal tissues at the apical foramen.

The audio-indicating devices use a feed-back audio-frequency generator whose frequency is controlled by means of the patient's resistance/capacity ratio. The meter in these audio units is set by establishing the gingival crevice or marker sound which, in turn, calibrates the device. An audio signal as well as the meter indicator signify the length at which the root canal instrument reaches the apical foramen.

The electronic apex locators currently available employ these same principles in order to establish endodontic working length. In certain devices, digital readings indicate the distance between the tip of the endodontic instrument and the apical foramen. In addition, meter indicators, auditory alarms, and visual signals have been incorporated into these units, in various combinations, in an attempt to increase simplicity and accuracy.

The Accuracy Controversy

Cash (58-60) has proclaimed electronic apex locators to be capable of determining the exact location of the apical foramen, regardless of where the canal exits. Furthermore, he claimed that information concerning the presence and location of accessory canals and the hermetic seal of the apex could be attained with these electronic devices. Their ability to reduce the number of necessary radiographs and the total endodontic treatment time were touted as well. In fact, he became so enamored with electronic apex locators that he formed the Society of Electronic Endodontology in 1973. However, not all of the literature concerning this topic has been as favorable. The accuracy of electronic root canal measuring devices has been clinically evaluated in several studies, with conflicting results. There has been an almost equal division between investigations which support their accuracy and those which refute such findings.

Bramante and Berbert (5) compared the radiographic methods of Best (51), Ingle (47), and Bregman (33) to Sunada's (13) electronic method for determining tooth length. Each of the 224 teeth were measured clinically by the various methods and then extracted to determine the actual tooth length. A statistical analysis of the data indicated that the Ingle method was the least variable and enjoyed the highest percentage of accuracy, whereas, the electronic method was highly variable. Sunada's method did, however, give more accurate measurements in the palatal roots of the 22 maxillary molars tested than did any of the radiographic techniques. In 1975, Seidberg et al. (14) performed a clinical investigation involving single-rooted teeth. The Sono-Explorer electronic apex locator was used to determine the working length in 50 teeth and another 50 teeth were measured by digital-tactile sense as a comparative control. Wire-grid radiology was employed to verify each method. The results indicated that electronic measurement was accurate in only 48 percent of the cases, while digital-tactile sense was slightly better at 64 percent. The authors concluded that this electronic method should not replace radiographs in endodontic therapy as a measuring technique. Becker et al. (15) measured root canal length in an experimental model composed of the severed halves of pig mandibles. The purpose was to determine the accuracy of an electronic device and that of the radiographic method by comparing both with the direct length measured following tooth extraction. The apex locator was used in two groups which differed in thoroughness of pulp extirpation. In the first group, instrumentation was conservative, while the second group aimed at complete removal of all pulp tissue. The electronic length determinations were less accurate in the first group than in the second. In both groups, however, the results were less accurate than the radiographic length determinations. In 1981, Chunn, Zardiackas, and Menke (61) attempted to determine if an electronic apex locator could be used to detect the position of the apical constrition within the root canal by measuring the canal 0.5 to 1.0 mm short of the apical foramen. Files were sealed in place with composite at the length indicated by the electronic device in 20 canals. The teeth were radiographed, extracted, and their apices ground and measured microscopically to evaluate the distance between the file tip and the apical constriction. The results revealed the apex locator to be inaccurate in more than 65 percent of the measurements, and radiographic evaluation to be inaccurate in more than 40 percent of the canals. It can be concluded from this investigation that radiographs are superior to electronic devices in the determination of root canal length. Tidmarsh, Sherson, and Stalker (62) compared radiographic and electronic methods of establishing endodontic working length in a total of 32 canals. Radiographic estimates were followed by electronic determination of working length in teeth undergoing endodontic therapy. The two electronic devices established lengths which ranged from 4.5 mm short to 2.0 mm long and from 2.5 mm short to 4.0 mm long, respectively. The authors suggested that radiographic methods were more accurate than electronic methods. More favorable results were obtained from a second in vitro study of extracted teeth in an agar solution which simulated physiologic resistance. The authors concluded that electronic instruments might have a place in endodontic therapy under certain conditions, despite their inherent variability. Nahmias, Aurelio, and Gerstein (63) examined three apex locators to evaluate their accuracy in an in vitro model which consisted of extracted teeth embedded in polystyrene tubes containing agar and phosphate-buffered saline. As a group, the devices were able to locate a position at a mean distance of 0.233 mm from the major diameter. Similarly, Fouad and Krell (64), in an in vitro study of five electronic root canal measuring devices, found the mean measurements of all the instruments to be within clinically acceptable limits of the apical foramen (0 to 0.25 mm short). In a follow-up clinical investigation, however, Fouad et al. (65) reported the accuracy of the same five electronic apex locators in determining canal length within ±0.5 mm from the apical foramen varied from 55 to 75 percent in 20 single-rooted teeth, as verified by direct measurement following extraction. They concluded that radiographic verification of working length is still desirable, though these devices might have a place in estimating initial canal length.

O'Neill (66) investigated 32 teeth condemned to extraction in order to evaluate the clinical accuracy of an electronic apex locator in determining endodontic working length. Root canal length was indicated by the electronic device, the teeth were extracted, and direct measurements were made on a standard endodontic gauge to the nearest 0.5 mm. The results showed that in 83 percent of the canals, the measurements were identical (to the apical foramen) and in the remaining 17 percent, measurements were short of the foramen by 0.5 mm. A high degree of accuracy is suggested by these results. In 1975, Blank, Tenca, and Pelleu (67) clinically evaluated two types of commercial devices which electronically locate the apical foramen. A total of 65 teeth were measured with the Endometer and the Sono-Explorer. The two devices measured root canal length which was then verified by direct measurement following extraction. Both electronic devices performed within acceptable limits in 85 percent (Endometer) and 89 percent (Sono-Explorer) of the canals tested. The authors concluded that electronic root canal measuring instruments have a definite place in the armamentarium of dentists engaged in endodontic therapy. Busch et al. (16) studied 72 single-rooted teeth to determine if the Sono-Explorer had sufficient accuracy to replace the current technique of using radiographs to establish working length in endodontic treatment. Canal length was determined by the electronic instrument and a radiograph exposed with the file in this position. Measurements were considered acceptable if the reamer or file was within ±0.5 mm of the radiographic apex. In 93.3 percent of the cases, the apex locator was shown to be accurate and its use as an aid in establishing working length was suggested by the authors, especially in situations where radiographs are difficult to obtain or interpret. In an investigation of 32 root canals in teeth scheduled for extraction, Plant and Newman (17), studied the accuracy of the Sono-Explorer. Following electronic determination of working length, the teeth were extracted and measured directly. The results revealed that in 30 of 32 canals the two lengths coincided at the apical foramen, while the remaining measurements were 0.3 and 0.5 mm short of the anatomic length. Furthermore, radiographic estimates of length from preoperative films were not as accurate as the experimental instrument. Under the conditions of this study, the electronic device was accurate in determining root canal length. Berman and Fleischman (68) used 29 canals in maxillary and mandibular premolars scheduled for orthodontic extraction to evaluate the accuracy of an electronic apex locator by comparing direct measurements after the teeth were extracted to radiographic measurements obtained prior to extraction. The results of this study indicated that the electronic device consistently located the canal terminus well within the limits acceptable in clinical practice. The means of the electronic estimates were approximately 0.5 mm short of the opening for the major diameter. In a comparable study, McDonald and Hovland (69) found an electronic root canal measuring device capable of locating the apical constriction within ±0.5 mm in 93.4 percent of the canals evaluated following extraction and sectioning buccolingually. Inoue and Skinner (70) and Trope, Rabie, and Tronstad (71), in similar investigations, studied the accuracy of the Sono-Explorer Mark III. A file was placed to the length indicated by the electronic device, a parallel radiograph exposed, and the distance between the tip of the file and the periodontal tissue measured upon examination of the film. Inoue showed 57 percent of his cases to be within 0.5 mm of the radiographic apex and an additional 27 percent to be 0.6 to 1.0 mm short of the apex. In 90.6 percent of the canals measured by Trope, the file was within 0.5 mm of the radiographic outline of the tooth. Despite these superior results, Trope and his co-authors concluded that apex locators cannot replace radiographs in endodontic therapy, but have a definite place in special situations when radiographs are not informative nor feasible.

The findings of several representative investigations are summarized in Table 1. It is difficult, after a review of the literature, to come to a definite conclusion with respect to electronic apex locators. In many instances, the interpretation of the results by the authors, and prejudice for or against these instruments, can skew the reader's evaluation of the data. At present, results are inconclusive as to the ability of electronic devices to determine accurately root canal length in a clinical environment. This dilemma is illustrated in an article by Kurahara (72), in which no significant difference between electronic and preoperative radiographic estimates of length were detected.

TABLE 1

SUMMARY OF ELECTRONIC APEX LOCATOR INVESTIGATIONS

Author(s), year	Sample	Methodology	Results
Inoue (1972)	101 canals	Electronic length verified by radiograph	92% accuracy locating radiographic apex
Bramante, Berbert (1974)	224 teeth-ant & post	Compared elec & rad to direct anatomic length	Radiographic superior, except in palatal
O'Neill (1974)	32 teeth	Electronic length verified by direct anatomic length	83% at apical foramen; 17% 0.5mm short
Seidberg et al. (1975)	100 teeth-1 rooted	Digital-tactile vs. elec; verified by radiograph	Digital-tactile 64%; Electronic 48%
Busch et al. (1976)	72 teeth-1 rooted	Electronic length verified by radiograph	93.3% within ±0.5mm of radiographic apex
Plant, Newman (1976)	32 canals	Electronic length verified by direct anatomic length	30 of 32 canals at apical foramen
Becker et al. (1980)	41 canals-pig molars	Compared elec & rad to direct anatomic length	Radiographic superior
Trope, Rabie & Tronstad (1985)	127 canals-ant & post	Electronic length verified by radiograph	90.6% within ±0.5mm of tooth outline
Fouad et al. (1990)	20 teeth-1 rooted	Electronic length verified by direct anatomic length	55-75% within ±0.5mm of apical foramen

Purpose

The purpose of this thesis was to evaluate the clinical accuracy of an electronic apex locator, the Sono-Explorer Mark III, in the determination of root canal length in the distobuccal and palatal canals of maxillary first and second molars.

MATERIALS AND METHODS

This investigation was conducted in the dental clinic of the Hines Veterans Administration Hospital with the cooperation of the Department of Oral and Maxillofacial Surgery. The patient sample consisted of 14 adult males from 47 to 75 years of age. The purpose of the study was presented to the participants with an explanation of their role in contributing to the advancement of clinical endodontic therapy. Following a thorough discussion of the clinical procedure and possible risks, the informed consent of all the subjects was obtained. A total of 26 teeth were selected, each of which had been condemned to extraction due to hopeless periodontal or restorative conditions. All teeth were maxillary first or second molars with mature apices and no radiographic evidence of periapical pathosis.

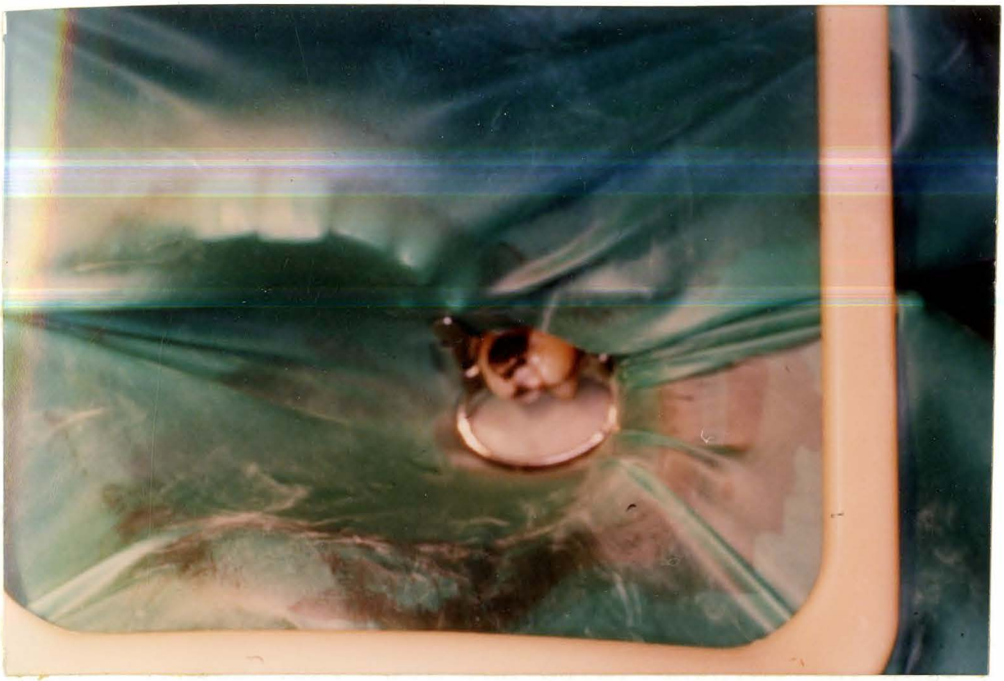
A preoperative periapical radiograph was taken using the long-cone paralleling technique with approximately a 10 degree mesial to distal angulation to separate the distobuccal and palatal roots. The patient was anesthetized via buccal and palatal infiltration with a self-aspirating syringe and a 27-gauge short needle

(73,74). Either 2% lidocaine with 1:100,000 epinephrine or 3% carbocaine without a vasoconstrictor was the employed anesthetic agent; the selection was based upon the medical history of the patient (75,76). The tooth was isolated with a rubber dam and surface disinfected with merthiolate. The occlusal table was reduced approximately 2mm, in order to establish a flat, definitive reference surface. Standard endodontic access (3) was gained through the occlusal surface and the pulp chamber was exposed with a high-speed handpiece and #557 bur. The pulpal tissue was removed from the chamber and extirpated from the distobuccal and palatal canals using barbed broaches and endodontic files in combination with sterile saline irrigation. In each of the two canals to be studied, files were placed to the root lengths estimated from the preoperative radiograph and a second film was exposed to verify instrument position (Figs. 3 and 4). Vertical notches were placed on the buccal and lingual surfaces of the tooth adjacent to the position of each file, marking the reference points on which the rubber stops were resting. This constituted an effort to locate radiographically the position of the apical foramen, by placing the tip of the file at the estimated site of exit of the canal onto the root surface. The concensus of two endodontic residents determined the positional accuracy of the files upon examination of the radiograph. If the files were shown to be within 1mm of the desired position, either short or long, the minor interpolation in estimated length was made and the measurement recorded as the radiographic tooth length. If the film showed the files to be more than 1mm shorter or longer than desired, the correction was made and a third radiograph taken to verify that the proper root canal length had been obtained. The lengths were measured from the tip of the file to the designated reference point on the tooth as indicated by the position of the rubber stop. Measurements were made to the nearest 0.5mm on a standard endodontic ruler. Following the radiographic determination of root canal length, the canals were irrigated with sterile saline, checked for the presence of pulp tissue remnants, and dried with paper points. Root length was next evaluated electronically. Only one apex locator, the Sono-Explorer Mark III, was utilized in this investigation. It has been shown to be as accurate as four other electronic devices in two separate investigations by Fouad and Krell (64,65). The Sono-Explorer Mark III was employed to determine root canal length to the apical foramen according to the instructions of the manufacturer. The device was turned on, the lip clip attached to the patient's lip, and a #15 K-Flex file placed in the reamer/file holder. In order to set the reference tuner, the tip of the file was inserted

0.5mm into the gingival sulcus of the involved tooth and the control knob adjusted until the reference needle was centered between the two "L" marks on the meter scale and the unit produced audible alarm beeps (Figs. 5 and 6). Because the presence of any conductor could influence adversely the accuracy of the electronic measurements, all metal restorations, such as gold crowns and amalgam fillings, were eliminated to the extent that they would not be contacted by endodontic files during electronic measurement. Additionally, other conducting media such as vital tissue, necrotic debris, hemorrhage, and inflammatory exudate were removed by instrumentation, saline irrigation, and the use of paper points to dry the canals. Once the reference tuner was set for the patient's individual capacity, a size #15, 20, or 25 K-Flex file was attached to the file holder depending upon canal diameter. The file was slowly inserted into the canal until the reference needle moved from the extreme left to the center of the meter scale and the alarm beeps were heard. This indicated the apical foramen had been reached. The file was removed and measured to the nearest 0.5mm on an endodontic ruler. Careful attention was given to placing the rubber stop at the exact reference point which had been previously established. The files were replaced to the electronically-indicated lengths and a radiograph exposed to confirm their positions (Figs. 7 and 8). Following the electronic measurement of root canal length, the profoundity of anesthesia was confirmed and supplemented if necessary. The tooth was extracted by one of two staff oral surgeons using standard oral surgical techniques (77-80). Removal of buccal bone was necessary in several instances to allow the tooth to be delivered intact. Those teeth which were fractured during the extraction procedure were excluded from the study. The patient was dismissed with postoperative instructions and scheduled for an evaluation appointment in one week. The extracted tooth was placed in 5.25 percent sodium hypochlorite to remove any periodontal tissue remnants from the apical portion of the roots. Direct anatomical measurement of root canal length was achieved by placing a #15 K-Flex file through the coronal access and advancing it until the tip was barely visible at the apical foramen as viewed through a disecting microscope positioned perpendicular to the site of exit. Measurement was made from the rubber stop (reference point) to the tip of the file on a standard endodontic ruler to the nearest 0.5mm. The direct root canal length was recorded and comparisons made between the electronic and radiographic methods. It is important to realize that in each of the three methods length determination was terminated at the apical foramen (major diameter).

Figure 3: Rubber dam isolation of the involved tooth. Tooth #14 isolated with a rubber dam prior to endodontic access.

Figure 4: Radiographic estimation of endodontic working length. Files in place to the root lengths estimated from the preoperative radiograph. A second radiograph was then exposed to verify the positional accuracy of the files.



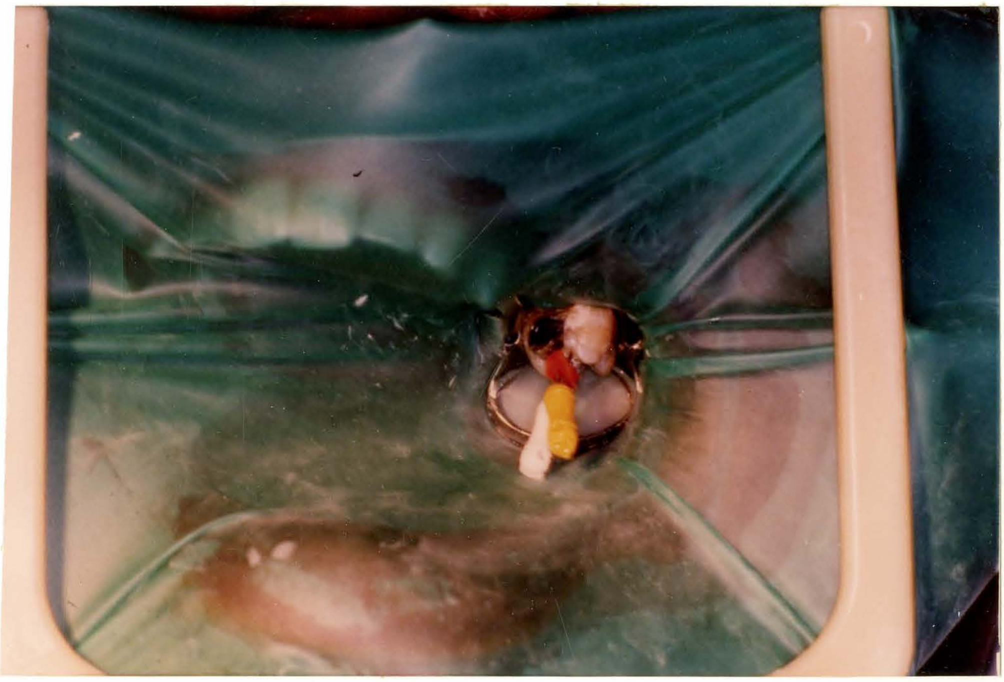


Figure 5: The Sono-Explorer Mark III electronic apex locator. The indicator needle (far left of the meter scale) is shown in the position it occupies prior to the introduction into the canal of a file attached to the electronic device.


APEX
BATTERY
REFERENCE TUNER
ON
OFF
BATTERY
PROBE
UNION BROACH
SONO-EXPLORER
MARK III

Figure 6: The Sono-Explorer Mark III electronic apex locator. The indicator needle (center of the meter scale) is shown in the position it occupies when the correct endodontic working length has been identified electronically.

APEX
BATTERY
REFERENCE TUNER
ON
OFF
BATTERY
PROBE
UNION BROACH
SONO-EXPLORER
MARK III

Figure 7: Electronic estimation of endodontic working length. Photograph of a file placed to the length indicated by the Sono-Explorer (indicator needle centered on the meter scale).

Figure 8: Radiographic verification of files in place. Clinical photograph of a periapical radiograph exposed with files inserted to the electronically indicated root canal length.


APEX
BATTERY
REFERENCE

Statistics

A comparison of the radiographic, electronic, and anatomic methods was performed by categorizing the tested canals into three groups: (a) all canals, (b) distobuccal canals, and (c) palatal canals. The percentage of acceptable measurements for each method was calculated using a maximum allowable deviation of ±0.5mm from the location of the anatomic apical foramen. Mean root canal lengths for the radiographic, electronic, and anatomic determinations were calculated and the correlated Student's t test was employed to locate significant differences between the three methods in each of the three groups. In this repeated measures design one variable was X (radiographic), another Y (electronic), and the third Z (anatomic).

RESULTS

The results of the radiographic, electronic, and direct anatomic measurements for each canal are listed in Table 2. In order to evaluate the data, the direct anatomic measurement of each canal was subtracted from the radiographic and electronic measurements of tooth length. A measurement beyond the apical foramen was indicated by a positive number, whereas a negative number indicated that the measurement was short. Measurements which were within ±0.5mm of the apical foramen were considered to be acceptable clinically. The position of the apical constriction can be approximated by subtracting 1.0mm from the radiographic and electronic estimates of the position of the major diameter. The subtraction of 1.0mm from the measurements in the acceptable range would result in working lengths 0.5 to 1.5mm short of the apical foramen. Endodontic procedures would therefore remain within the confines of the root canal and avoid iatrogenic damage to the surrounding periapical tissues. Since the use of a standard endodontic ruler restricted length measurements to the nearest 0.5mm, the use of smaller, more precise numbers would have been inappropriate.

TABLE 2

COMPARISON OF TECHNIQUES FOR MEASUREMENT OF ROOT CANAL LENGTH: RADIOGRAPHIC, ELECTRONIC, AND ANATOMIC

Case (#)	Tooth (#)	Canal	Radiographic (mm)	Electronic (mm)	Anatomic (mm)
1	14	DB	20.0	21.0	19.5
1	14	P	21.0	21.0	21.0
2	15	DB	19.0	19.5	19.0
2	15	P	18.5	17.5	18.0
3	14	DB	20.0	19.5	19.5
3	14	P	21.5	21.5	21.5
4	14	DB	19.0	21.5	19.0
4	14	P	19.0	20.0	18.5
5	15	DB	18.0	18.0	18.0
5	15	P	19.5	19.5	19.0
6	3	DB	21.0	21.5	20.5
6	3	P	20.5	20.5	21.0
7	3	DB	19.0	19.0	18.5
7	3	P	19.5	20.5	20.0
8	15	DB	19.5	19.5	19.5
8	15	P	19.5	20.0	18.5
9	3	DB	22.0	22.0	21.5
9	3	P	23.0	23.0	22.5
10	14	DB	19.0	19.0	18.5
10	14	P	19.5	20.0	19.5
11	15	DB	15.0	15.0	15.0
11	15	P	15.5	16.0	16.0
12	2	DB	20.5	20.0	19.5
12	2	P	19.0	19.0	18.5
13	3	DB	18.5	20.0	18.5
13	3	P	19.5	20.0	18.5
14	14	DB	19.0	19.0	18.5
14	14	P	19.0	20.0	20.0
15	15	DB	20.0	20.0	20.0
15	15	P	19.0	19.5	18.5
16	3	DB	18.5	18.5	18.0
16	3	P	19.0	19.5	19.0
17	14	DB	17.5	17.5	17.5
17	14	P	17.0	17.5	17.5
18	14	DB	20.5	21.5	20.0
18	14	P	21.5	21.5	21.5
19	2	DB	21.5	21.5	21.0
19	2	P	22.5	22.5	22.0
20	15	DB	20.0	20.5	20.0
20	15	P	19.5	18.5	19.0
21	14	DB	19.5	19.0	19.0
21	14	P	21.0	21.0	21.0

TABLE 2--Continued

Case (#)	Tooth (#)	Canal	Radiographic (mm)	Electronic (mm)	Anatomic (mm)
22	15	DB	20.0	22.5	20.0
22	15	P	20.0	21.0	19.5
23	3	DB	19.0	19.0	19.0
23	3	P	20.5	20.5	20.0
24	14	DB	21.0	21.5	20.5
24	14	P	20.5	20.5	20.0
25	2	DB	19.5	21.0	19.5
25	2	P	20.0	20.5	19.0
26	3	DB	21.0	20.5	20.0
26	3	P	20.0	20.0	19.5

Comparison of the Distobuccal and Palatal Canals

The percentage of acceptable measurements for the distobuccal and palatal canals combined were determined in this section. Direct anatomic tooth lengths were compared to radiographic and electronic measurements in Tables 3 and 4, respectively. The radiographic estimates of root canal length were within the previously described range of acceptability in 88.5 percent of the investigated canals. Acceptable measurements were determined in 46 canals; six were unacceptable. The measurements ranged from 1.0mm short of, to 1.0mm beyond, the apical foramen. The electronically determined root canal lengths were acceptable in 73.1 percent of the cases. Of the 52 canals, 38 were within the ±0.5mm range, while 14 were not. The lengths ranged from 2.5mm long to 0.5mm short.

The correlated Student's t test was employed to determine whether statistically significant differences existed between the mean root canal lengths derived from each method. Statistically significant differences existed between the radiographic and anatomic methods at $p < .001$, between the electronic and anatomic methods at $p < .001$, and between the radiographic and electronic methods at $p < .01$.

TABLE 3

COMPARISON OF RADIOGRAPHIC AND ANATOMIC MEASUREMENTS OF ROOT CANAL LENGTH: DISTOBUCCAL AND PALATAL CANALS

Case (#)	Tooth (#)	Canal	Rad (mm)	Anat (mm)	Difference (mm)	Acceptable (+ or 0)
1	14	DB	20.0	19.5	+0.5	+
1	14	P	21.0	21.0	0.0	+
2	15	DB	19.0	19.0	0.0	+
2	15	P	18.5	18.0	+0.5	+
3	14	DB	20.0	19.5	+0.5	+
3	14	P	21.5	21.5	0.0	+
4	14	DB	19.0	19.0	0.0	+
4	14	P	19.0	18.5	+0.5	+
5	15	DB	18.0	18.0	0.0	+
5	15	P	19.5	19.0	+0.5	+
6	3	DB	21.0	20.5	+0.5	+
6	3	P	20.5	20.0	+0.5	+
7	3	DB	19.0	18.5	+0.5	+
7	3	P	19.5	20.0	-0.5	+
8	15	DB	19.5	19.5	0.0	+
8	15	P	19.5	18.5	+1.0	0
9	3	DB	22.0	21.5	+0.5	+
9	3	P	23.0	22.5	+0.5	+
10	14	DB	19.0	18.5	+0.5	+
10	14	P	19.5	19.5	0.0	+
11	15	DB	15.0	15.0	0.0	+
11	15	P	15.5	16.0	-0.5	+
12	2	DB	20.5	19.5	+1.0	0
12	2	P	19.0	18.5	+0.5	+
13	3	DB	18.5	18.5	0.0	+
13	3	P	19.5	18.5	+1.0	0
14	14	DB	19.0	18.5	+0.5	+
14	14	P	19.0	20.0	-1.0	0
15	15	DB	20.0	20.0	0.0	+
15	15	P	19.0	18.5	+0.5	+
16	3	DB	18.5	18.0	+0.5	+
16	3	P	19.0	19.0	0.0	+
17	14	DB	17.5	17.5	0.0	+
17	14	P	17.0	17.5	-0.5	+
18	14	DB	20.5	20.0	+0.5	+
18	14	P	21.5	21.5	0.0	+
19	2	DB	21.5	21.0	+0.5	+
19	2	P	22.5	22.0	+0.5	+
20	15	DB	20.0	20.0	0.0	+
20	15	P	19.5	19.0	+0.5	+
21	14	DB	19.5	19.0	+0.5	+
21	14	P	21.0	21.0	0.0	+

TABLE 3--Continued

Case (#)	Tooth (#)	Canal	Rad (mm)	Anat (mm)	Difference (mm)	Acceptable (+ or 0)
22	15	DB	20.0	20.0	0.0	+
22	15	P	20.0	19.5	+0.5	+
23	3	DB	19.0	19.0	0.0	+
23	3	P	20.5	20.0	+0.5	+
24	14	DB	21.0	20.5	+0.5	+
24	14	P	20.5	20.0	+0.5	+
25	2	DB	19.5	19.5	0.0	+
25	2	P	20.0	19.0	+1.0	0
26	3	DB	21.0	20.0	+1.0	0
26	3	P	20.0	19.5	+0.5	+

TABLE 4

COMPARISON OF ELECTRONIC AND ANATOMIC MEASUREMENTS OF ROOT CANAL LENGTH: DISTOBUCCAL AND PALATAL CANALS

Case (#)	Tooth (#)	Canal	Elec (mm)	Anat (mm)	Difference (mm)	Acceptable (+ or 0)
1	14	DB	21.0	19.5	+1.5	0
1	14	P	21.0	21.0	0.0	+
2	15	DB	19.5	19.0	+0.5	+
2	15	P	17.5	18.0	-0.5	+
3	14	DB	19.5	19.5	0.0	+
3	14	P	21.5	21.5	0.0	+
4	14	DB	21.5	19.0	+2.5	0
4	14	P	20.0	18.5	+1.5	0
5	15	DB	18.0	18.0	0.0	+
5	15	P	19.5	19.0	+0.5	+
6	3	DB	21.5	20.5	+1.0	0
6	3	P	20.5	20.0	+0.5	+
7	3	DB	19.0	18.5	+0.5	+
7	3	P	20.5	20.0	+0.5	+
8	15	DB	19.5	19.5	0.0	+
8	15	P	20.0	18.5	+1.5	0
9	3	DB	22.0	21.5	+0.5	+
9	3	P	23.0	22.5	+0.5	+
10	14	DB	19.0	18.5	+0.5	+
10	14	P	20.0	19.5	+0.5	+
11	15	DB	15.0	15.0	0.0	+
11	15	P	16.0	16.0	0.0	+
12	2	DB	20.0	19.5	+0.5	+
12	2	P	19.0	18.5	+0.5	+
13	3	DB	20.0	18.5	+1.5	0
13	3	P	20.0	18.5	+1.5	0
14	14	DB	19.0	18.5	+0.5	+
14	14	P	20.0	20.0	0.0	+
15	15	DB	20.0	20.0	0.0	+
15	15	P	19.5	18.5	+1.0	0
16	3	DB	18.5	18.0	+0.5	+
16	3	P	19.5	19.0	+0.5	+
17	14	DB	17.5	17.5	0.0	+
17	14	P	17.5	17.5	0.0	+
18	14	DB	21.5	20.0	+1.5	0
18	14	P	21.5	21.5	0.0	+
19	2	DB	21.5	21.0	+0.5	+
19	2	P	22.5	22.0	+0.5	+
20	15	DB	20.5	20.0	+0.5	+
20	15	P	18.5	19.0	-0.5	+
21	14	DB	19.0	19.0	0.0	+
21	14	P	21.0	21.0	0.0	+

TABLE 4--Continued

Case (#)	Tooth (#)	Canal	Elec (mm)	Anat (mm)	Difference (mm)	Acceptable (+ or 0)
22	15	DB	22.5	20.0	+2.5	0
22	15	P	21.0	19.5	+1.5	0
23	3	DB	19.0	19.0	0.0	+
23	3	P	20.5	20.0	+0.5	+
24	14	DB	21.5	20.5	+1.0	0
24	14	P	20.5	20.0	+0.5	+
25	2	DB	21.0	19.5	+1.5	0
25	2	P	20.5	19.0	+1.5	0
26	3	DB	20.5	20.0	+0.5	+
26	3	P	20.0	19.5	+0.5	+

Distobuccal Canal

The radiographic and electronic length estimates for the distobuccal canal were compared individually to direct anatomic measurements in Tables 5 and 6. The radiographic method attained a 92.3 percentage of acceptability (Table 5). Of the 26 distobuccal canals, 24 were within the ±0.5mm range, whereas only two were not. The length measurements had a 1.0mm range with two extended 1.0mm beyond and none short of the apical foramen. The electronic method achieved acceptable measurements in 69.2 percent of the investigated canals (Table 6). The number of lengths within the acceptable range fell to 18, whereas eight were unacceptable. The Sono-Explorer indicated lengths which ranged from the apical foramen to 2.5mm beyond that point. None of the electronic readings were short of the apical foramen.

The mean root canal lengths for each of the three methods were compared in the correlated Student's t test to locate statistically significant differences. Statistically significant differences existed between the radiographic and anatomic methods at $p < .001$, between the electronic and anatomic methods at $p < .001$, and between the radiographic and electronic methods at $p < .05$.

TABLE 5

COMPARISON OF RADIOGRAPHIC AND ANATOMIC MEASUREMENTS OF ROOT CANAL LENGTH: DISTOBUCCAL CANAL

Case (#)	Tooth (#)	Canal	Rad (mm)	Anat (mm)	Difference (mm)	Acceptable (+ or o)
1	14	DB	20.0	19.5	+0.5	+
2	15	DB	19.0	19.0	0.0	+
3	14	DB	20.0	19.5	+0.5	+
4	14	DB	19.0	19.0	0.0	+
5	15	DB	18.0	18.0	0.0	+
6	3	DB	21.0	20.5	+0.5	+
7	3	DB	19.0	18.5	+0.5	+
8	15	DB	19.5	19.5	0.0	+
9	3	DB	22.0	21.5	+0.5	+
10	14	DB	19.0	18.5	+0.5	+
11	15	DB	15.0	15.0	0.0	+
12	2	DB	20.5	19.5	+1.0	0
13	3	DB	18.5	18.5	0.0	+
14	14	DB	19.0	18.5	+0.5	+
15	15	DB	20.0	20.0	0.0	+
16	3	DB	18.5	18.0	+0.5	+
17	14	DB	17.5	17.5	0.0	+
18	14	DB	20.5	20.0	+0.5	+
19	2	DB	21.5	21.0	+0.5	+
20	15	DB	20.0	20.0	0.0	+
21	14	DB	19.5	19.0	+0.5	+
22	15	DB	20.0	20.0	0.0	+
23	3	DB	19.0	19.0	0.0	+
24	14	DB	21.0	20.5	+0.5	+
25	2	DB	19.5	19.5	0.0	+
26	3	DB	21.0	20.0	+1.0	0

TABLE 6

COMPARISON OF ELECTRONIC AND ANATOMIC MEASUREMENTS OF ROOT CANAL LENGTH: DISTOBUCCAL CANAL

Case (#)	Tooth (#)	Canal	Elec (mm)	Anat (mm)	Difference (mm)	Acceptable (+ or 0)
1	14	DB	21.0	19.5	+1.5	0
2	15	DB	19.5	19.0	+0.5	+
3	14	DB	19.5	19.5	0.0	+
4	14	DB	21.5	19.0	+2.5	0
5	15	DB	18.0	18.0	0.0	+
6	3	DB	21.5	20.5	+1.0	0
7	3	DB	19.0	18.5	+0.5	+
8	15	DB	19.5	19.5	0.0	+
9	3	DB	22.0	21.5	+0.5	+
10	14	DB	19.0	18.5	+0.5	+
11	15	DB	15.0	15.0	0.0	+
12	2	DB	20.0	19.5	+0.5	+
13	3	DB	20.0	18.5	+1.5	0
14	14	DB	19.0	18.5	+0.5	+
15	15	DB	20.0	20.0	0.0	+
16	3	DB	18.5	18.0	+0.5	+
17	14	DB	17.5	17.5	0.0	+
18	14	DB	21.5	20.5	+1.5	0
19	2	DB	21.5	21.0	+0.5	+
20	15	DB	20.5	20.0	+0.5	+
21	14	DB	19.0	19.0	0.0	+
22	15	DB	22.5	20.0	+2.5	0
23	3	DB	19.0	19.0	0.0	+
24	14	DB	21.5	20.5	+1.0	0
25	2	DB	21.0	19.5	+1.5	0
26	3	DB	20.5	20.0	+0.5	+

Palatal Canal

A comparison of radiographic and electronic methods to direct anatomic measurements for the palatal canal are shown in Tables 7 and 8. Radiographic root canal length determination was accurate to within ±0.5mm in 84.6 percent of the cases (Table 7). Of the 26 palatal canals, 22 lengths were acceptable, whereas only four were unacceptable. The measurements ranged from 1.0mm long to 1.0mm short of the apical foramen. The Sono-Explorer Mark III gave acceptable readings in 76.9 percent of the palatal canals (Table 8). Acceptable lengths were obtained in 20 canals, six were unacceptable. The measurements ranged from 1.5mm beyond to 0.5mm short of the apical foramen.

The correlated Student's t test was employed to determine statistically significant differences between the mean root canal lengths derived from the three methods. Statistically significant differences existed between the radiographic and anatomic methods at $p < .01$ and between the electronic and anatomic methods at $p < .001$. At the $p < .05$ level the difference between the radiographic and electronic methods was not statistically significant.

TABLE 7

COMPARISON OF RADIOGRAPHIC AND ANATOMIC MEASUREMENTS OF ROOT CANAL LENGTH: PALATAL CANAL

Case (#)	Tooth (#)	Canal	Rad (mm)	Anat (mm)	Difference (mm)	Acceptable (+ or 0)
1	14	P	21.0	21.0	0.0	+
2	15	P	18.5	18.0	+0.5	+
3	14	P	21.5	21.5	0.0	+
4	14	P	19.0	18.5	+0.5	+
5	15	P	19.5	19.0	+0.5	+
6	3	P	20.5	20.0	+0.5	+
7	3	P	19.5	20.0	-0.5	+
8	15	P	19.5	18.5	+1.0	0
9	3	P	23.0	22.5	+0.5	+
10	14	P	19.5	19.5	0.0	+
11	15	P	15.5	16.0	-0.5	+
12	2	P	19.0	18.5	+0.5	+
13	3	P	19.5	18.5	+1.0	0
14	14	P	19.0	20.0	-1.0	0
15	15	P	19.0	18.5	+0.5	+
16	3	P	19.0	19.0	0.0	+
17	14	P	17.0	17.5	-0.5	+
18	14	P	21.5	21.5	0.0	+
19	2	P	22.5	22.0	+0.5	+
20	15	P	19.5	19.0	+0.5	+
21	14	P	21.0	21.0	0.0	+
22	15	P	20.0	19.5	+0.5	+
23	3	P	20.5	20.0	+0.5	+
24	14	P	20.5	20.0	+0.5	+
25	2	P	20.0	19.0	+1.0	0
26	3	P	20.0	19.5	+0.5	+

TABLE 8

COMPARISON OF ELECTRONIC AND ANATOMIC MEASUREMENTS OF ROOT CANAL LENGTH: PALATAL CANAL

Case (#)	Tooth (#)	Canal	Elec (mm)	Anat (mm)	Difference (mm)	Acceptable (+ or 0)
1	14	P	21.0	21.0	0.0	+
2	15	P	17.5	18.0	-0.5	+
3	14	P	21.5	21.5	0.0	+
4	14	P	20.0	18.5	+1.5	0
5	15	P	19.5	19.0	+0.5	+
6	3	P	20.5	20.0	+0.5	+
7	3	P	20.5	20.0	+0.5	+
8	15	P	20.0	18.5	+1.5	0
9	3	P	23.0	22.5	+0.5	+
10	14	P	20.0	19.5	+0.5	+
11	15	P	16.0	16.0	0.0	+
12	2	P	19.0	18.5	+0.5	+
13	3	P	20.0	18.5	+1.5	0
14	14	P	20.0	20.0	0.0	+
15	15	P	19.5	18.5	+1.0	0
16	3	P	19.5	19.0	+0.5	+
17	14	P	17.5	17.5	0.0	+
18	14	P	21.5	21.5	0.0	+
19	2	P	22.5	22.0	+0.5	+
20	15	P	18.5	19.0	-0.5	+
21	14	P	21.0	21.0	0.0	+
22	15	P	21.0	19.5	+1.5	0
23	3	P	20.5	20.0	+0.5	+
24	14	P	20.5	20.0	+0.5	+
25	2	P	20.5	19.0	+1.5	0
26	3	P	20.0	19.5	+0.5	+

DISCUSSION

Selection and Rationale

Because of the large number of studies already reported on electronic devices, a careful analysis of rationale was necessary prior to performing additional research on this topic. Factors instrumental in the decision to investigate this subject were:

(a) radioigraphic complexities inherent to the maxillary molars and the fact that no previous investigation has been limited to those teeth.

(b) the variable designs of earlier studies.

(c) variation in results obtained in previous studies.

Problems of the maxillary molars. Although several studies have included maxillary molars in their overall samples (5, 71, 72), no other investigation has focused solely on the problems with these teeth. Because of the multiple anatomic structures which overlap when radiographing maxillary molars, these teeth are the most difficult to interpret for working length during endodontic therapy. These anatomic structures include the inferior border of the maxillary sinus, septa and vascular canals within the sinus, bony nodules on the sinus floor, the zygomatic process of the maxilla, the zygomatic bone proper, unerupted or malpositioned maxillary second, third, and even fourth molars, and the overlapped roots of adjacent teeth or of the involved tooth itself. The individual anatomic variations found in the patient also influence the extent to which this superimposition is manifested. Additionally, the vertical and horizontal angulation of the x-ray tube and film placement are factors that may influence the resultant radiographs.

Another problem encountered during the radiographic evaluation of maxillary molars undergoing endodontic treatment is the potential for early exit of the canal short of the actual anatomic apex of the root. Though this may occur in any root of the maxillary molars, it is particularly problematic in the palatal root, where the canal exits short of the apex to the buccal frequently (3) thus making it difficult to detect on a periapical radiograph, even one taken from an extreme horizontal angle. Should the apex locator produce meaningful information as compared to the more commonly employed radiographic method, accuracy in determination of working length for these teeth would be enhanced.

<u>Variable design of other studies</u>. An analysis of the existing research on this topic revealed that in the majority of the investigations length measured by an

electronic device was compared to either radiographic or anatomic lengths alone. In only two studies, however, were both radiographic and electronic methods employed to estimate root canal length which was then verified by direct anatomic measurement (5, 15).

Variation in results of previous studies. The results of previous studies have been inconclusive as to the ability of electronic apex locators to determine accurately root canal length in a clinical environment. There is an almost equal division between investigations which support their accuracy and those which refute such findings.

The presence of bias in the study of electronic apex locators must be addressed as well. It is certain that investigators such as Sunada (13) and Inoue (11) were influenced by the fact that they introduced the concept of electronic length determination. They undoubtedly approached their research in the hope of producing data which supported their ideas and beliefs. Conversely, those studies which denounced the use of electronic apex locators, in many instances, were undertaken in order to accomplish that very objective. These investigators attempted to support the radiographic method in order to defend the many years they employed this technique for the determination of endodontic working length. The intent here is not to imply that any of these individuals were dishonest, but rather to point out that bias could influence experimental design, the evaluation of results, and the conclusions of the author.

Every effort was made to eliminate bias from our investigation. There was no financial assistance provided by the manufacturer nor was there any attempt to support either the radiographic or the electronic method in defense of our own clinical technique. Our objective was simply to identify the most effective method of determining endodontic working length in maxillary molar teeth. In order to acheive this goal, the most difficult teeth to interpret radiographically were selected and the investigation was designed to allow both methods to be performed as recommended for clinical endodontics. Additionally, direct anatomic measurements were compared to the radiographic and electronic estimates of tooth length for each respective canal. The absolute nature of these direct anatomic measurements allowed them to be used as controls in the context of our experimental design.

Factors for selection.

The reasoning behind the use of the distobuccal and palatal canals was that operators are frequently more concerned with the difficulty presented by the mesiobuccal canal(s) (5); therefore, a tendency exists for a reduction in the clinician's level of concentration when treating the two "easier" canals which can be a factor in the determination of their working lengths and indeed in their longterm success. Also contributing to the selection of these canals was the ability to separate the distobuccal and palatal roots on a single periapical radiograph taken from approximately a 10 degree mesial to distal angulation.

The Sono-Explorer Mark III electronic apex locator was chosen in part because of the frequency of its appearance in previous investigations. Additionally, recent studies by Fouad and Krell (64) and Fouad et al. (65) have shown the Sono-Explorer to be as accurate as four other electronic devices utilized in their research. The Mark III is the latest, most refined model of Sono-Explorer which is a descendant of the original as designed and introduced by Inoue in 1972.

Operation of the Electronic Apex Locator

In order to minimize errors unrelated to the electronic device itself, considerable time was spent becoming comfortable and familiar with the proper usage of the Sono-Explorer Mark III in accordance with the operating instructions of the manufacturer. The only major difficulty encountered during the operation of the electronic apex locator was that calibration of the device for individual capacitance was time consuming and required two operators.

The manufacturer has stated that the Sono-Explorer has been "improved" several times over the past 19 years. The initial change involved the incorporation of an indicator scale making a visual reference to the relative distance from the apical foramen possible. Further modifications were aimed at simplification and refinement of the indicator scale and the reference tuner. In addition, an audible alarm signal was added to help identify instrument penetration beyond the apex. The majority of the modifications, however, were concerned with the reduction of the size and weight of the device in order to enhance its use in a clinical setting. In the Mark III, this was accomplished by the adoption of integrated electronic circuits resulting in a more compact, lightweight unit. The amazing aspect of these "improved" models is that each has claimed to provide greater simplicity, accuracy, and reliability than its predecessors. This is difficult to accept based upon Inoue's original claim that the Sono-Explorer was accurate 91 percent of the time (52). Indeed, if the manufacturer is correct, the cumulative effect of each new model would result in the accurate location of the apical foramen in virtually every canal. Our results disprove clearly these inflated commercial claims of unparalleled accuracy and reliability. This is not a complete surprise, because none of the changes made in the Sono-Explorer involved the adoption of new functional principles. In fact, the function of the Sono-Explorer is still based upon the electrical resistance theory and the addition of micro-circuitry, visual scales, and audible alarms does not in any way alter the performance of the device to the extremes suggested by the manufacturer.

Analysis of the Statistical Information

The direct anatomic measurements, by definition, were absolutely accurate. Comparing the measurements obtained anatomically to both the radiographic and electronic, the correlated Student's t test determined statistical differences of $p < .001$ for the calculated tooth length of the distobuccal and palatal canals grouped together, and of the distobuccal canal alone. In the palatal canal, the statistical significance was still impressive, but dropped to $p < .01$ (rad. vs. anat.).

A comparison of radiographic and electronic length determination to one another using the correlated Student's t test revealed statistical significance at $p < .01$ and $p < .05$ for the distobuccal and palatal canals together and for the distobucal canal, respectively. The correlated t test, however, failed to show statistical significance ($p < .05$) between the two methods in the palatal canal.

This statistical information, in combination with the fact that statistically significant differences were calculated between the anatomic and both the radiographic and electronic methods, allows the two experimental techniques to be compared for superiority. Statistically significant differences were present between the radiographic and anatomic measurements based upon t values of 5.263 for the two canals grouped together, 4.762 for the distobuccal canal, and 3.093 for the palatal canal; whereas, a comparison between the electronic and anatomic methods produced t values of 6.452 for the two canals grouped together, 4.861 for the distobuccal canal, and 4.237 for the palatal canal. These t values indicate that in each category direct anatomic measurements were more closely approximated by radiographic estimates of endodontic working length. The fact that the correlated Student's t test found radiographs to be superior to the electronic device is important, but quantitatively reveals little concerning the difference between the two methods. Only a comparison of the radiographic and electronic methods to anatomic tooth length can determine quanitatively the superior technique and reveal information which is clinically significant.

Isolated Failures of the Sono-Explorer

In regard to the measurements attained from the electronic device, there were three instances in which the Sono-Explorer was unable to indicate the location of the apical foramen. This involved only one of the two canals in three separate teeth, all from different patients. In each of these canals, the indicator needle approached the center of the meter scale, but did not reach that center point. These canals were re-dried and repeated measurements were attempted without success. Following extraction of these teeth, it was determined that in each of the three canals the endodontic files had extended beyond the apical foramen though the apex locator indicated they were short of the desired length. The data from these teeth was excluded from the results of this study. If the data had been considered, the results would have changed markedly with radiographic estimates improving to the 89.0 percent acceptability level and electronic estimates decreasing to the 69.0 percent level. In addition, 17 out of 17 unacceptable electronic readings would have extended beyond the apical foramen and into the periapical tissues. This would indicate that erroneous electronic length measurements are long 100 percent of the time. Clearly, the risk of relying solely on electronic apex locators to determine endodontic working length cannot be justified when in over 30 percent of the canals (17 of the 55 canals) it would lead to overinstrumentation and probable overfilling. The detrimental effects of canal preparation and filling beyond the root apex are well documented (29-31) and every effort should be made to terminate endodontic procedures short of the apical foramen at the minor diameter (4). Some discussion is required with regard to the cause of these three erroneous electronic measurements. No teeth included in this investigation had radiographically visible apical bone loss or pathosis. However, periapical lesions may have been present which were not identified radiographically because of insufficient demineralization of the bone in this area. This would lead to a possible explanation of the failed readings in these three canals. It is possible that the endodontic files encountered inflamed periapical tissue as opposed to normal periodontal ligament and therefore resulted in inaccurate measurements due to an alteration in the electrical resistance of this periradicular tissue. There does not appear to be a more reasonable interpretation of these particular erroneous results.

Clinical Implications

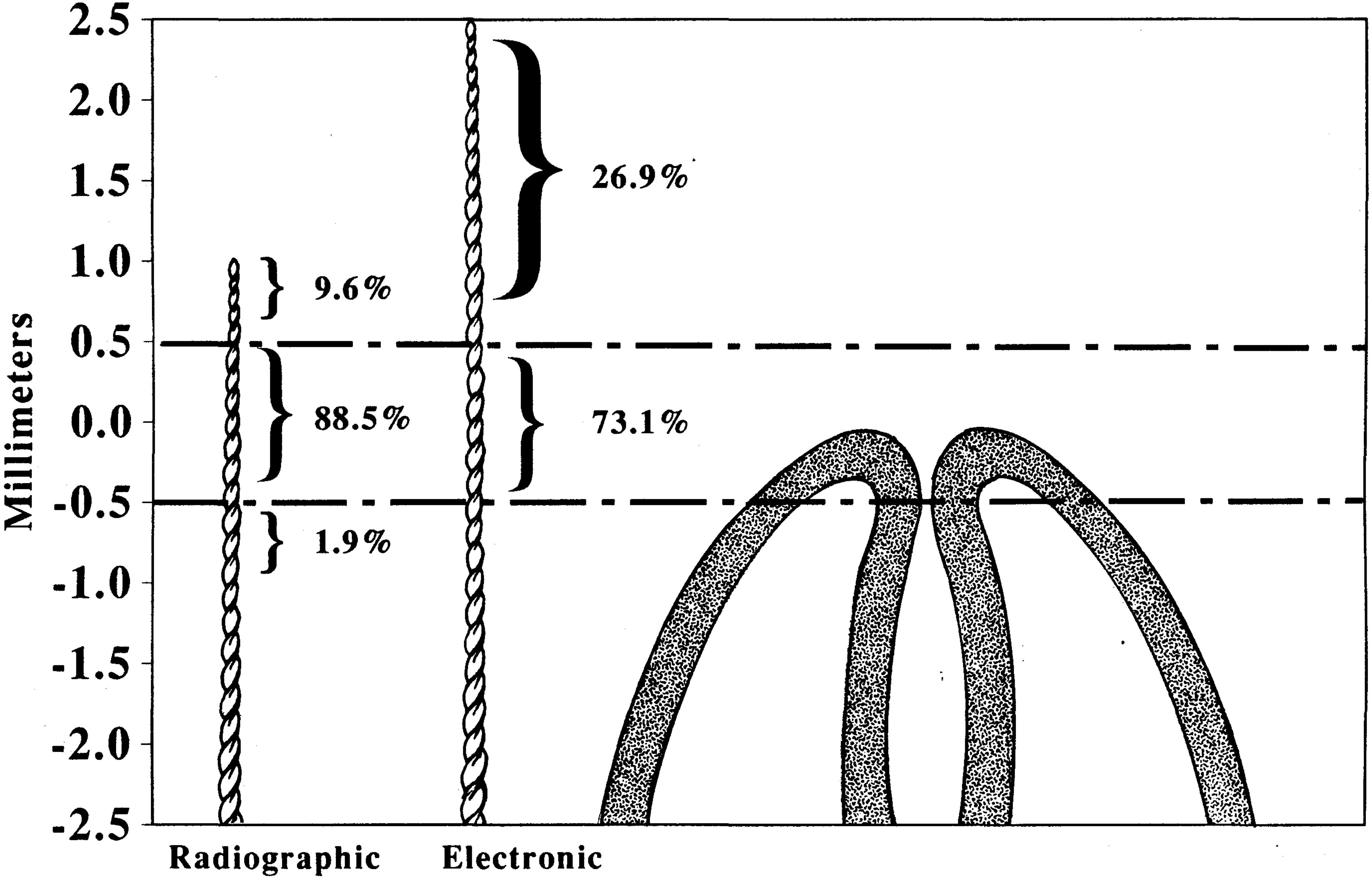
The range of measurements for both the radiographic and electronic methods and the percentage of acceptable length measurements are presented in Figure 9. A clinical appreciation of the accuracy and reliability of each technique is enhanced by this figure which allows for visual interpretation of the results. Radiographic estimates of root canal length were within ±0.5mm of the apical foramen in 88.5 percent of the investigated canals; whereas, the electronic method was within the acceptable range in 73.1 percent of the cases. Additionally, the variability was greater among the electronic measurements, the vast majority of which extended beyond the apical foramen. In fact, only two of 52 electronically measured canals were short of the major diameter, each by 0.5mm. The electronically determined lengths lying outside the ±0.5mm range were long in every instance and 12 of the 14 unacceptable measurements extended 1.5 to 2.5mm beyond the apical foramen. Conversely, the radiographic measurements exhibited greater consistency with no lengths deviating more than 1.0mm from the major diameter.

These data illustrate the inherent deficiencies of electronic apex locators. The unacceptable electronic lengths were without exception always beyond the apical foramen and the only consistency displayed by the Sono-Explorer was an overwhelming tendency to indicate lengths which were too long. Scientific investigations by Seltzer et al. (29, 30) concluded that optimum endodontic results were obtained when instrumentation was confined to the root canal, whereas canal preparation beyond the root apex led to periapical lesions which developed rapidly and exhibited an increased potential for epithelial proliferation. These results are in agreement with studies by Grahnen and Hansson (81) and Strindberg (82) which reported fewer treatment failures in teeth that could not be instrumented to the apex than in those which were prepared to the apex (actually beyond the apex). Davis, Joseph, and Bucher (31) also supported the preparation and filling of root canals short of the apical foramen by demonstrating exemplary healing in canals treated in this manner.

The harmful biologic effects of instrumentation beyond the root apex combined with the likelihood of doing so when an electronic device estimates root canal length (Fig. 9) indicates that sole reliance on apex locators is far too risky. Overinstrumentation would lead to substantial postoperative pain and increase the possibility of longterm endodontic failure. Despite an improved percentage of acceptable measurements by the Sono-Explorer in the palatal canal, the radiographic method remained superior by a considerable margin (76.9% vs. 84.6%). In addition to allowing length estimates to be made from endodontic working films, radiographs provide information concerning canal width, degree of canal curvature, and the relationship of several canals in the same root.

The most significant result of this study was to emphasize the still-present necessity for accurate radiographs during endodontic treatment. Introduction of electronic devices may be useful and helpful during certain types of cases. However, since their accuracy for this study design was inferior, we cannot support their use as a replacement of radiographs in endodontic therapy.

Figure 9: Diagramatic representation of the results. The range of instrument penetration within and beyond the root canal for both the radiographic and electronic methods is depicted relative to the root apex.



Millimeters
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
26.9%
9.6%
88.5%
73.1%
1.9%
Radiographic
Electronic

CONCLUSIONS

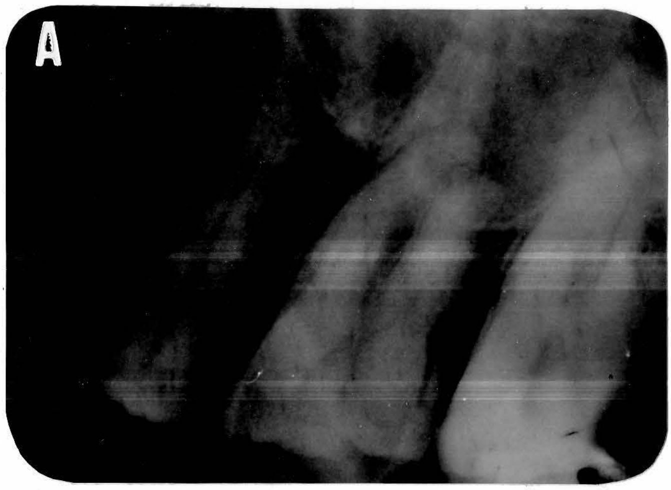
The results of this investigation indicate that the radiographic method of length determination is superior to the electronic method. This statement is supported by the percentage of acceptable measurements calculated for both techniques and by statistical analysis. The electronic device was most effective in the palatal canal, but still remained inferior to radiographic estimates of tooth length. Additionally, the radiographic method allows the interpolation of length adjustments to be based upon visualization of the image of the tooth, whereas the electronic method can only allow for such adjustments based on the assumption that the apical foramen has been identified. This goal was seldom achieved by the Sono-Explorer and in fact length estimates frequently deviated from the canal terminus by substantial distances (Fig. 10).

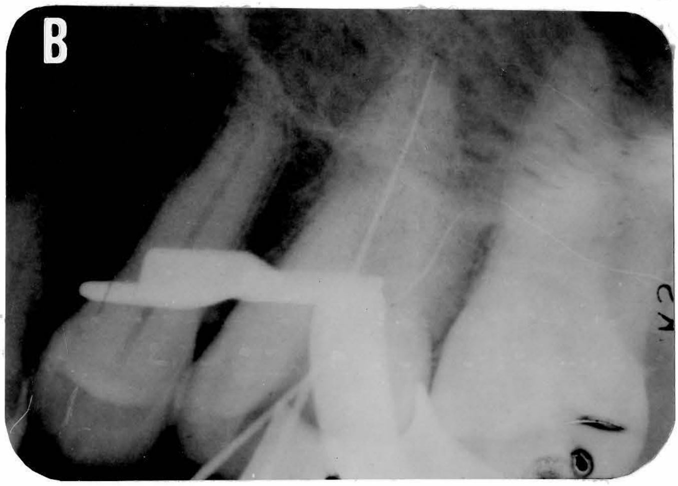
Despite the overall superiority of the radiographic method, electronic estimates of root canal length were accurate in 73.1 percent of the investigated canals (Fig. 11). In various clinical situations an electronic apex locator is of value. The apices of the maxillary molars can be obstructed radiographically by anatomic structures, making radiographic length determination difficult (Fig. 12). Also, certain patients present difficulties related to radiographs of the maxillary molars. Some individuals cannot tolerate the placement of films in the posterior region of the mouth (83). In addition, physical and psychological conditions can place limitations on the use of radiographs. This list includes pregnant females, patients undergoing radiation therapy, and those who object psychologically to x-rays out of concern for their harmful effects.

There is a psychological aspect involved in the determination of root canal length as well. In this regard, the electronic apex locator can give the operator a feeling of security that the appropriate working length has been established by an accurate, independent outside source, hence contributing to its popluarity.

In conclusion, the results of this investigation do not support the routine use of electronic apex locators as a replacement for radiographic root length determination. It is recommended that their use be limited to special situations where radiographic information is inadequate or where it is determined that electronic verification of radiographic estimates is deemed necessary.

Figure 10: Inaccurate electronic measurement. **A**, preoperative radiograph. **B**, radiographic estimation of length. **C**, electronic length illustrated radiographically. The electronically calculated lengths extend well beyond the apical foramen and are clinically unacceptable.


A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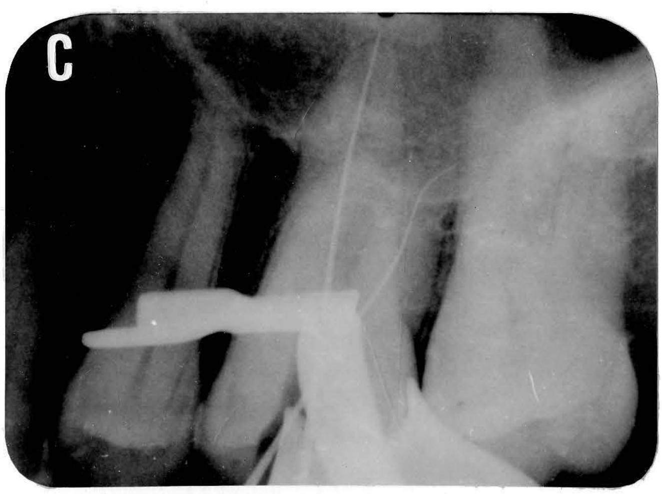

C

Figure 11: Accurate elecronic and radiographic measurement. **A**, preoperative radiograph. **B**, radiographic estimation of length. **C**, electronic length illustrated radiographically. Both methods indicate tooth length within the range of acceptability.

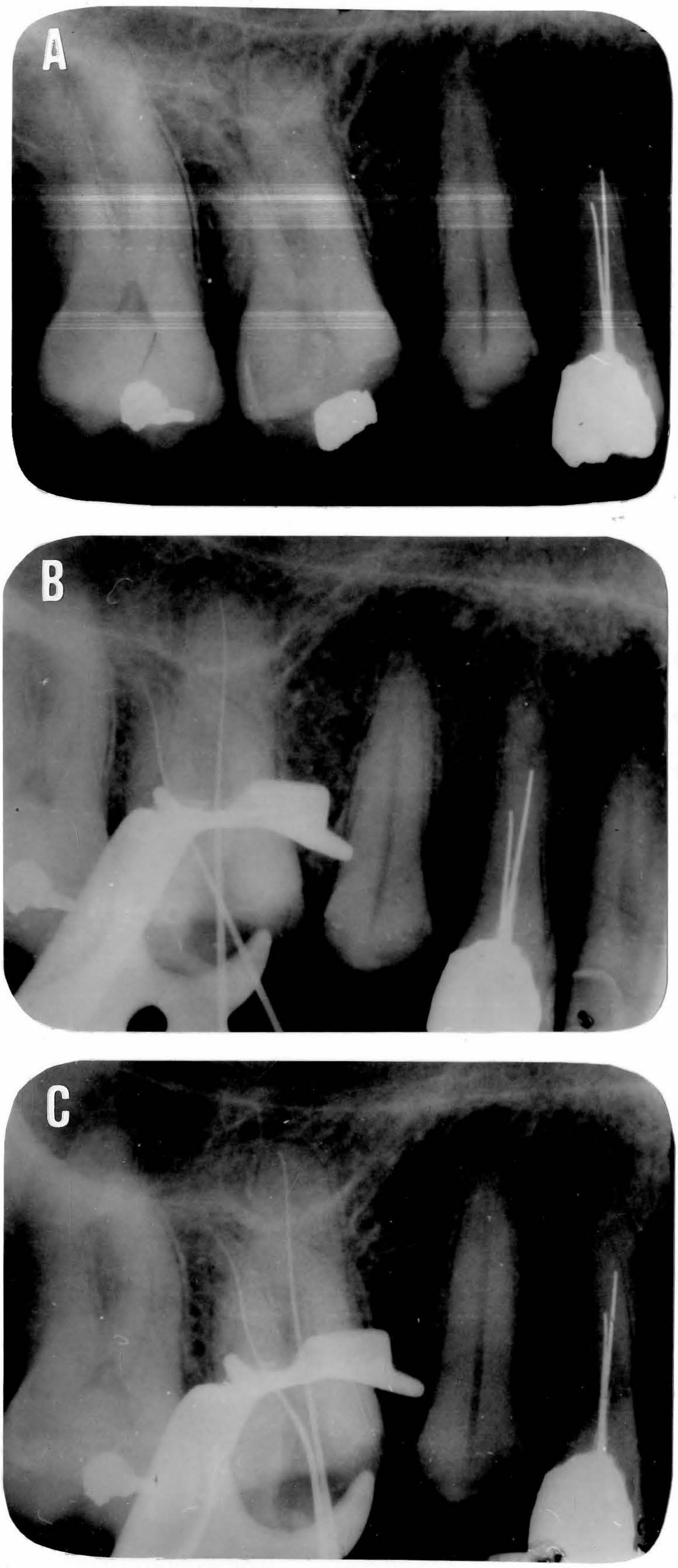
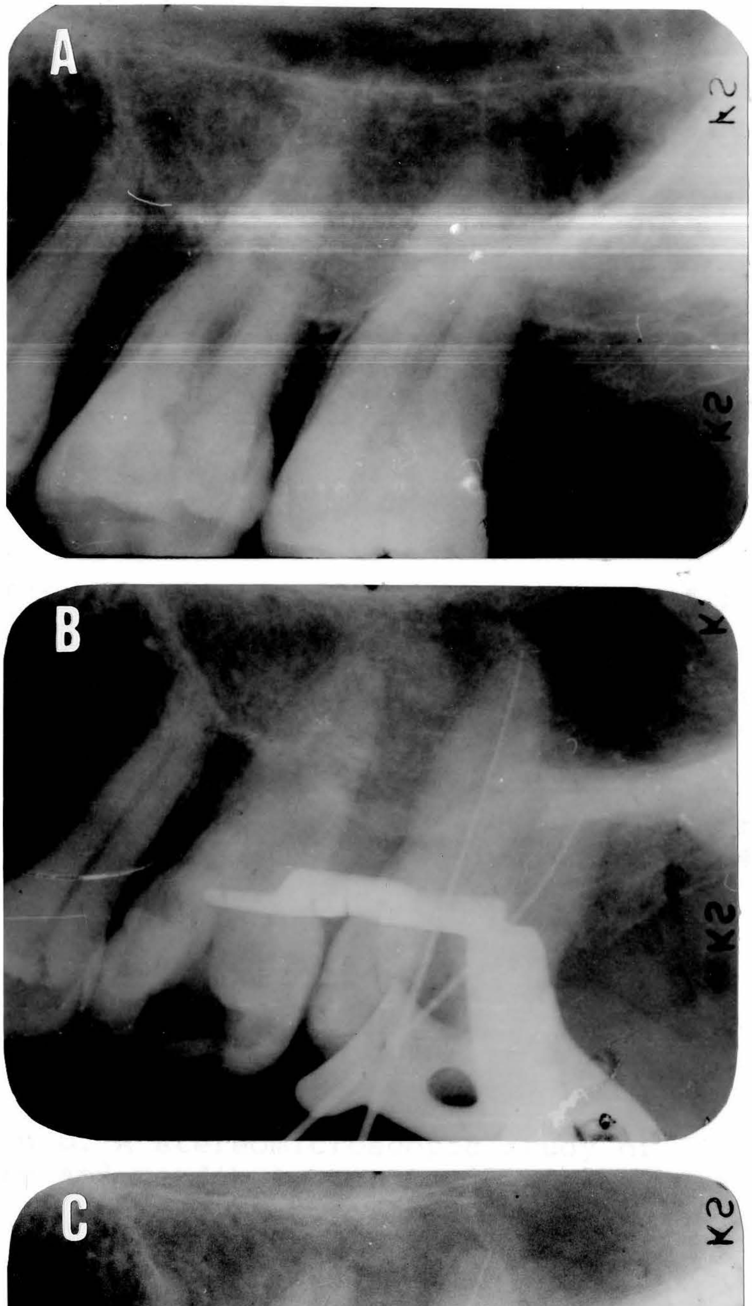

A
B
C

Figure 12: Anatomical obstruction of root apices. **A**, preoperative radiograph. **B**, radiographic estimation of length. **C**, electronic length illustrated radiographically. In each film the distobuccal apex is obstructed visually making length determination difficult.


A
B
C

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The final copies have been examined by the director of the thesis and the signature which appears below verifies the fact that any necessary changes have been incorporated and that the thesis is now given final approval by the Committee with reference to content and form.

The thesis is therefore accepted in partial fulfillment of the requirements for the degree of Master of Science.

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