INTRODUCTION

Accurate determination of working length during endodontic therapy is a crucial step in achieving a predictable outcome. This is determined by the use of electronic apex locators, dental radiography, tactile perception, and knowledge of average tooth lengths. Currently, conventional films remain the gold standard in which all other imaging methodologies are compared.[1] Recently, digital radiology has gained popularity among general dentists and endodontists and is challenging this gold standard. The advantages of digital radiography are many, including:

1. Decreased exposure to radiation.
2. Faster acquisition of images.
3. Decreased cost over time.
4. Environmental compatibility due to lack of processing chemicals.
5. Enhanced patient education.
6. Ease of image manipulation to a certain degree.

However, many studies have examined the diagnostic quality of digital images versus conventional film, and the findings conflict.

Radel et al.[1] recently compared Kodak RVG 6000, Schick CDR, and Kodak InSight digitized film with regard to working length determination. They found that Kodak RVG 6000 was significantly more accurate in determining working lengths. Some studies have shown that conventional film was superior in length measurements compared with older digital systems, whereas other studies show them to be comparable.[1] Friedlander et al.[2] compared phosphor plate-based digital images with conventional radiographs and found that perceived clarity of fine endodontic files and periapical lesions was significantly less with phosphor plate-based digital images than conventional films. Mentes and Gencoglu[3] compared direct digital and conventional film for working length determination in curved canals and concluded that both systems were comparable. Loushine et al.[4] determined that calibrated digital images were more accurate than uncalibrated images. Several other studies have examined the utilization of digital imaging for file length measurements with positive results.[5-11]

Altering the projection geometry, kilovolt peak (kVp), milliampere (mA), exposure time, source-film distance and source-object distance, can affect the interpretability of any image. Specifically, increasing the exposure time causes the image to be darker, whereas decreasing the exposure time causes the image to be lighter. Magnification is a factor of the source-film distance and source-object difference. Specifically, source-film distance is directly proportional to magnification, whereas the source-object distance is indirectly proportional. Although increasing the source-film distance decreases magnification, it also causes the image to be lighter; therefore, exposure time, kVp, or mA must be increased.

Many of the studies evaluating image quality use standard source-film/sensor distance and exposure time. Kaeppler et al.[12] altered the tube potential setting from 60kV to 90kV as well as by reducing the milliampere setting at unchanged tube potential. They evaluated peri-implant and decayed lesions and they found that intraoral films and storage phosphor plates demonstrated equal quality regardless of exposure at 60kV or 90kV.

With the advent of digital radiography, it has been possible to reduce the total absorbed dose by decreasing the tube potential level. Kaeppler et al.[12] concluded that it is more effective in practice to reduce the milliampere-seconds (mAs) product and to use more sensitive films or digital systems while maintaining the low tube potential level (60 kVp or 70 kVp). Velder et al.[13] found that it was possible to accurately determine working lengths with size 20 and size 25 files with a 95-percent dose reduction compared with Ektaspeed films. As digital technology improves, it should be possible to continually decrease the radiation exposure to the patient while still maintaining diagnostic quality of the images. Berkhout et al.[14] studied the range of diagnostically acceptable images and film as a function of exposure time. They concluded that all digital systems required less radiation exposure than film for diagnostically acceptable radiographs. They also found that phosphor plate systems produce good quality radiographs even at high exposure times, which may result in unnecessarily high doses.[14, 15] Borg et al.[16] found that photostimulable phosphor (PSP) systems provided clinically acceptable image quality over a wide exposure range and that the CDR (computed digital radiography) had the best image quality, but over the narrowest exposure ranges. Sheaffer et al.[17] found that underexposed films are perceived as inferior to slightly overexposed radiographs for endodontic file length assessment regardless of the film speed used (with conventional film).

REVIEW OF LITERATURE

HISTORY OF ENDODONTICS

The presence of a toothache has plagued mankind for centuries. Its description has been found on Egyptian tablets, Hebrew books, and Chinese, Greek, and Roman medical writings.[18] Fu Hsi (2953 BC) is credited with one of the earliest descriptions of toothaches.[19] In the European and Mediterranean Basin, root canal treatments were performed in antiquity, and the Greeks describe attempts at hermetically sealing root canal systems.[19] A recipe for a medicament to cure “the gnawing of the blood in the tooth” was found on the Ebers papyrus[20] dated to about 1500 BC. In the Middle Ages, it was thought that tooth decay was caused by the presence of “worms.” Andrew Boorde[21] in 1552 described a “deworming technique” that involved allowing the “perfume of a candle” to enter the tooth to allow one to take the worm out and “kill them on your nail.” This theory was discredited by Peter Lowe in 1654, and he used techniques such as cautery to treat the teeth.[19] Abulcasis (1050-1122) used cautery to control toothaches by inserting a red hot needle into the pulp.[18] Guy de Chauliac used a mixture of camphor, sulfur, myrrh, and asafetida as a filling material to cure toothache caused by worms.[18] Lazarre Rivierre recommended placing a cotton pellet moistened with oil of cloves in the cavity to relieve the toothache, a technique still used today.[18] The founder of modern dentistry, Pierre Fauchard, criticized these many early remedies for curing toothaches in 1728. He recommended rinsing the mouth with one’s own urine every morning.[18] For a tooth causing pain, he recommended “penetration into the tooth's inner cavity." In 1756, L.B. Lenter recommended electricity or even magnets to cure a toothache, and in 1770 Thomas Berdmore[22] addressed the practice of "counter-impression" in which techniques were used to divert one's attention away from the pain. This involved sedatives, and in some cases, burning of the ear with a hot iron.

Considerable advances have been made in the treatment and obturation of root canals since these early times. In 1838, Edward Maynard used a watch spring as the first root canal broach.[23] Barnum[18] introduced the rubber dam in 1862; Magitot[24] suggested the use of electric current for vitality testing, and Bowman[25] popularized the use of gutta-percha for filling root canals in 1867. Perry[26] described the wrapping of gutta-percha around a gold wire, perhaps an early version of ThermaFil. Kells[27] used x-rays to assess root canal obturation in 1899. Price[28] identified the value of x-rays in root canal work and the diagnosis of the non-vital pulp in 1901. In 1929, silver cones were introduced for the obturation of root canals by Trebitsch.[25]

Endodontics is the branch of dentistry concerned with the morphology, physiology, and pathology of the human dental pulp and periradicular tissues. Its study and practice encompass the basic clinical sciences, including the biology of the normal pulp; the etiology, diagnosis, prevention and treatment of diseases and injuries of the pulp; and associated periradicular conditions.[29] This is the most current definition of endodontics, but the true nature of endodontics did not occur until its recognition as a specialty; it wasn't until the early 20th century that the concept of endodontics began to take shape.[18]

In 1928, Dr. Harry B. Johnston was the first clinician to identify his practice as limited to endodontics. In 1943, a group of dentists met to discuss an association of clinicians interested in endodontics, and they called this association the American Association of Endodontists. Drs. Davis, Hospers, and Grossman called forth a meeting at the Palmer House in Chicago for the purpose of organizing a society for the practice of root canal therapy. By 1963, more than 200 dentists were limiting their practice to endodontics.[18] That same year, the American Dental Association recognized endodontics as a dental specialty.

Before there were endodontists, considerable study was accomplished in the area of the histological structure of the tooth and dental pulp. In 1675, Van Leeuwenhoek[30] described “transparent pipes” in the tooth bone, in referring to the canal system. Malpighi[31] in 1686 described “Substantia tubulosa,” known as dentin today. The nerve cells of the dental pulp were described as “ivory cells with fibrous processes” by Schwann[32] in 1839. The first adequate description of pulp histology was provided in 1852 by Kolliker.[33] The term odontoblast was first introduced by Waldeyer in 1865.[34]

Based on studies describing the complex anatomy of the root canal system, Grossman[25] posed the following question: “One may well ask at this point if root canal work is justified in view of the complexity of the canals, since by no method can all the minute ramifications be filled.” In response, Kronfield[35] states: “Microscopic findings on extracted teeth with clinically well-filled, uninfected main canals prove that nature takes care of the remaining unfilled lateral branches and apical ramifications. All these fine canals contain living tissue that remains vital after the pulp has been removed from the main canal and forms cementum that eventually may completely obliterate lateral canals.”

In the early 1900s, the dental profession took a devastating blow from the advocation of the focal infection theory. William Hunter[36] described sepsis as “the most prevalent and potent infective disease in the body.” He focused on the presence of staphylococcal and streptococcal organisms throughout the body as compromising specific organ systems.[18] He identified teeth and supporting structures as the foci of sepsis, particularly in poor patients who couldn’t otherwise afford dental treatment.[36] Several diseases such as gastritis, anemia, ulcers, colitis, and nephritis were attributed to oral sepsis, and Hunter went on to state that this “evil was so common and widespread that it is impossible to deal adequately with.”[36]

In 1912, Rhein[37] responded not by harshly criticizing Hunter, but rather urging the dental profession to forget “the antique methods of preserving dead pulp tissue, and become familiar with a scientific method of obtaining strictly aseptic conditions.” He went as far as to say that we owed Hunter “a debt of gratitude.” In 1913, Logan[38] demonstrated the treatment of chronic dentoalveolar abscess with extraction to prevent the spread of sepsis. Logan[39] in 1937 showed that the presence of bacteria did not necessarily indicate infection.

Even still, the dental profession was being damaged by the widespread acceptance of the focal infection theory. Not only were pulpless teeth being extracted, but so was any tooth with the possibility of chronic infection or inflammation, along with the surrounding periodontium.[18] With the works of clinicians such as Logan, endodontics eventually regained its place in the treatment of disease and infected teeth.

A physician by the name of Dr. Hatton[40] spoke out against this practice. He criticized the presumption of diagnosis made from dental radiographs alone and said it was “folly that no good physician would be guilty of in the study of any other part of the body.” He also said pulpless teeth are not dead, but owe to their supporting structures and vascularization, and that they can be “treated and filled even after infection has occurred.” Since then, the focal infection theory still lives on, but to a much lesser extent. However, throughout the tireless work of practitioners before us, it has been demonstrated that root canal treatment can predictably treat infected teeth.

In a landmark study by Kakehashi et al,[41] they found that in order for pulpal disease to occur and progress, bacteria must be present. This formed the basis for endodontic therapy in providing treatment with the goal of complete disinfection of the root canal system. The study also allowed practitioners to accurately determine when pulp capping or pulp amputation was indicated.

ENDODONTIC THEORY

According to Grossman[42] biomechanical preparation of the root canal is the attainment of free access to the apical foramen, through the root canal, by mechanical means without injuring periapical tissue. Several instruments can be used to reach this goal and many instruments serve several functions. Instruments such as barbed broaches can be used to extirpate the pulp as well as foreign debris, paper points, and cotton pellets. For enlarging the canal space, instruments such as reamers and files, either hand or rotary, can be used. For obturation, instruments such as Lentulo spirals, spreaders, and root canal pluggers can greatly aid the clinician’s ability to obtain a satisfactory result.

There are many different types of instruments as well as many variations of the same instruments available to the clinician. The rate at which new instruments are being introduced makes it nearly impossible for the practicing clinician to keep up with the latest research. Therefore, it is important that the clinician is well versed in the basic principles that govern proper biomechanical preparation of the root canal. Grossman[43] suggests the following principles be observed with endodontic treatment:

1. An aseptic technique should be followed.
2. Instruments should be confined to the root canal.
3. The root canal should be entered with fine, smooth canal instruments.
4. Canals needed to be enlarged no matter what their initial size.
5. The canal should be flooded with an antiseptic solution during instrumentation.
6. The antimicrobial agent should be nonirritating to the periapical tissues.
7. A fistula requires no special treatment.
8. A negative culture should be obtained before obturation.
9. A hermetic seal of the canal must be obtained.
10. The root canal filling material should be biocompatible.
11. Drainage must be established in the case of an acute alveolar abscess.
12. Drainage may be via the root canal alone, or via an incision into the soft tissue.
13. Injection into an infected area should be avoided.
14. Not all pulpless teeth are amenable to non-surgical treatment, and some may need surgery as in the case of a cyst.

Similarly, Weine[44] summarized the principles of endodontic therapy; 1) The objective of endodontic therapy is restoration of the treated tooth to its proper form and function in the masticatory apparatus in a healthy state; 2) The three phases of this therapy include the diagnosis, the preparatory phase and the final phase of obturation. Weine states this should be done to a level as close as possible to the cementodentinal junction; 3) Another principle emphasizes the importance of debridement versus obturation. When a canal is properly prepared, any of the accepted methods of filling will likely produce a successful result; 4) The use of a rubber dam should be considered mandatory. Its use not only prevents contamination of the root canal system, but protects the patient against caustic chemicals and the swallowing of instruments and potentially harmful debris; 5) The next principle urges the clinician to keep instrumentation and filling materials completely within the canal. Even though endodontic therapy typically involves working within the tooth, it is the surrounding structures and their response that determine success or failure; 6) For the highest chance of success great emphasis should be placed on proper restoration; 7) Postoperative observation is necessary to evaluate the status of healing; 8) Case presentation should be provided for the patient to explain how root canal therapy fits into the overall treatment plan.

IRRIGATION SOLUTIONS

The ideal properties of an irrigation solution were outlined by Walton.[45] These properties include:

1. Dissolves tissue and debris.

2. Minimal to no toxicity.

3. Low surface tension.

4. Lubrication.

5. Sterilization (or at least disinfection).

6. Ability to remove the smear layer.

The most common irrigation solution used in endodontics is sodium hypochlorite.[45, 46] Full strength concentrations are 6 percent, but sodium chlorite has been diluted and used as an endodontic irrigation solution at as low as 0.5 percent. Some attractive features of sodium hypochlorite include tissue dissolution, effective disinfection, and low cost. The tissue-dissolution properties of NaOCl are lessened with a decrease in concentration.[46, 47] However, if the temperature of the solution is raised to 140 ^{o}F, the tissue dissolution property is improved. Fresh tissue is most readily dissolved followed by necrotic tissue, and fixed tissue, the least dissolvable.[47] One of the negatives associated with NaOCl is its concentration related to extreme tissue toxicity.[48]

Other agents, such as ethylenediaminetetraacetic acid (EDTA) or citric acid, are used to remove the smear layer. EDTA can be used alone or in conjunction with NaOCl for smear layer removal. When using NaOCl and EDTA together, the tissue-dissolution properties and the smear-layer removal abilities are enhanced.[49, 50]

Chlorhexidine has received considerable attention in the endodontic literature recently. Some desirable properties of CHX include its substantivity and superior activity against *E. faecalis* in concentrations of 0.2 percent to 2.0 percent.[51, 52] The interaction between bacteria and CHX results in cell lysis and coagulation of intracellular components. However, the properties of CHX are reduced in the presence of organic matter and dentine.[53]

OBTURATION

The obturation of the root canal is an important step in endodontic therapy that allows the clinician to seal the canal space with various materials. Gutmann and Witherspoon[54] stated that the purpose of obturation is to eliminate all avenues of leakage from the oral cavity or periradicular tissues into the root canal and to seal within the system any irritants that were not removed during the instrumentation phases of treatment.

Grossman[25] provided a list of properties for an ideal root canal filling material. The material should be:

1. Easily introduced.
2. Liquid or semisolid material that becomes solid.
3. Able to seal apically and laterally.
4. Able to withstand shrinkage.
5. Impermeable to moisture.
6. Bacteriostatic.
7. Non-staining.
8. Non-toxic to the periapical tissues.
9. Removed easily.
10. Sterile or sterilizable.
11. Radiopaque.

The primary obturation materials used today are gutta-percha and Resilon. Gutta-percha has the longest history and is the most widely used in the dental profession. It is derived from the dried juice of the Taban tree (*Isonandra percha*). The gutta-percha used in dentistry is a mixture of 19-percent to 22-percent gutta-percha, 59-percent to 79-percent zinc oxide, 1-percent to 17-percent heavy metal salts, and 1-percent to 4-percent waxes or resins.[55]

Resilon was developed in an attempt to achieve an adhesive bond between dentin and the filling material creating a “mono-block” obturation. It is a thermoplasticized, synthetic, polymer-based root canal filling material.[55] Resilon contains bioactive glass and radiopaque fillers that comprise approximately 65 percent of the total weight. The handling properties are similar to gutta-percha, and many of the obturation techniques used for gutta-percha can be used for Resilon as well.

TERMINATION OF THE ROOT CANAL

The success of endodontic treatment is dependent on the complete cleaning and shaping of the root canal system. Thus, it is of critical importance that the clinician accurately determines the end point of the instrumentation and know where the pulp tissue ends, and the apical tissue begins. This has led many authors to study the intricacies of the root canal system, including the apical terminus of the root. Considerable controversy exists with regard to the best location to terminate instrumentation and obturation. Davis[56] was the first to recognize that great care must be practiced when working near the apical tissue in order achieve the best outcomes of root canal treatment. Many studies since then have confirmed these early observations.[57-61]

In a study probing the etiologic factors of flare-ups, Seltzer and Naidorf[62, 63] stressed the importance of proper length control. They conclude, “Thorough debridement of root canals using files and irrigation solutions is essential for the success of endodontic treatment. However, dentinal chips, pulpal fragments, necrotic debris, irrigation solutions, and microorganisms are inevitably pushed out from the root canal into the periapical tissues during chemo-mechanical preparation. Extrusion of these elements may cause undesired consequences such as induction of inflammation and postoperative pain, and delay of healing.”

ANATOMY OF THE ROOT APEX

Grove[64] showed that the pulp tissue within the canal is different than the tissues in the foramen. He found that the apex does not contain pulpal tissue but rather it contained cementum. This dentinocemental junction that he described was the end point at which the pulpal tissue should be removed. In his conclusion he states, “A definite point should be specified in order to avoid overfilling or underfilling of root canals, and according to our present histologic knowledge, the only safe point is the dentinocemental junction.”

In contrast, Skillen[65] stated a definite junction is not found between the dentin and cementum. He commented on irregularities and that a definite junction could not exist. Many studies followed examining the anatomy of the apical structures to determine the level in which removal of pulp tissue would be optimized.

Kuttler[66] studied the apices of 268 extracted human teeth. He described a major and minor diameter and noticed a difference in regard to age. Clinically, the apical foramen and the apex of the tooth did not coincide in 68 percent of 18-to-25 year olds and 80 percent in the 55 years and older age group. Of the 18-to-25 year old groups the apical foramen deviated 0.5 mm and 0.6 mm in the 55-and-older group. Additionally the average diameter of the apical foramen was 0.5 mm in younger patients and 0.68 mm in older patients. The minor diameter or apical constriction followed an opposite pattern in that it was smaller in older patients at 0.21 mm and 0.24 mm in younger patients. The actual distance from the apical foramen to the minor constriction was 0.52 mm in younger patients and 0.66 mm in older. Based on his findings, he described the classic concept of the apical foramen as a funnel shape. He went on to explain that this portion of the canal could not be filled hermetically.

Green[67] examined the root apices of 100 mandibular molars using a stereo-binocular microscope. He found that the apical foramina in mesial roots were 0.45 mm from the anatomic apex and the average diameter was 0.52 mm. In the distal roots, the apical foramen was 0.43 mm from the anatomic apex with an average diameter of 0.64 mm. Additionally, Green discovered that in some cases, the apical foramen was 3.0 mm short of the anatomic apex in some roots.

In a follow-up study, Green[68] looked at 400 maxillary and mandibular anterior teeth using a stereomicroscope. As with Kuttler,[66] Green also described the apical foramen as funnel-shaped. He described that the diameter of the apical foramen at the apex was twice as large as its diameter 1.0 mm coronally. He found that the average distance from the apical foramen to the apex was less than in mandibular molars.

Mandibular incisors were 0.2 mm away and the average distance of all major foramina (excluding mandibular incisors) was 0.3 mm from the anatomic apex.

In the final article of his series, Green[69] conducted a study examining 700 root apices of maxillary and mandibular posterior teeth. In these teeth, the diameter of the apical foramen was one-half its size at approximately 0.75 mm from the surface opening. The major foramina opened directly on the apex only 50 percent of the time. He recognized that when a root curved, the canal always followed the curve. The average diameter of posterior teeth was 0.3 mm to 0.65 mm and the average distance from the apex was 0.3 mm to 0.5 mm.

In contrast, Burch and Hulen[70] found that 92 percent of the time the apical foramen was short of the anatomic apex. They examined 877 teeth to determine the relationship of the apical foramen to the anatomic apex. The average distance from the anatomic apex to the apical foramen in teeth that deviated was 0.59 mm. Premolars showed the greatest deviation with 0.63 mm in maxillary premolars and 0.59 mm in mandibular premolars. Canines were next with a deviation of 0.62 mm followed by incisors with a deviation of 0.49 mm in maxillary incisors and 0.46 mm in mandibular incisors.

Dummer et al.[71] challenged the traditional concept of a single apical constriction. They evaluated 270 teeth of unknown age and determined the distances of the apex to foramen and the apex to constriction. The mean apex-to-foramen distance was 0.38 mm and the mean apex to constriction distance was 0.89 mm. They found that the traditional apical constriction was not always found. He classified the apical constriction into four types: traditional single constriction, the tapering constriction, the multiconstricted, and the parallel constriction. This is in agreement with Skillen's[65] original assessment that there was not a definite dentinocemental junction. Dummer concluded that the anatomy of the apical constriction was not constant but varied among specimens.

Tamse et al.[72, 73] conducted a two-part morphological and radiographic series with regard to the apical foramen. In Part 1[72] they compared the location of the apical foramen of distal roots of mandibular first and second molars prior to extraction as determined from clinical radiographs to the same tooth after extraction. This was interpreted from a post-extraction radiograph as well as by morphological examination. He found that the apical foramen exited the distal aspect of the root the majority of the time. The canal openings were interpreted as short of the apex 65 percent of the time with the clinical radiographs. In comparison with previous studies the apical foramen was found at the anatomic apex in only 10 percent to 15 percent of cases. Using the same design, Part 2[73] of their series examined the distance between the apical foramen and the root end. They found that the morphological apex-to-foramen distance was 0.24 mm less than that of the apex to foramen distance as interpreted from clinical radiographs. Thus, the distance from the apex to foramen with clinical radiographs was closer in actuality.

Stein and Corcoran[74] studied 111 teeth from 47 patients with an age range of 26 years to 77 years. They looked at the anatomy of the root apex and the histologic changes with age. The width of the foramen and the deviation from the apex both increase with age. The mean width of the cementodentinal junction was 0.189 mm, the width of the foramen opening was 0.54 mm and the distance of the foramen opening to the cementodentinal junction was 0.724 mm. In older patients the width of cementodentinal junction was 0.211 mm, the width of the foramen opening was 0.644 mm and the distance from the foramen opening to the cementodentinal junction was 0.821 mm. The range of distances from the foramen opening to the cementodentinal junction was 0.144 mm to 2.52 mm. They postulated that the increased distance from the apical foramen to the cementodentinal junction with age was due to thickening of the apical cementum.

Olson et al.[75] evaluated the property of radiographs to determine the location of the apical foramen. They compared radiographs of extracted teeth and radiographs of teeth still embedded in cadaver sections of bone. They found that there was no difference between extracted teeth and dried jaw specimens. They did find that 30.5 percent of root canals did not exit at the anatomic apex. Radiographically, however, the tip of the instrument was at the apical foramen in 82 percent of canals.

Mizutani et al.[76] conducted an anatomical study of the apical portion of 90 maxillary cuspids and incisors. When evaluating the terminus of the root apex and apical foramen, they found the majority were displaced distolabially. In contrast, the lateral incisors were displaced distolingually. In addition, for 16.7 percent the apical foramen and root apex coincided in central incisors and cuspids, but the two matched in only 6.7 percent of lateral incisors. The distance from the root apex to the apical constriction was 0.863 mm, 0.825 mm and 1.010 mm in central incisors, lateral incisors and canines, respectively.

Gutierrez and Aguayo[77] examined 140 extracted teeth under a scanning electron microscope (SEM). They found that distances from the apical foramen opening to the anatomic apex ranged from 0.20 mm to 3.80 mm.

Using optical microscopy, Ponce and Vilar Fernandez[78] studied the cemento-dentino-canal junction, the apical constriction, and the apical foramen. They determined that these anatomic landmarks are not reliable when used as references to terminate apical preparations. They defined the cemento-dentino-canal junction as the point where the cementum meets the dentinal canal, and where the cemental cone extends from the junction. They found that the diameter of the cemento-dentino-canal junction was .35 mm in canines, .29 mm in lateral incisors and .30 mm in central incisors. A great amount of variability was found in their measurements of the extension of cementum into the root canal.

Olson et al.[29] examined the longitudinal position of the apical constriction in human maxillary central incisors. They found that over 70 percent of teeth deviated more than 0.1 mm in the longitudinal position of the apical constriction. The average was 0.17 mm with a maximum of 0.39 mm. They concluded that when using the apical constriction as a reference point, the working length does not end in an apical constriction point, but in an apical constriction zone. The authors pointed out that although this has implications in determining optimal working length, it may not be clinically relevant as we are only able to work clinically in 0.5 mm increments. With improvement of electronic apex locators, the results of this study may be more relevant in the future.

CLINICAL EFFECTS OF APICAL TERMINATION

When examining his records, Blayney[79] recognized that his treatment success resulted from filling the root canal flush to the apex. He went on to say that filling to within 1 mm of the apex is preferred to overfilling. Later, Blayney[80] added that chemicals, instruments, or excess filling materials should not penetrate the foramen. To prevent this, the apical constriction should remain unchanged so it can act as a natural barrier to extrusion of materials and instruments. When foreign substances are introduced into a root canal, they can be extruded through the apical foramen. These substances can act as foreign bodies or mechanical irritants inducing inflammation as stated by Hopewell-Smith.[81]

Early on, Coolidge,[82] had recognized the variability found with the dentinocemental junction. He argued that success does not depend on amputating the pulp to any certain point, but rather somewhere close to the apical foramen. This was based on the idea that success is dependent on maintaining the normal functional relation of tissues at the root apex.

When filling a canal, the final result can fall into one of four categories as outlined by Kuttler:[83] 1) overfilling, 2) underfilling or short of the cementodentinal junction, 3) exact or foraminal filling otherwise known as flush with apex, or 4) cementinodentinal junction filling, in which the operator is able to fill exactly to the cementodentinal junction. He went on to outline and define different filling techniques and offered a definition for the ideal root filling: “One which thoroughly fills the dentinal portion of the canal, seals it at the cementodentinal junction and stimulates the obliteration of the cemental portion of the canal with new cementum.” This is not possible when root filling materials are extruded past the apex. He further states that this can result in the deposition of scar tissue incapable of forming new cementum.

In an experiment involving overfilling in mesial roots of lower molars in rats, Erausquin et al.[84] found that extensive damage occurred when root fillings were placed past the apex. He found that necrosis of the periodontal ligament was inevitable, which in turn provoked necrosis of the cementum and alveolar bone adjacent to the filling materials. In general, the periodontal ligament was regenerated within 7 days, but repair of the bone and cementum took much longer to occur. This necrosis was attributed to infarction as a result of obliteration of the vessels in the area by the filling materials. Following the same rats histologically, Murazabal[85] examined the reaction of the surrounding tissues to the foreign materials. In general, if the material hardened, the body tended to encapsulate the mass. On the other hand, if the material did not harden, it tended to disintegrate into the periapical tissues provoking a more severe tissue reaction and lessened the time needed for resorption.

Seltzer et al.[60] instrumented teeth short of the apex as well as teeth beyond the apex. They examined histologically the response in the PDL and surrounding bone for up to one year. They found that granulomas formed in teeth that were instrumented beyond the apices, and these granulomas persisted during the time frame of their study.

A similar study by Seltzer et al.[86] studied the reaction of teeth that were either overfilled or underfilled in monkeys with a follow-up period of 14 days and 270 days. These teeth were free of pulpal inflammation; therefore, any presence of an adverse reaction was directly related to the endodontic procedures performed.[61] They found a greater preponderance of epithelial proliferation in overfilled teeth. The inflammatory infiltration seemed to subside over time in roots that were filled short of the apex. Epithelial proliferation does not necessarily equate with treatment failure, but they did find that the presence of foreign material delays, not prevents repair. To achieve the best results, they advocated that treatment center on preserving the vitality of the apical pulp stump.

Seltzer et al.[87] also looked at the reaction of human and animal teeth for up to six months and one year, respectively. The root canals were instrumented 2 mm to 10 mm beyond the apices and then filled either beyond or short of the apex. They found a more violent, persistent reaction when instrumentation was beyond the apex and filled long. In general, if the root fillings were short of the apex, this inflammation subsided within 3 months, and complete repair was eventually seen. However, the overfilled teeth showed persistent chronic inflammatory changes including epithelial proliferation and cyst formation. In canals packed with dentin filings, periapical inflammation was prevented or minimized.

In a study involving dogs, Davis et al.[88] instrumented teeth widely to simulate hollow tubes and compared these teeth with conventionally prepared and filled teeth. They found that teeth that were widely prepared but filled short compared favorably to those that were prepared and filled conventionally. In contrast, that canals that were overfilled were the least successful.

Bergenholtz et al.[89] conducted a clinical study in 556 canals originally treated by dental students were retreated. They found that 35 percent of the teeth indicated for retreatment were classified as overfilled. Fifty-two percent of those cases presented with large periapical radiolucencies. Regardless of the indication for retreatment, there was a much higher incidence of periapical lesions with overfilled teeth. There was also an adverse affect on the incidence of healing in overfilled teeth after retreatment.

Swartz et al.[90] examined their records from the previous 20 years and recorded the radiographic success based on the level of the root filling. They reported an overall success rate of 89.66 percent, but in canals that were overfilled, the success dropped to 63.41 percent. The canals that were underfilled had a success rate of 91.9 percent, and those that were filled flush with the apex, 89.77 percent. They did not define underfills but noted a “four times higher failure rate in overfilled canals.”

Seltzer et al.[62] described why flare-ups occur in previously asymptomatic teeth with chronic granulomatous lesions. They explained that when the body adapts to the inflammatory lesion and the irritant, chronic inflammation absent of perceptible swelling or pain is the result. When instrumentation or obturation results in the extrusion of foreign debris into the lesion, liquefaction necrosis can occur causing purulence. When this reaction is subjected to pressure from the surrounding tissues, severe pain and swelling can result.

Matsumota et al.[91] correlated the level of apical filling to the clinical and radiographic success in a study of 223 root-canal-treated teeth. Success was defined as 1) the absence clinical symptoms, 2) the absence of a periapical radiolucency before or after treatment after a certain period of time, and 3) the presence of a periapical radiolucency before treatment that had reduced in size following treatment. The follow-up period ranged from two to three years after obturation. They found that overextended teeth were successful only 40 percent of the time. Teeth that were flush to 0.4 mm underextended had a 61.5 percent success rate, and 0.5 mm to 1.0 mm, an 88 percent success rate. The best results were afforded to teeth that were 1.1 mm to 2.0 mm underextended at 100 percent success rate.

In another article concerning the various factors that influence the success of treatment, Sjogren et al.[92] also found that overfilled teeth suffered from a lower success rate at 76 percent. This involved 635 teeth over an eight-to-10-year period. They had an overall success rate of 91 percent, but if a previous lesion existed, success was in only 86 percent. In teeth that were not instrumented to total length or filled 2 mm short of the apex, the success rate was 69 percent and 68 percent, respectively. In contrast to Bergenholtz,[89] the level of root filling had no affect on success. They concluded that, “The outcome of treatment for roots with pulp necrosis and apical periodontitis was dependent on the level of the root filling in relation to the root apex. The prognosis for treatment of nonvital teeth with periapical lesions was as good as that for vital teeth when the instrumentation and filling of the root canal could be carried out to an optimal level.”

In a clinical study of 36 patients aged 16 years to 65 years, Riccuci and Langeland[93] histologically examined the response of the intracanal pulp tissue. This included tissue in the lateral canals, apical ramifications, and periapical tissues in teeth that were instrumented or filled short of or beyond the apical constriction. Biopsies were obtained of the apex with surrounding periapical tissues over a period of 18 days to 10 years and 8 months. They found that overfilling cases demonstrated a severe inflammatory reaction and periapical necrosis. Also, inflammation was observed around extruded sealer. In healed cases with previous periapical radiolucencies, a vital pulp stump was present. They concluded, “The best prognosis for root canal treatment is adequate instrumentation and homogenous obturation to the apical constriction." In their view, the worst prognosis for root canal treatment is instrumentation and filling beyond the apical constriction. The second worst is obturation more than 2 mm short of the apical constriction, combined with poor instrumentation and obturation.

When the apical constriction is disrupted, the amount of debris extruded would be greater. Tinaz et al.[94] demonstrated this when they compared the amount of apical extrusion during manual instrumentation and compared with engine driven rotary files. Both techniques showed a greater amount of debris extrusion when the diameter of apical patency was equivalent to a 30 file versus a 15 file.

DENTAL RADIOGRAPHY

On November 8, 1895, Wilhelm Conrad Roentgen discovered the x-ray.[95] He noticed the property of these x-rays to penetrate substances and act on ordinary photographic emulsions. Professor Roentgen termed these rays as x-rays, but as an ode to Professor Roentgen, others termed them roentgen rays. Some of the early terms for the actual pictures themselves include skiagraph, skiagram, radiograph and radiogram. Skiagraph gained acceptance early on due to its Greek translation: shadow picture.[27] In order to describe the image produced on the films, R. Otelengui provided descriptive terms related to the structures of interest resistant to x-ray passage. A radiopaque presentation was described as a structure that was impervious to the x-ray; radioparent described a structure that allowed passage of the x-ray freely, and radiolucent described a structure that offered some resistance to the passage of the x-ray.[27]

A year after Roentgen announced his discovery, Otto Walkoff of Germany made the first dental radiograph in 1896. The diagnostic quality of the radiograph was questionable, however. The time to expose these original films lasted from five to 15 minutes and another 30 to 60 minutes to develop. In 1899 Edward Kells introduced the first endodontic application of dental radiography by placing a lead wire inside an immature traumatized tooth to see if it was out of the apex.[27] The first dental radiographs to be taken in the US were made by Kells, Blum and Rollins.[96]

Kodak produced the first prepackaged dental x-ray film in 1913, which consisted of a waxed paper packet containing two pieces of single-coated film. At this time, the film was photographic film, and it wasn't until 1919 that Kodak produced the first dental x-ray film designed for direct exposure by x-rays. This packet contained thin sheets of lead to reduce backscatter radiation.[96]

Over time, the speed of the films has increased thus reducing radiation required for exposure. The F-speed films that were introduced in 2000 require 1/60 of the radiation required for the film available in 1919.[96]

The x-ray units themselves also underwent considerable advancements over the years. The original vacuum tube known as the "Crookes Tube" was invented by William Crookes in 1869.[27] Roentgen's discovery of x-rays prompted many physicists to begin experimenting with the Crookes tube. Early problems with these vacuums included the presence of air. This eventually led to the introduction of the Queen's tube, which possessed the capability of automatic regulation. A bulb would be heated off and on, depending on the status of the vacuum.[27] One of the problems with the Queen tube was its propensity to elicit extreme heat. Advancements to solve this problem was to cool the tube with water, oil, air, or various other gases. Eventually, the Coolidge tube was introduced in 1913 by General Electric based on the findings of William David Coolidge. The Coolidge tube was based on the property to make tungsten ductile.[96] "Modern x-ray tubes are sometimes referred to as Coolidge tubes."[96]

EXPOSURE VARIABLES

With the increasing use of radiography in the field of dentistry much effort was put forth to determine optimal conditions to enhance the diagnostic quality of dental images. Selman[97] states that the four factors that influence the diagnostic quality of a radiograph are distortion, definition, density, and contrast. Distortion is present in all radiographs because a radiograph is a two-dimensional representation of a three-dimensional object. A distortion of size results from varying degrees of magnification due to varying distances of different parts of the object from the film. One of the factors that influence distortion is angulation, either vertical or horizontal.[98] Vertical angulation is the projection of x-rays in a vertical plane. Horizontal angulation is sometimes referred to as directional angulation[98] and it is the projection of x-rays in a horizontal plane. Vertical angulation creates more obvious distortions than the horizontal type. These distortions are detected as foreshortening or elongation of the shadow images.[98]

Geometric unsharpness, or definition, is the term that indicates the degree of "diffusion of detail" to be found in all radiographs.[99] This phenomenon is controlled by focal spot-film distance, object-film distance, and the size of the focal spot used in the x-ray tube. The focal spot-film distance is the distance between the focal spot of the x-ray tube and the film packet. The object-film distance is the distance between the film and the object or objects that cast a shadow on the film. The focal spot of the x-ray tube is that area on the anode or target bombarded by the stream of electrons.[99] Since structures closer to the film will show a minimum diffusion of detail and structure further away showing increased magnification and adumbration, it is possible to minimize the degree of diffusion by increasing the focal spot-film distance and changing the placement of the film. With the focal spot moved further from the film and object, the paths of x-rays are more nearly parallel. This makes it possible to move the film further from the object without discernable adumbration.[99] The smaller the focal spot, the more concentrated the diverging x-rays and superimposed shadows. This results in a sharper and better defined radiographic image if all other factors remain constant.[99] To maximize the degree of definition of the image on the film, the object-film distance must be minimized. If this is not easily accomplished, then one must increase the distance between the focal spot and film to minimize enlargement and prevent adumbration.[99, 100]

Updegrave[100] suggested the optimum focal spot-film distance was 8 inches. He noted that utilizing the paralleling technique at this distance would result in a distorted image. To correct this, he advocated combining an extension cone technique with the paralleling technique to produce a radiograph of "true anatomic size possessing maximum sharpness and detail."[100] One of the disadvantages was realized when applying the time-distance law. The time-distance law states that the time required for a given exposure is directly proportional to the square of the anode-film distance. A basic increase from 8 inches to 16 inches would require an exposure of four times greater. In order to circumvent this increase in exposure, Updegrave suggested using faster films and with the introduction of digital sensors, the increased exposure time needed would be negligible.[100]

In the same study by Updegrave,[100] he describes density and contrast. “Density of a radiograph is controlled by the quantity of radiation that reaches the film, which is governed by the amount of current in milliamperes flowing through the tube for a definite period of time in seconds (s). This time-milliamperege combination is known as milliampere-seconds (mAs) and is computed by multiplying the time by the milliamperes.”[100]

He goes on to describe contrast, “Contrast in the radiograph is dependent on the inherent qualities of the film and developer plus those changes produced through the medium kilovoltage. Since the film and developer are constant the only variable that can be controlled by the dentist is kilovoltage.”[100] Low kilovoltage will produce high contrast images whereas high kilovoltage will produce low contrast images. Lower contrast films produce images that are of greater detail. However, when adjusting kilovoltage, it is necessary to adjust the milliampere-seconds as well. Adequate kilovoltage must be employed to penetrate the object and adjustment of the milliampere-seconds cannot compensate for this.[100]

A right-angle paralleling technique was described by Vande Voorde and Bjorndahl[101] in their study of pre-extraction tooth length radiographs. They exposed 101 anterior teeth using the right-angle paralleling technique. Once the teeth were extracted, they accessed and determined the location of the apical constriction via tactile sense. They measured and then passed the file through the apex and measured again. They found that the length of the tooth from the incisal edge to the apex was 1.2

mm less than the diagnostic radiograph. This is a 5.4 percent magnification of the actual tooth length. The apical foramen was an average of 0.3 mm from the actual root tip of the extracted teeth. The apical constriction was 1.1 mm from the actual root tip and 0.8 mm from the apical foramen. They concluded that the right-angle paralleling technique is consistent enough in predetermining the tooth's working length.

Updegrave[100] recognized that although the bisecting angle technique can minimize longitudinal distortion, a dimensional distortion will be produced. This distortion is accentuated as the angle is increased and is often seen when the bisecting angle technique is employed.[102] So every effort should be made to "approach parallelism between the film plane and the objects being radiographed." To simplify this Updegrave[102] introduced an apparatus in which the film holder was connected to a bar that was perpendicular to the film surface. This allowed the operator to align the cone along this axis.

Contrast affects image resolution and kVp affects contrast. Therefore, kVp must affect resolution. Milliampere-seconds and kVp affect film density, and the film density is used as a measure of contrast. Thunthy and Manson-Hing[103] studied the manner in which mAs, kVp, film density, and contrast affect image resolution. Resolution is defined as the smallest distance between objects that can be detected in the image by the human eyes. In their experiment they altered kVp and mAs and controlled for other variables such as type and speed of film, quantum mottle, film graininess, and film processing that can affect image resolution. They kept the anode-film distance constant at 16 inches as suggested by Updegrave.[100] They used an x-ray test pattern to detect the number of line pairs per millimeter (lp/mm) on the image. The kVp was adjusted from

50 kVp to 95 kVp and the mAs were adjusted from 1.00 mAs to 8.00 mAs. They found that "When the film density was kept constant, (1) the higher the kVp, the lower the resolution; (2) the higher the kVp, the lower the image contrast percentage; (3) the higher the mAs, the higher the resolution; and (4) the higher the mAs, the higher the image contrast percentage." However, when the film density is not held constant they found, "(1) the higher the kVp, the lower the resolution; (2) the higher the kVp, the lower the image contrast percentage; (3) the higher the resolution, the higher is the image contrast percentage; (4) the higher the film density, the lower is the resolution; and (5) negligible correlations were found for mAs and resolution and for mAs and image contrast percentage."[103]

Based on these principles, several authors have examined the affects of altering certain exposure variables on interpreting dental films. From the early history of dental radiography, it was recognized that the time needed to produce a diagnostic quality image was too long. Since then, great effort has been made to reduce the amount of time needed and thus the dosage of x-radiation exposure to the patient. The speed of a film is defined as the reciprocal of exposure (in roentgens) required to produce a density of 1.0 above base and fog densities under conditions of exposure and processing.[104] Using the fastest film possible produces the least radiation exposure to the patient.[105]

Although many of the radiographic techniques and exposure parameters are based on experiments using step wedges of various materials, it is difficult to correlate this with clinical practice. Webber et al.[106] recognized this and conducted a study using a human skull to develop an objective method of determining diagnostic quality of posterior bitewings as well as to determine the effect of clinically accepted exposure parameters on diagnostic quality. They further analyzed the aspect of the operators preferences and how it correlated to “valid measurements of diagnostic quality.” The images were exposed at 65 kVp and 90 kVp and a focal film distance of 17 inches (43 cm). This is similar to the distance of 16 cm as suggested by Updegrave.[100] They studied the ability to detect carious lesions, some already present and some created by the investigators. They found that more errors were observed at a 90 kVp versus 65 kVp. They also found the subjective preferences of the examining dentist had little correlation to the measured ability to diagnose proximal lesions.

Kaffe et al.[104] studied the speed and quality of the resulting image (sharpness, resolution, and contrast) when comparing Ektaspeed and Ultraspeed films. They found that with the use of the faster Ektaspeed film, the exposure time was reduced 50 percent while still allowing no loss of contrast or resolution. Additionally, base and fog production was no higher than Ultraspeed films.

In contrast, Kleier[107] found that viewers preferred Ultraspeed to Ektaspeed. He compared image quality (detail and definition), contrast, and rater satisfaction when using lamina dura, periodontal ligament space, alveolar bone trabecular pattern, apical pathosis, pulp chamber, and root canal space as major radiographic landmarks.

Jarvis et al.[108] compared the image quality produced on individual films within a double film packet using Ultraspeed films. They made this comparison by exposing the films against a step-wedge, a dried skull, and clinical endodontic therapy. They found that the films closer to the object and thus radiation source had superior image quality and should be used for radiographic interpretation. They found no difference between the *in vitro* and *in vivo* model thus justifying *in vitro* studies if the variables are closely controlled.

Ellingsen et al.[10] compared D-speed and E-speed films with regard to working length determination using size 8 and size 10 files. They found the file tips were accurately determined on all D and E-speed films when using magnification. However, D-speed films were judged better than E-speed films 90 percent of the time. Part 2[11] evaluated this difference in an *in vivo* model. They found that D-speed films were superior to E-speed films 100 percent of the time with regard to recognition of small file tips. D-speed films were accurate 95 percent of the time compared with 70 percent for E-speed films.

Kappler et al.[12] studied the diagnostic accuracy of storage phosphor plates when the tube potential setting and milliampere setting were changed. Tube potential settings varied at 60 kVp and 90 kVp and the milliampere settings were reduced at an unchanged tube potential setting. Images of periapical lesions using F-speed films and storage phosphor plates were compared. They found that intraoral films and storage phosphor plates were of equal quality regardless of whether a 60 kV or 90 kV exposure was used.

McDonnell and Price[109] compared the image quality Sens-A-Ray digital imaging system to D and E speed films using an aluminum foil test object. Observers were asked to identify patterns of holes in the test object. They found that D and E speed films were significantly better when compared with the Sens-A-Ray. There was no significant difference between the D and E speed films.

Velders et al.[13] evaluated the effect of dose reduction when comparing Ektaspeed films to Sidexis (Siemens, Bensheim, Germany) and Digora (Soredex, Helsinki, Finland). They found with size 20 and size 25 files, the digital images were comparable to film when the exposure was reduced to 6 percent (94 percent dose reduction) of that used for Ektaspeed films. Size 15 and size 10 files showed shorter lengths on digital images than those on film. Borg and Grondahl[110] compared the subjective image quality, detectability of small mass differences and burn-out effects of two charged-couple devices and one phosphor system. They found that storage phosphor systems produced higher image quality over wider exposure ranges than either film or charge-couple device systems. In 1999, Borg[111] compared solid-state and photo-stimulable phosphor systems with regard to physical and psychophysical performance, subjective image quality, and the influence of image processing. Both solid-state and phosphor systems showed an increase in noise with increased exposure. They also found that lower doses were required for solid-state systems to reach their highest contrast index compared with phosphor systems. When they compared subjective image quality, all systems produced diagnostically acceptable images, but the photo-stimulable phosphor systems had a much wider range than solid-state systems.

Berkhout et al.[14] compared the quality of digital images and conventional film with regards to exposure time. The range of exposure times that produced diagnostically acceptable images for Ektaspeed Plus film was 0.23 seconds (s) to 1.02 s with a preferred exposure time of 0.52 s. The preferred time for solid-state systems was 0.13 s for Sirona and 0.35 s for MPDx with a narrow exposure range. The phosphor plate systems required a higher exposure time for preferred radiographs with 1.21 s for Digora and 1.16 s for Gendex DenOptix with a wide exposure range. They concluded that regardless of the digital system used, less exposure time was required for diagnostically acceptable images. They also made the observation that solid-state systems alert the clinician when too lengthy an exposure time is used by reduced image quality. However, phosphor-plate systems allow a wide range of exposure times to produce a diagnostically acceptable image, which could unnecessarily expose the patient to a higher dose of radiation.

De Almeida et al.[15] compared the image quality of four direct digital radiographic systems. They varied kVp from 60 to 70, maintained milliamperage at 10 mA and varied the exposure pulses at 3, 5, 8, 12, 24 and 48 pulses. They compared images of step-wedge as well as images of maxillary incisors and mandibular molars in dry skulls. They concluded that charge coupled devices produced a higher percentage of acceptable images at lower radiation doses. However, the storage phosphor systems allowed a larger range of exposure settings to produce acceptable images.

Sheaffer et al.[17] assessed film speed and density and its effects on endodontic working length determination and on perceived radiographic image quality. They concluded that regardless of film speed, underexposed radiographs are perceived as inferior to slightly overexposed radiographs for endodontic file length assessment.

Van Dis et al.[112] evaluated a prototype video imaging system in its property to detect radiographic detail on nonscreen film versus conventional viewing methods. The system allowed the image to be altered with respect to contrast, overall brightness or density, and regional brightness. These images were compared with Kodak Ultraspeed at 70 kVp and 90 kVp and Kodak Ektaspeed at 70 kVp and 90 kVp. They found that the viewing method, kilovoltage, and optical density all influenced the interpretation of the images. The ability to detect detail on light images was enhanced on the real-time analog enhancing device when compared with the conventional radiographs on a viewbox. They attributed this to the increased amount of light transmitted through a light image on a viewbox, which thereby strained the eyes. When a bright image is viewed on a monitor, the image can be darkened, lessening the visual strain caused by excessive light. Alternatively, darker images present more detail on conventional radiographs on a viewbox, but less detail when using the real-time analog enhancing device.

Fujita et al.[113] digitally processed periapical radiographs using an image-processing system. They found that more noise and artifacts were present and affected the intepretation of the images. However, low-contrast radiographs were altered in a way that improved their interpretability. They also pointed out that some information was lost in the process of converting the conventional radiograph to a digitized image.

Wenzel et al.[114] compared the accuracy of conventional film radiographs, digitized radiographs, and radiovisiography for the detection of occlusal dentinal caries. They found that when contrast enhancement features were used with the radiovisiography, the accuracy in detection of occlusal carious lesion was better than or equal to the accuracy of conventional radiographs.

Regardless of whether ideal exposure parameters are achieved, the operator must be able to view the films and images under optimum viewing conditions. Optimal viewing conditions are produced in a situation in which ambient light is reduced, a view box masked of extraneous light, magnification utilized, and films mounted in an opaque mount.[112]

RADIATION SAFETY

Since the early years of dental and medical radiography it was recognized that x-radiation poses a certain risk to not only the subject but also the person exposing the films. Several studies have been conducted over the years to estimate this proposed risk. In 1990 the International Commission on Radiological Protection (ICRP) determined that the effective dose was the preferred unit of measure for comparing radiographic examinations.[115] Effective dose was created to provide a dose quantity that could pose a detriment to health due to exposure to low doses of ionizing radiation.

Greer[116] examined the absorbed dose of radiation in various aspects of the head and neck including the body of the mandible, submandibular areas, base of the tongue, sella turcica and in the orbits. Only the submandibular, base of the tongue, and sella turcica showed significant differences as the KVp was increased, with increased absorbed dose as KVp was increased.

Danforth and Torabinejad[117] estimated the relative risk of adverse effects of radiation exposure during endodontic radiography. When using 90 KVp, the risk of leukemia, thyroid gland neoplasia, or salivary gland neoplasia is 1 in 7.69 million, 667,000, and 1.35 million respectively. Using 70 KVp only slightly reduced these risks. Patients would have to be subjected to 10,900 endodontic radiographic surveys to receive a threshold dose to the eyes significant enough to produce cataract changes.

Kaeppler et al.[118] set out to determine the effectiveness of a dose reduction in intraoral radiography by either using digital radiography or increasing tube potential setting and decreasing milliampere seconds. They used the Alderson phantom to simulate patient tissue and calculated the entrance dose and exit dose. Storage phosphor plates allowed a 52 percent dose reduction compared with film. They concluded that a significant dose reduction was better achieved by using more sensitive films or by using digital radiography. This allows the operator to maintain a low tube potential and a reduction in milliampere seconds setting.

In 2007, the ICRP updated the method of calculating the effective dose based on the latest available information on radiation exposure. Certain tissues received adjusted weighting factors to accurately assess their risk to exposure. Salivary glands, oral mucosa, and extrathoracic airway tissues were included for the first time in the weighting scheme. They found that “the estimate of detriment from dental radiography is substantively greater according to the 2007 ICRP method compared to the 1990 method.”[119] In fact, the risk associated with dental radiography was 32 percent to 422 percent higher than the estimates from the 1990 ICRP guidelines. Salivary glands and oral mucosa received the highest equivalent doses of all tissues examined. Full mouth series with D-speed film and round collimation resulted in the largest effective dose.[119] Based on their findings the ICRP is recommending the following to reduce patient exposure: (1) F-speed film, PSP and charge-coupled device (CCD) sensors should be used rather than E-speed film; (2) Rectangular collimation should be used for periapical and bitewing radiographs, and (3) Clinical examination and patient needs should dictate radiographic selection.

DIGITAL RADIOGRAPHY

In 1987 a French dentist named Francis Mouyen introduced the first direct digital intra-oral radiography system for dentistry at the first meeting of dental and maxillofacial radiology in Geneva. This system would eventually be known as RadioVisioGraphy.[120] Since then, several authors have studied the merits and demerits of this new system.[5-7, 11, 114, 121-125] This early system used a black and white, TV-quality monitor to display the image. This was due to the fact that in the 1980s, the monitor resolution of personal computers displayed only a limited number of gray shades via a VGA graphic card. Once the S-VGA graphic cards were introduced, computer monitors were then used to display the images. This allowed a display of 64 of its 256 shades of gray at a time.[126] As advancements in computer software were made, image enhancement such as contrast, brightness, and gamma curve functions were made possible.

The first stimulable phosphor system, Digora, was introduced for dental imaging in 1994. This technology had been used for years in medical radiography.[127] These phosphor plates had physical characteristics of film but were read by a scanner following exposure.

Digital radiography has been gaining in popularity among general dentists and specialists alike. Although the following quote by Updegrave[100] was referring to the paralleling extension-cone technique, the principles hold true for digital radiography: “Before a new technique is accepted, it must first be made known, it must prove practical, it must produce improved results, additional equipment must be obtainable, and improvement of results must warrant the effort and expense.”

Hellen-Halme et al.[128] conducted a survey of 139 general dentists in Sweden. The purpose of the survey was to evaluate how digital radiography was used in general dental practices. Sixty-five percent of dentists experienced several problems and 40 percent utilized some form of quality control. They state the computer monitor was one of the weaker links in digital radiography. Adjustments in the brightness and contrast settings of the monitor as well as lower ambient light allowed better diagnosis of radiographic caries.

The charged coupled device was first introduced in the 1960s. These are silicon solid state devices that are arrays of light or x-ray sensitive pixels.[129] The pixels are small boxes in which electrons produced by x-ray or light photons are deposited. The electrons that are deposited are a direct result of the interaction with photon or light energy.

In 1970 Savara et al.[130] described the use of intraoral fluoroscopy. This was the first intraoral use of a phosphor screen in dental radiography. They attached a thin phosphor screen to a fiber optic bundle. When the x-radiation hits the phosphor screen, it causes an emission of light. The fiber optic bundle transmitted the visible image produced on the phosphor screen. This traveled through an image intensifier, and the image was recorded on a television camera, stored on a video disc recorder, and eventually displayed on a TV display monitor. This was an early prototype for dental digital radiography. The benefit of this system was not only near real-time images, but a significant decrease in the amount of radiation needed to produce an image.

The process of charge coupling involves the transferring of accumulated light or x-ray photons from one electron well to the next. This occurs in a sequential order that eventually leads to a readout amplifier.[129] An electron current can be conducted in silicon if the electrons in the silicon are excited. The nature of silicon allows this to occur as each atom of silicon is covalently bound to another. The breaking of this bond occurs with excitation of light energy greater than 1.1 v.[129]

The energy of the incoming light dictates the depth in which the silicon is penetrated.[129] High energy particles, x-rays, and cosmic rays have the potential to break thousands of bonds. When these bonds are broken, a potential well is created as the charge produced is stored. In order to contain this charge within the wells, a layer of silicon dioxide covers the surface. This layer contains the negatively charged particles by forming a positively charged barrier. Up to 1 million electrons can be stored in these potential wells.[129]

Silicon crystals can be sliced into very thin sheets. Typically, these devices contain wafers that are only 500 μm in thickness.[129] Thousands of potential wells are created when the silicon dioxide and gate structures are arranged into a matrix. These wells are arranged in a particular sequence so that when light or x-ray photons penetrate they propagate from well to well in one direction. These charge packets can be transferred thousands of times with very little degradation of charge.

The two-dimensional, charge-coupled device imagers consist of many potential wells arranged in columns. The wells contained within each column function independently of each other in charge storage function. One column is representative of single pixels or picture elements. A pixel consists of three gates in which an electrode rests on top of a silicon chip.[129] Two gates act to shift charge while the other gathers light. Once a pixel traps electrons from the incoming photons, the charge can be transferred to pixels up the column while picking up charge from pixels down the column.[129] The parallel register is the combination of the stored photons of energy in the charge-coupled device within the pixels.

On the other hand, the serial register is a one-dimensional CCD and is located adjacent to the parallel register. The role of the serial register is realized in the CCD readout. The charged pixels from the parallel register are shifted one row at a time toward the serial register. The second electrode gate structure in each pixel is given a positive charge. This charge is equal to the first electrode gate creating a potential well under the second electrode gate. Once the charge is high enough on the second electrode gate, electrons from the first potential well are transferred. This creates a potential of zero in the first well since all electrons were just transferred. Now, the third gate’s potential is increased and the potential of the second gate is decreased, allowing for further propagation of the charge. Once the charge reaches the serial register, the row of charged packets progress toward an output amplifier. The signals produced by the output amplifier are proportional to the charge in each packet. As these charged packets are shifted from the parallel register to the serial register, the empty rows without a charge are available for new exposure. This electric charge is read as a voltage. These readings are transferred to an analog-to-digital converter. Each pixel is assigned a number, and this information is stored in an image file in the computer. This allows the user to apply mathematical operations to alter the pixel values; this is known as image processing.[131] Once this is digitized, the signals are converted into analog signals for viewing on a monitor.[132]

The image output of charge-coupled devices is limited by the sensors' property to accumulate and measure the total photocharge released at each pixel during the exposure time. Pixel requirements include charge-storage capacitance and high dark resistance.[133] The efficiency of CCD imaging is measured by power of resolution, signal-to-noise ratio of the output signal, and quantum efficiency of the photoreceptor.[129]

Full frame, frame transfer, and interline transfer are the three configurations of CCDs used for electronic imaging.[129] Full frame transfer CCD utilizes a shutter to control exposure. The frame transfer is composed of two parallel CCDs that can create a continuous system. The interline transfer CCD is very similar to full frame CCD, but interline has less image clarity. It is composed of a parallel register subdivided into sections and functions much like a full-frame CCD. The techniques using CCD are applied in several areas including astronomy, physics, biochemical spectroscopy, picture archiving, and communications systems, video cameras, and high-definition television.[134]

The first generation of intraoral solid-state sensors used CCD technology. Newer systems have advantages over these initial products in that they have a smaller active area, less bulk, and lower absorption and conversion efficiency of incident radiation.[132]

Complementary metal oxide semiconductors (CMOS) are used similarly for image acquisition. These use less power and are less expensive to manufacture. The circuitry of CMOS is built directly into the sensor, which results in more fixed pattern noise and a smaller active area.[132]

When comparing resolution between digital images and films, one must evaluate spatial resolution and dynamic range. Spatial resolution is expressed in terms of line pairs per millimeter (lp/mm). Film has a resolution of 16 lp/mm and is improved to 20 lp/mm to 24 lp/mm with magnification. Solid-state sensors have similar, and in some cases, higher spatial resolution. Even though the spatial resolution is higher, it generally does not influence diagnostic efficiency.[132] Dynamic range refers to the "range of exposures that the sensor would tolerate and still produce a diagnostically acceptable image."[132]

Giger and Doi[135] evaluated the effects of pixel size on the signal-to-noise ratio as well as to threshold contrast. Threshold contrast is the contrast needed to detect an object or pattern. To measure this parameter, they produced images of square objects of 0.1 mm and 20 mm sizes. They found that the threshold contrasts were similar for pixel sizes of 0.1 mm and 0.2 mm. However, when the pixel sizes increased beyond 0.2 mm, the threshold contrasts increased dramatically.

Kassebaum et al.[136] examined the process of digitizing dental radiographs and the potential effects on image quality. They used the Kodak Ektascan Image Transmission System to digitize periapical, bitewing, and panoramic dental radiographs. The examiners compared specified pathologic conditions on the digitized films to the original films. They concluded that the original radiographs provided the best diagnostic accuracy regardless of the imaging modality. In regard to the digitized films, the accuracy was improved with decreasing pixel size. They stated that a 0.2 mm pixel size produced the best diagnostic image.

Webber and Stark[137] were the first to demonstrate superiority in diagnostic results with electronic processing of radiographic information when compared with original radiographs. They compared original radiographs to several “preprossessed” (altered) images and then tasked examiners to evaluate the images for relevant information. They explain that when the human eye is tasked to interpret a complex visual situation, it is affected by “noise” created by familiar visual stimuli. When the eye is presented with unfamiliar stimuli, it reacts by “separating desired from irrelevant information when random noise can be neglected.” Thus, in situations where an image is altered by contrast enhancement, it renders “task-related elements of an image more discrete and detailed in appearance.” This alteration reduced the noise in the image by making sharper edges and rendering the information more discrete and detailed.

Southard[138] demonstrated that dental radiographs can be effectively scanned and stored digitally on a laser optical disk memory recorder. They scanned several dental and medical radiographic images and asked observers to evaluate the original and digital images independently. All examiners judged the digital images to be of diagnostic quality, and only one observer judged the digital images to be slightly inferior to the original radiographs.

Borg et al.[16] compared the subjective image quality of two solid-state detectors (Visualix-1 and 2 from Gendex dental systems), computed dental radiography (CDR) and CDR Active Pixel Sensor (APS from Schick) and two photostimulable phosphor (PSP) systems (Digora and DenOptix). They found that both the CDR systems had the highest quality, but at the narrowest exposure range. The solid-state detectors had the lowest scores and the PSP systems produced diagnostically acceptable images at both low and high exposure ranges. For image enhancement, there was no improvement in the images with the exception of solid-state systems at very low exposures.

In a recent study by Farman and Farman,[139] they reviewed the most commonly used solid-state receptors. They provided support to the view that most sensors performed comparably with film. “The Kodak 6000 CMOS-based sensor and the RVG-ui (CCD) displayed the highest spatial resolution of 20 line pairs/mm (same as Kodak F-speed Insight film).” In regard to contrast resolution, Visualix HDI, RVG-ui, Kodak 5000, Kodak 6000, and Schick CDR were the best. The PSP sensors as well as the Kodak 6000 and Kodak 5000 showed the widest latitude.

APPLICATIONS OF THREE-DIMENSIONAL IMAGING

Although three-dimensional imaging in endodontics is primarily used for research purposes, more clinical applications will be found as bit-depth and spatial resolution of images increase. Cone-beam CT (CBCT) is being explored further for applications in endodontics. However, if CBCT is used, clinically board-certified radiologists must read the data acquired with the large-area sensors.[132, 140] The advantages of three-dimensional imaging over conventional radiography include “lack of distortion, magnification, and artifacts associated with conventional radiography.” This will allow the clinician to accurately diagnose and prepare a treatment plan as well as follow-up long-term and evaluate healing.[132]

Gambill et al.[141] used computed tomography to compare root canal preparations completed with either nickel-titanium hand files or stainless steel hand files. The authors stated that this imaging modality “provided a repeatable, noninvasive method of evaluating certain aspects of endodontic instrumentation," which included canal transportation, dentin removal, and final canal preparation.

Velvart et al.[142] compared the ability to gather information concerning the location of important anatomic structures, presence or absence of a lesion, and cortical bone thickness and correlated this to findings on conventional (2D) dental radiography and high resolution CT images. The presence of a lesion was detected 100 percent of the time with the CT scan and in 61 out of 78 conventional radiographs. The mandibular canal was found in 31 cases in dental radiographs and again, in all of the CT scans. The thickness of cortical bone could only be determined with CT scans. The authors concluded that the "presence, extent, and location of the lesion and its relation to the mandibular canal can be predictably evaluated in a CT scan of the area. The use of CT provides additional, beneficial information not available from dental radiographs for treatment planning in apical surgery of mandibular premolars and molars."

Ohishi et al.[143] used CT to examine root anatomy in three cases of paramolar tubercles. "The images clearly showed the structure of the paramolar tubercles, including their root canal morphology. The root of the paramolar tubercle was united with the distobuccal root in each case. Canals were observed in all tubercles and were connected with the canals in distobuccal roots at various levels. In one case, the imaging information was helpful for endodontic treatment."

Bjorndal et al.[144] used fractal analysis to correlate the external and internal macromorphology of roots. They suggest that this 3D analysis can serve as a basis for preclinical training in endodontic procedures.

Peters et al.[145] used micro-CT to compare four Ni-Ti preparation techniques. The use of the micro-CT allowed the authors to describe the morphological changes that occurred with these different techniques. Peters et al.[146] used micro-CT to image several teeth prior to shaping with ProTaper NiTi instruments (Dentsply Maillefer, Tulsa, OK) and compared with micro-CT images following preparation.

Rigolone et al.[147] employed CT imaging prior to planning apical surgery on the palatal root of maxillary first molars. The images obtained provided information pertaining to the location of the sinus and allowed them to plan potential surgeries via a vestibular rather than palatal approach. This would allow surgeons to avoid potential complications associated with palatal access, including a laborious flap and hemorrhage from the palatine artery.

Volumetric CT (VCT) or CBCT has received attention recently with regard to endodontic imaging. Whereas medical grade CT used a fan-shaped beam, CBCT uses a cone beam allowing acquisition of images of the entire volume. The receptor captures two-dimensional images and is either solid-state (digital) or an image intensifier. The image intensifier captures photons and converts them to electrons. The electrons then contact a fluorescent screen, which then emits light and is eventually captured by CCD camera. The solid-state receptors absorb the photons, which are converted to an electric charge and are measured by a computer. This favors improved photon utilization, but the cost of production is high.[140] The source and receptor rotate once around the patient and many exposures are made. This occurs over a time period of 8.9 s and 40 s. The software then reconstructs the exposures into as many as 512 axial slice images.[140] In comparison with medical-grade CT, CBCT offers high resolution, isotropic images that can be used to evaluate root canal morphology.[132] Still, the resolution is not as high as conventional radiographs, but as far as 3D imaging goes, CBCT is the imaging modality of choice when assessing the intricacies of the root canal system.[132] The applications in endodontics include diagnosis and evaluation of endodontic treatment. Assessing the configuration and length of the root canals and the presence of accessory canals are also evaluated.[148, 149] Hannig et al.[150] used a flat panel VCT to detect vertical root fractures in extracted teeth. They found they were able to successfully detect the vertical root fractures in all teeth at a spatial resolution of 140 μm. Clinical applications may be possible if sensor technology is improved in these flat panel devices, particularly for the reduction in the exposure dose. Another author[151] used CT to determine the course of the mandibular nerve in relation to the root apices and inferior border of the mandible in cadavers. They were able to accurately assess the position of the mandibular nerve as confirmed macroscopically on the cadaver specimens.

Tuned aperture computed tomography (TACT) has also been evaluated for its applications in endodontics.[(152-158)] TACT uses several conventional 2D images to reconstruct a 3D volume that can be studied in incremental slices.[132] The benefits of TACT include relatively low doses; inexpensive equipment; image acquisition is simple; artifacts such as starburst patterns do not exist; resolution is comparable to conventional radiographs, and patient motion is tolerated.[132] Nance et al.[153] compared conventional D-speed film to TACT in the ability to detect extra canals. They found that TACT was significantly better at finding 4th canals in maxillary molars (36 percent versus 0 percent) as well as 3rd canals in mandibular molars (80 percent versus 0 percent). They concluded that TACT would be useful in detecting root canals that might otherwise be missed with conventional radiography. In contrast, in a similar study,[154] the authors found that TACT did not provide a significant advantage in locating second mesiobuccal canals in maxillary first molars. Nair et al.[155, 156] found that TACT was superior in its property to detect artificially induced oblique or vertical root fractures as well as trauma-induced radicular fractures in unrestored, maxillary anterior teeth. Furthermore, the diagnostic accuracy of TACT improved after three iterative restorations.[157, 158] Even though the fractures were induced in these studies, they were done with cadaver specimens[155-158] emulating the clinical situation closely.

WORKING LENGTH DETERMINATION

With conventional films, working length determination could be made by using a simple millimeter ruler. This is not possible with digital images. Instead, when the clinician measures using the cursor, the internal software determines the number of pixels that make up the line. This software can recognize the pixel size from the specific sensor based on an internal table of sensor characteristics.[131] This value can be converted to millimeters directly on the screen. The original image is subjected to the same projection errors such as distortion, elongation, and foreshortening. This is where the calibration tool becomes invaluable. The user simply calibrates the image by measuring an object of known distance (typically length of file or width) and applying it via the calibration software to the image. This allows greater accuracy in estimating the actual distance being measured.

Bregman[159] described a method in which 25 mm long flat probes with acrylic resin stops were inserted into canals, but only 10 mm of the probe penetrated into the canal. Measurements were made for CRA (Apparent tooth length, as seen on radiograph), CRI (real instrument length), and CAI (apparent instrument length, as seen on radiograph). This was applied to a formula to determine the CRD or real tooth length. The formula is represented here:

$$CRD = (CRI \times CAD)/CAI$$

A simplified method was proposed by Ingle.[160] In this technique a diagnostic radiograph was obtained, then another radiograph was taken with the instrument in position. The distance from the file tip to the apex was determined by adding or subtracting the length of the instrument, if it was short of or beyond the apex.

Best et al.[161, 162] described a technique in which a 10-mm steel pin was fixed parallel to the long axis of the tooth. The radiograph was exposed and carried to the BW gauge, which would indicate the tooth's length.

Sunada[161] used an apparatus called the electroconductometer, an early version of the modern electronic apex locator. He used two electrodes; one was attached to the patient's cheek and the other to the instrument. The instrument was passed into the canal until a reading of 40uA was obtained. This indicated the file tip had reached the apical area. When this reading was obtained, a stop was placed on the instrument to correspond to the cusp tip or incisal edge and the measurement was made.

Bramante and Berbert[163] compared the methods of Best,[162] Bregman,[159] Ingle,[160] and Sunada[161] for determining tooth length. They examined 224 teeth scheduled for extraction and applied the methods mentioned above. The most accurate and consistent results were found when the Ingle method was applied. The least accurate and consistent results were seen with the methods proposed by Best and Bregman. The

Sunada method was more accurate than the Best method and Bregman method, but the measurements had a high degree of variability. However, the Sunada method had the best results of any other method in the palatal roots of maxillary premolars and molars.

Everett and Fixott[164] described a method that would allow quick and accurate measurements of dental radiographs. They described a wire grid etched into Plexiglass and then taped to the film. When the radiograph was exposed, this wire grid would be superimposed over the final film. They utilized this primarily in measuring the extent of alveolar resorption over time, but they also mentioned that it could be used in endodontics for file measurements or root lengths.

Forsberg[165] took a different approach and compared paralleling, modified paralleling, and bisecting-angle radiographic techniques. A 0.3-mm diameter wire simulating an endodontic file was placed either 2 mm past the apex, flush with apex, or 2-mm short of the apex, and films of the teeth were exposed using the three techniques above. Exposure parameters of 72 kV and 12 mA remained constant. They found that the paralleling technique resulted in a better reproduction of the distance from the file to the apex of the tooth than did the bisecting-angle technique. If the bisecting-angle technique employed only a 10-degree vertical angulation, it was nearly as accurate as the paralleling technique. This, however, can rarely be achieved in a clinical situation. When the techniques were purposely executed in a non-ideal manner, “considerable variations in the accuracy of the radiographic techniques” were found.

Variations in projection geometry can result in radiographic distortion and magnification. One way to account for this change is to include a radiopaque object of known dimensions into the image to serve as a base for calibration. Loushine et al.[4]

determined the affect of calibrating digital images prior to working length measurement on the accuracy of those measurements. They included an orthodontic wire of known dimensions to serve as the calibration object. They found that calibrated images were statistically more accurate than uncalibrated images.

Griffiths et al.[125] determined the accuracy of radiography (D-speed film), xenoradiography and radiovisiography (positive and negative prints) in estimating endodontic working length. Working lengths were determined *in vitro* with size 10 files in extracted teeth. Inaccuracy was determined to be measurements that were >0.5 mm from true. They found that conventional radiography and xenoradiography were the most accurate at 94 percent accurate, 81.8 percent for radiovisiography negative and 68.7 percent for radiovisiography positive. The radiovisiography unit studied was a first-generation system.

Hedrick et al.[128] compared Trophy and Regam direct digital radiographic systems with conventional E-speed films with regard to working length determination. They placed size 15 K files in 19 teeth of cadaver specimens using a standardized jig. Files were either placed short or long of the radiographic apex. The digital images were read as either positive or negative images. They found that conventional radiographs were significantly more accurate than the Regam system by 0.27 mm. The difference between Trophy and conventional radiographs were not statistically significant. The authors concluded that although there were statistical differences between Regam and conventional, the results were not clinically significant.

Leddy et al.[6] compared working length determination in human cadaver sections using either RadioVisioGraphy or Kodak Ektaspeed conventional films. The digital images were evaluated in positive and negative modes. They found that there was no difference between positive and negative images in terms of accuracy. Similarly, they found no statistical difference between digital images and conventional film in making accurate file length assessments.

Ellingsen et al.[10] compared radiovisiography to D-speed and E-speed films for visibility of file tips of size 8 and size 10 files using an *in vitro* model. Using the zoom feature and converting the image from negative to positive produced equivalent results to D-speed films and superior results to E-speed films. Part 2[11] of their study used the same criteria, except the images were obtained in an *in vivo* model. They found that D-speed films were superior to the radiovisiography images with four of the five images equivalent to E-speed films. Accurate determination of the file tips was achieved 95 percent of the time with D-speed films, compared with 70 percent of E-speed, 95 percent of zoomed negative-to-positive radiovisiography, 86 percent of enhanced, 82 percent of standard zoom and 77 percent of images in negative-to-positive conversion.

Ong and Ford[166] compared root length measurements with radiovisiography to D-speed film *in vitro* and an *in vivo*. They found no statistically significant difference. Almenar Garcia and Navarro[167] compared direct and indirect methods of measuring working length with conventional and digital films. The direct method involved measuring the file with an endodontic ruler or calipers. The indirect method involved using calipers to measure on conventional radiographic film and the measure tool built into the digital software. They found no difference between the indirect and direct methods except at 30-degree vertical angulation. This resulted in a 1.5 mm shortened image when using the indirect method.

Cederberg et al.[9] compared working length determination between Ektaspeed Plus film and Digora photostimulable storage phosphor luminescence imaging. They found that the two systems performed similarly when measuring root lengths. However, when measuring the distance from the file tip to the root apex, PSP was able to detect smaller differences especially with smaller file tips sizes compared with film. They concluded that PSP was more accurate than film when assessing trial file length.

Eikenberg and Vandre[8] compared the ability to determine accurate working lengths between D-speed films and a digital radiographic system (Dexis). They found that digital images resulted in a lower measurement error compared with film-based images. They mention that this may not be clinically significant and that choosing a particular method may hinge on “equipment cost, reliability, speed of image acquisition, disposal of developing chemicals, desire for electronic record keeping, patient radiation exposure, and ease of use. They also estimated a 150 percent dose reduction compared with film.

Olsen et al.[168] compared two digital radiographic storage phosphor systems: Digora (Soredex, Finland) and DenOptix (Gendex, USA). “Digora had a larger dynamic range and, in general, a better image quality.” Peipenbring et al.[169] used a Schick CDR to measure the working length using size 8, size 10, size 15 and size 20 FlexOFiles. They found “all files were within 0.5 mm of known lengths and were always shorter than known lengths.” They also said, “The larger the file size the less deviation from the known lengths (more accurate).”

Lozano et al.[170] compared radiovisiography (RVG 4, Trophy), photostimulable storage phosphor (Digora, Soredex), and conventional films (Kodak DF58-D speed) with regard to working length determination. Root canal measurements were done with size 8, size 10 and size 15 files and the projection geometry was varied from 0^o degrees to 20^o degrees to the mesial. They found that digital and conventional films were comparable when a size 15 file is used. Conventional film was more precise with smaller file sizes, but the authors admit that the differences are not of clinical significance.

Melius et al.[171] determined the difference between E speed film and Schick CDR digital radiography in terms of the distance between the minor foramen and the anatomic apex. They inserted a minimum size 15 file to the minor foramen as viewed under a stereomicroscope and exposed radiographically. The digital images were measured using the software available and the films were measured under X10 magnification with a calibrated ruler. They found that there was no clinically significant difference between the conventional film and digital images.

Friedlander et al.[2] compared the perceived clarity of size 6 K-files between phosphor-plate digital images and conventional radiographs. They used 20 extracted mandibular molars with 06 K-files placed 2 mm short or flush with the apical foramen in teeth with either small or large periapical lesions. They found that the clarity of size 6 files were significantly less with phophor-plate digital images than with conventional radigraphs regardless of file position or size of apical lesion.

Mentes et al.[3] also compared a digital imaging system with E-speed films for working length determination. The canals varied in curvature from 5^o to 52^o. They found that both modalities were comparable with the digital imaging system improving as canal curvature increased.

Radel et al.[1] showed that Kodak RVG 6000 images produced significantly higher acceptability ratings compared to Shick CDR and digitized Kodak Insight film. The authors placed size 10 and size 15 files 0.5 mm to1.5 mm from the apex in cadaver molars and compared the two modalities.

MATERIALS AND METHODS

SELECTION OF TEETH

Twelve human extracted teeth were collected for use in this study. All teeth were obtained from the Oral Health Department under IUPUI/Clarian IRB study number NS0808-01. The teeth were stored in a sealed container with sterile water at room temperature to prevent dehydration. Criteria for tooth selection included a relatively intact crown with completely formed apices. Radiographs were recorded in a buccal-lingual direction to confirm that canal systems were visible and demonstrated the typical morphological characteristics of the tooth type selected. Teeth consisted of a maxillary central incisor, maxillary canine, maxillary premolar, three maxillary first molars, mandibular central incisor, mandibular canine, mandibular premolar and three mandibular first molars. The canal(s) selected had a single orifice with a single foramen. Teeth with abnormal canal anatomy or root morphology were discarded. Calculus and soft tissue debris were removed from the root surface with hand-scaling instruments. Following debridement of the root surface, the teeth were immersed in 5.25-percent sodium hypochlorite (Chlorox Co; Oakland, CA) for 30 minutes to dissolve organic debris and then mechanically debrided with a soft brush. The teeth were then autoclaved by IUSD central sterilization. See Figure 1 for a summary of experimental design.

SPECIMEN PREPARATION

Ideal access preparations were made for each tooth as set forth by Walton.[45] If a #15 K-flex file (Kerr, Remulus, MI) could not pass through the apical foramen, then a smaller file size was used until patency was established. If the #15 file still could not pass through the apical foramen, then the tooth was excluded from the study and another selected. The palatal canals of both the maxillary first molars and the distal canals of the mandibular first molars were used.

WORKING LENGTH DETERMINATION

Working length determination was determined by passing a #15 stainless steel K-flex file (Kerr, Remulus, MI) to the apical foramen using a dental operating microscope at X20 magnification (Global Surgical Co., St. Louis, MO). The file was removed and the length was measured. Each tooth or root was assigned a random working length, then the rubber stopper of each file was set to be either 0.5 mm, 1.0 mm, or 1.5 mm from the previously measured distance. This measurement was the working length for each respective tooth. This file and canal relation remained constant throughout the study for all selected teeth.

MOUNTING OF TEETH

The files were secured in place with super glue to eliminate movement. Using a plastic mold, the teeth were mounted in a plaster resin mix to simulate soft tissue. Wax was placed at the apex of each root to simulate a periapical radiolucency and provide definition to the apex. The teeth were mounted perpendicular to the tray bottom in plastic trays utilizing a plaster/ortho resin mix with a ratio of 50:50 to approximate bone density. The files were approximately perpendicular to the tray bottom to allow for accurate calibration and achieve a paralleling technique (Figures 2 and 3).

IMAGE ACQUISITION

The mounted teeth were then subjected to radiographic exposure using conventional Insight Kodak dental films (Kodak, Rochester, NY) and Schick digital sensors (Figure 4) utilizing CDR Dicom software (Schick Technologies; Long Island City, NY) for Microsoft Windows. A custom fabricated jig (Figures 5 through 7) for precision control of angulation and source-film distance ensured consistency between images. The distance between the film/sensor and the back of the jig tray remained constant at 1 cm. The source film/sensor distance varied at 4 cm, 8 cm, and 12 cm. The mAs/exposure time was varied from 0.06 s, 0.12 s, and 0.20 s for the Schick system and 0.08 s, 0.25 s and 0.40 s for the Insight films. These parameters were based on a pilot study to determine the appropriate ideal and extremes. Four teeth were mounted as described and were subjected to variations in exposure time and source film/sensor distance. A comparison of image quality was made between the conventional films and digital images. We were able to determine comparable exposure parameters specific to each imaging modality. The data obtained was subjected to statistical analysis to determine the number of teeth that would yield statistically significant results. A Siemens dental x-ray unit (Figure 8) was used at 60 kVp and 7mA. Each image and film was labeled to aid in randomization (Figure 9) and to blind the examiners to the exposure parameters of each image and film.

RADIOGRAPHIC EVALUATION

Two endodontists and two endodontic residents with experience in working length determination for conventional films as well as CDR digital software were selected. These examiners had no prior knowledge of file lengths for the individual teeth selected. The examiners were given a tutorial on how to operate the software with the digital system as well as how to measure the lengths on the conventional films. Examiners were expected to determine the distance from the tip of the file to the radiographic apex of the tooth (Figure 10). For conventional films examiners were asked to use magnification of X4.0 using a graded ruler accurate to 0.5 mm. The magnifying lens remained at a constant distance from the film. The films were viewed using a light box under dim lighting conditions. The portion of the light box not being used to view the film was blocked out with black poster paper. The working lengths were recorded in half-millimeter increments (Figures 12 and 13). For Schick images, under dim lighting conditions, examiners calibrated each image and used the software's measuring tool (Figure 10 and 11). The 2 mm bar on the shank of each file was used for calibration. The working lengths were recorded in 0.1 mm increments. Working lengths ending in 0.1 or 0.2 were rounded down and working lengths ending in 0.3 or 0.4 were rounded up. The principle investigator manually recorded each measurement. The examiners were presented with the images in a random order. They were told that the true working length was not the same for each tooth and that the working lengths varied from 0 mm to 2.0 mm from the radiographic apex. They were allocated 20 seconds to record the length to simulate a clinical situation. The examiners were instructed not to alter the images in any way. Ten randomly selected images and 10 randomly selected films were chosen and the examiners were asked to repeat their measurements no sooner than two weeks after their initial measurements to assess intra-examiner repeatability. See Figure 1 for a summary of the experimental design.

GROUPS

Group 1: Schick CCD sensor and CDR digital software.

Group 2: Kodak Insight films.

SAMPLE SIZE

For each tooth and each examiner, differences between measured lengths and the actual length were calculated and summarized. Means and standard deviations of differences between lengths measured using conventional images and rounded from digital images were used for sample size estimation. Separate sample size estimates were generated for each examiner.

A sample size of 12 will have 80-percent power to detect a difference in means of -0.44 (e.g. a mean difference in length of 0.00 between a conventional image and the actual length and a mean difference of 0.44 between a rounded digital image and the actual length), assuming a standard deviation of differences 0.50, using a paired t-test with a 0.05 two-sided significance level.

STATISTICAL METHODS

The error in working length was calculated as the observed value minus the known working length for each tooth type. A mixed-effects, full-factorial analysis of variance (ANOVA) model was used to model the error in working length. Included in the ANOVA model were fixed effects for type of image, distance, exposure time, and all two-way and three-way interactions. Tooth type and examiner were included in the model as random effects assuming a compound symmetry covariance structure. Intra-examiner repeatability was assessed for each film type. Ten randomly selected digital films and another 10 randomly selected conventional films were scored a second time by each examiner. The intra-class correlation coefficient (ICC) and a 95-percent confidence interval were estimated for each examiner and film type. Analyses were completed using the statistical software program SAS version 9.1 (SAS Institute, Cary NC).

RESULTS

The repeatability of the each examiner on each film type was assessed by estimating the intra-class correlation coefficient (ICC). The repeatability of each examiner on digital film was good with ICCs ranging from 0.67 to 1.0. Repeatability on the conventional film was poor with ICCs varying from -0.29 to 0.55. Results from the mixed effects ANOVA model are contained in the table below. There was an overall difference between the conventional and digital films ($p < 0.001$). After adjusting for the effects of distance and exposure time, the error in the working length from the digital image was 0.1 mm shorter (95 percent CI: 0.06, 0.14) than the error in the working length from the film image. There was no difference among distances ($p = 0.999$) nor exposure time ($p = 0.158$). While there was a significant interaction between the distance and exposure time ($p = 0.021$), among the other two-way and three-way interactions, none was significant ($p > 0.05$). The results are represented in Tables I through IV.

TABLES AND FIGURES

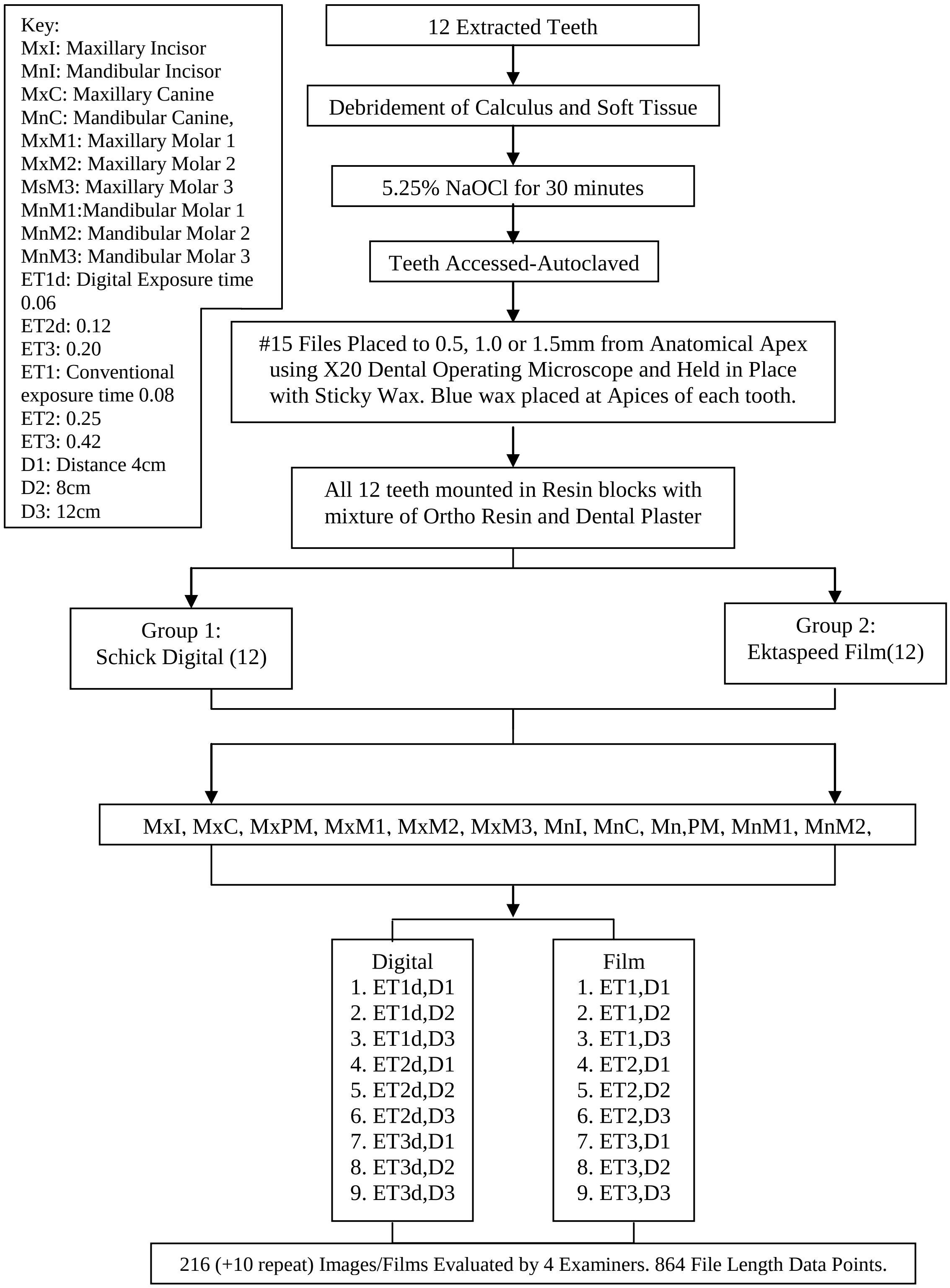

FIGURE 1. Summary of experimental design.

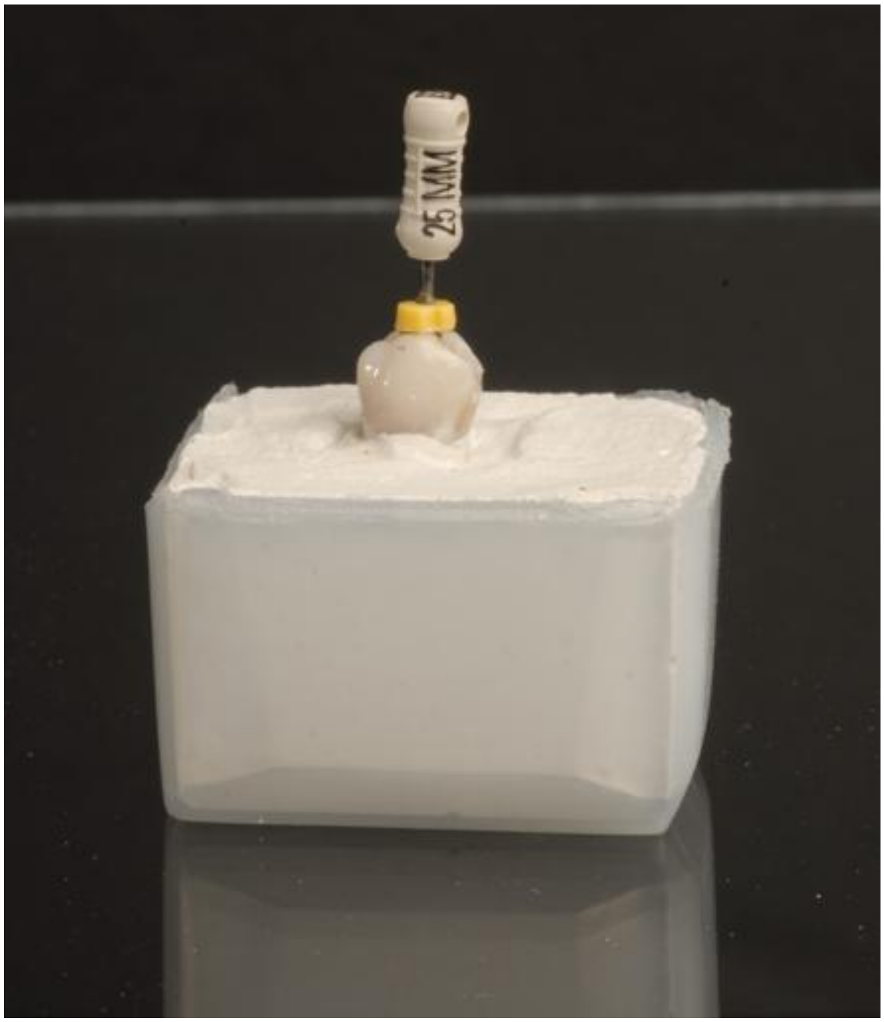

FIGURE 2. File cemented into place and tooth mounted.

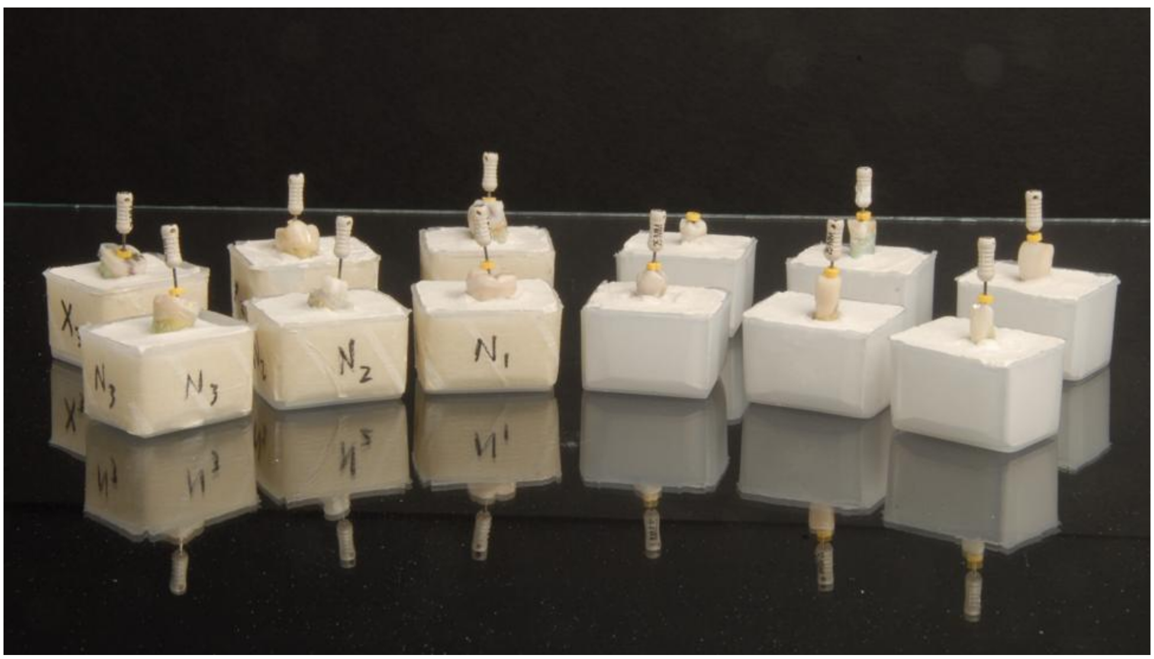

FIGURE 3. All teeth mounted with files cemented in place.

FIGURE 4. Schick digital sensor.

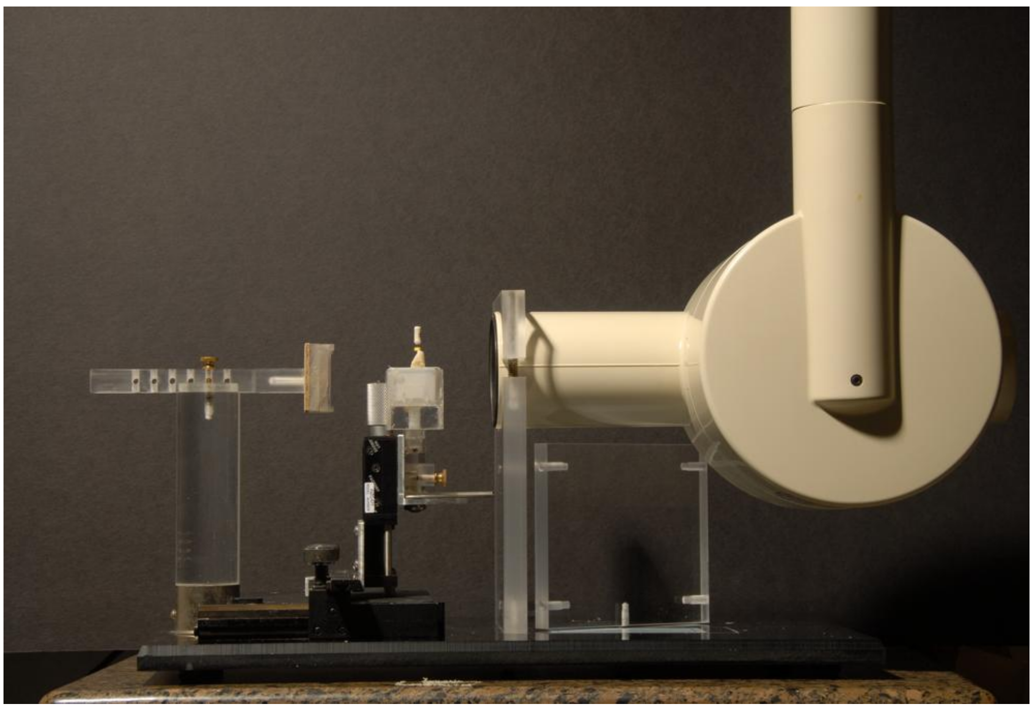

FIGURE 5. Custom-fabricated jig.

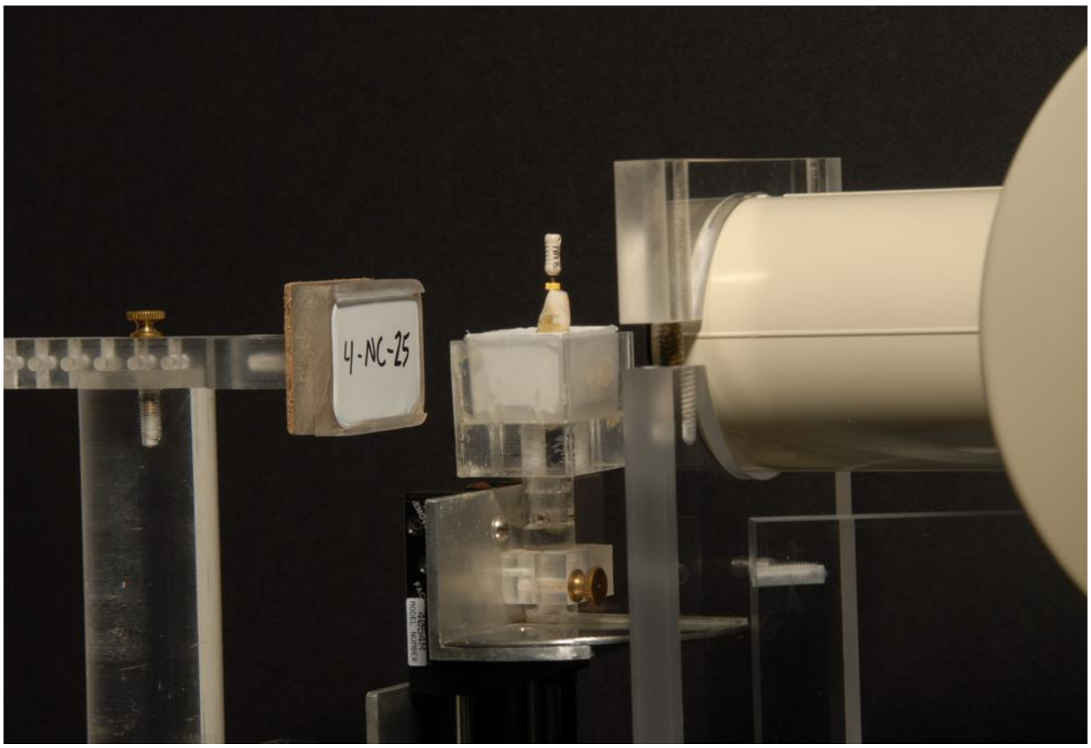

FIGURE 6. Custom-fabricated jig with labeled Kodak Insight film and tooth.

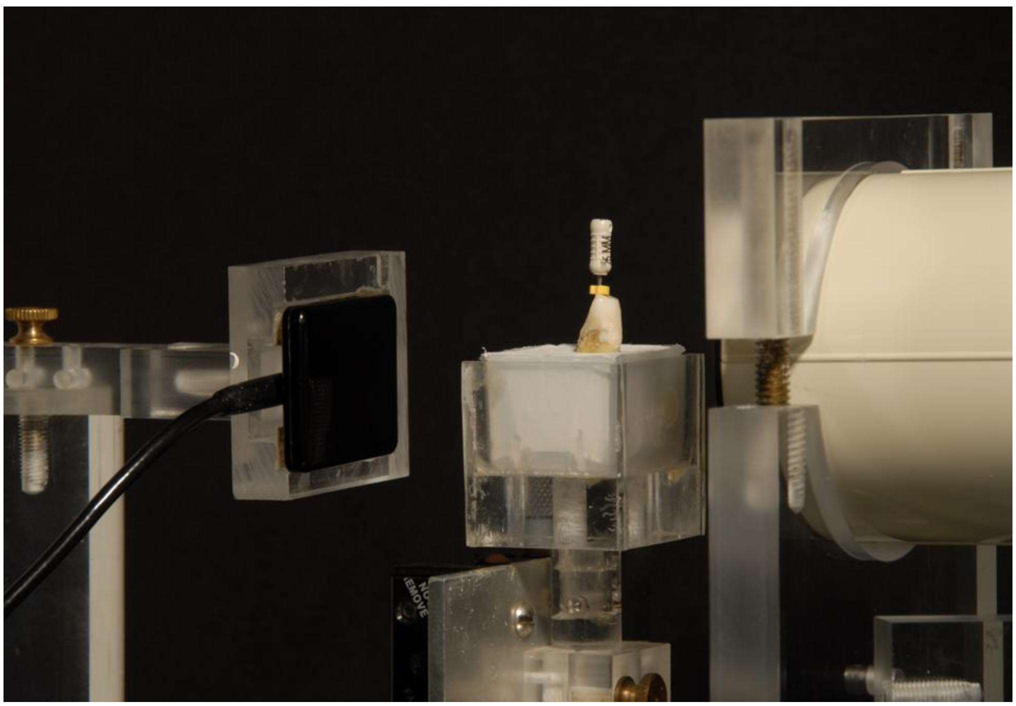

FIGURE 7. Custom-fabricated jig with digital sensor and tooth.

FIGURE 8. Siemens dental x-ray unit.

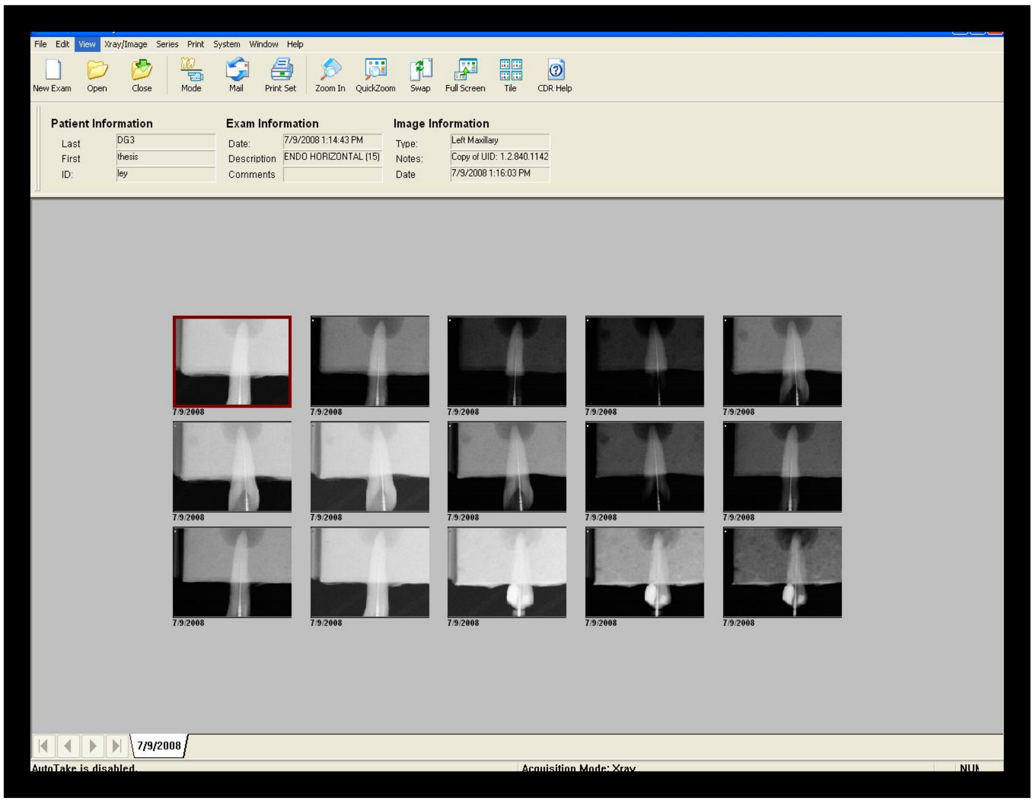

FIGURE 9. Grid of images before randomization.

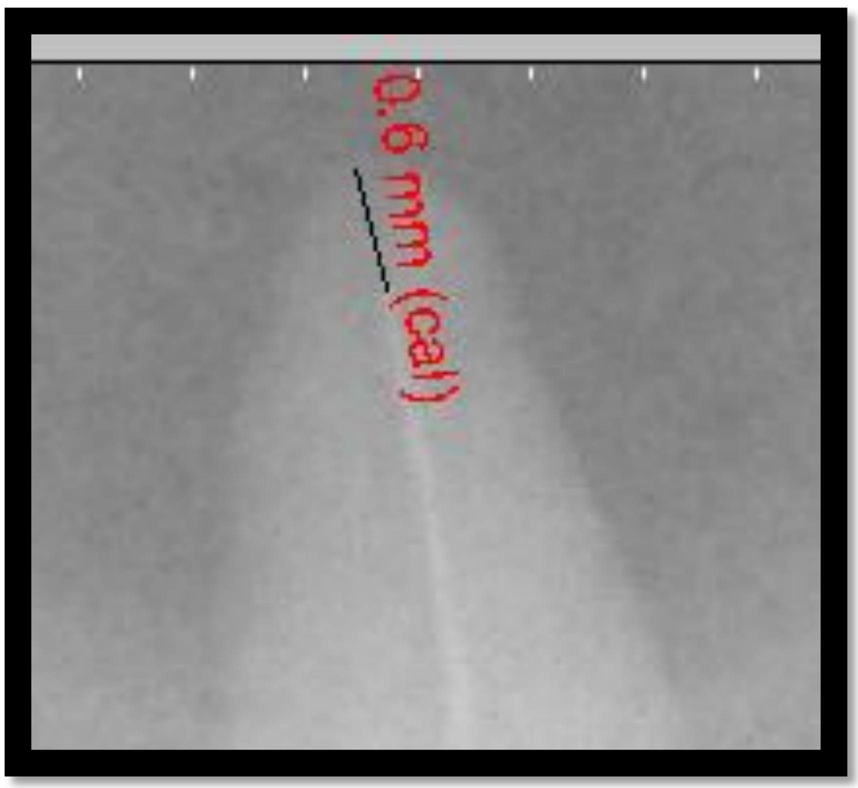

FIGURE 10. Measurement from file tip to radiographic apex.

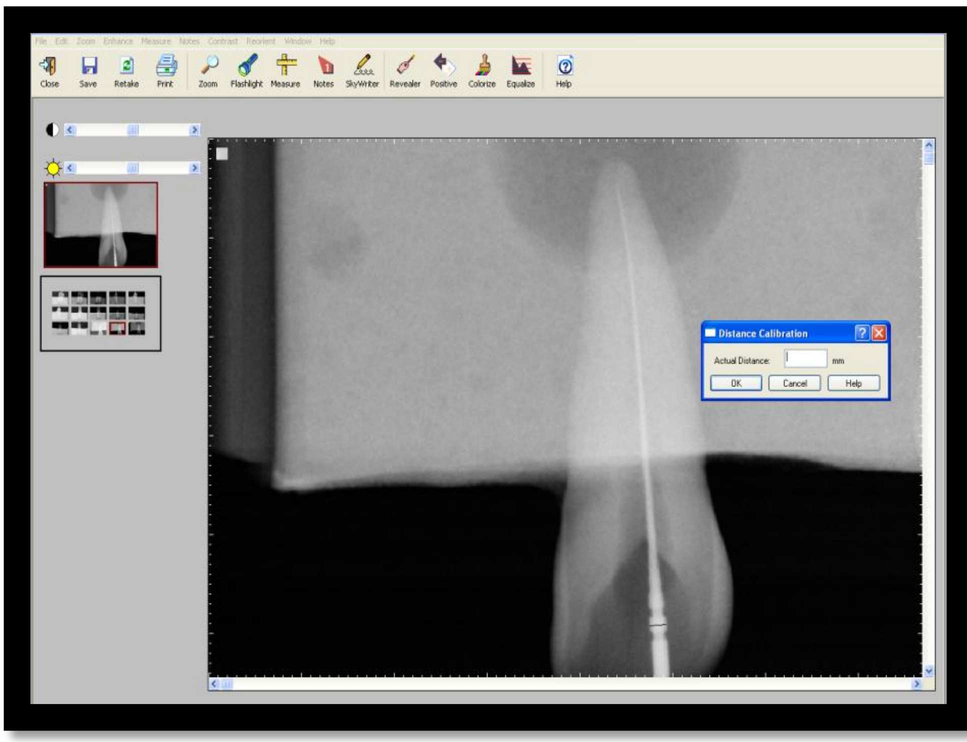

FIGURE 11. Calibration tool with randomized grid on left.

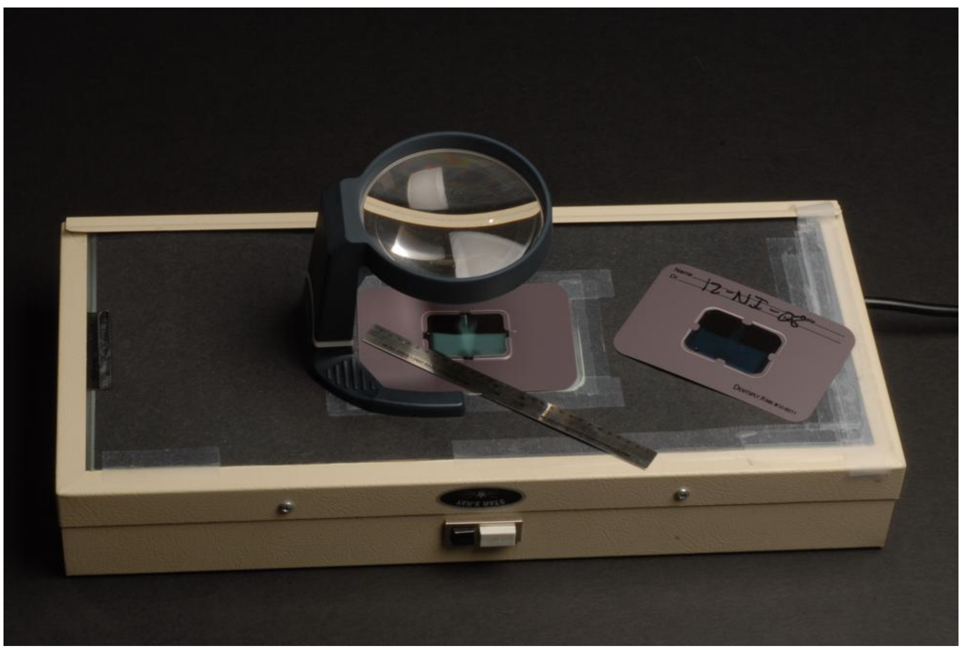

FIGURE 12. Light box, magnifying glass X4.0, calibrated ruler, conventional image.

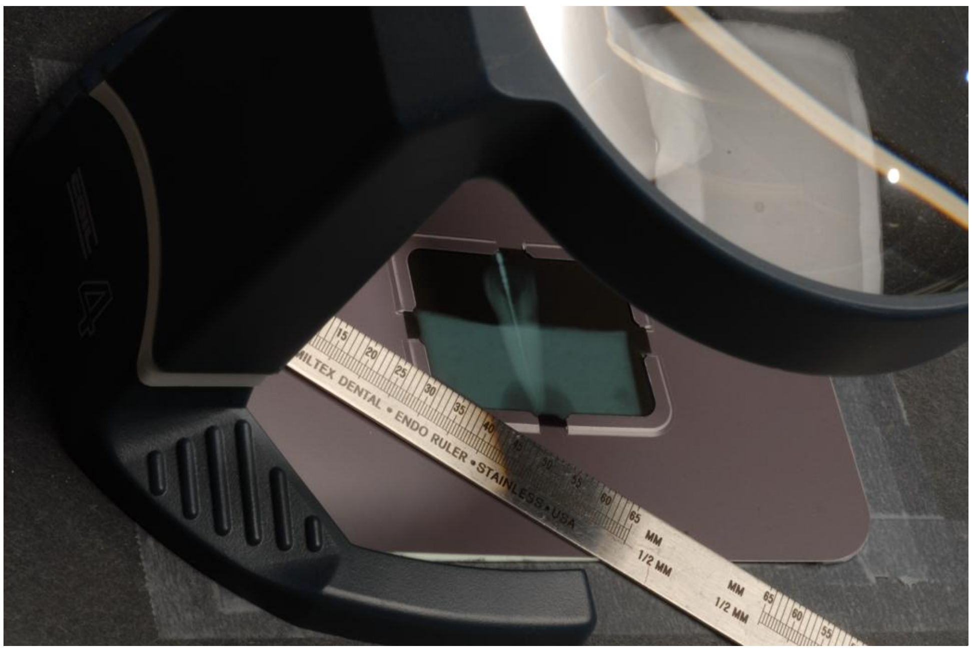

FIGURE 13. Light box, X4.0 magnifying lens, calibrated ruler, conventional image.

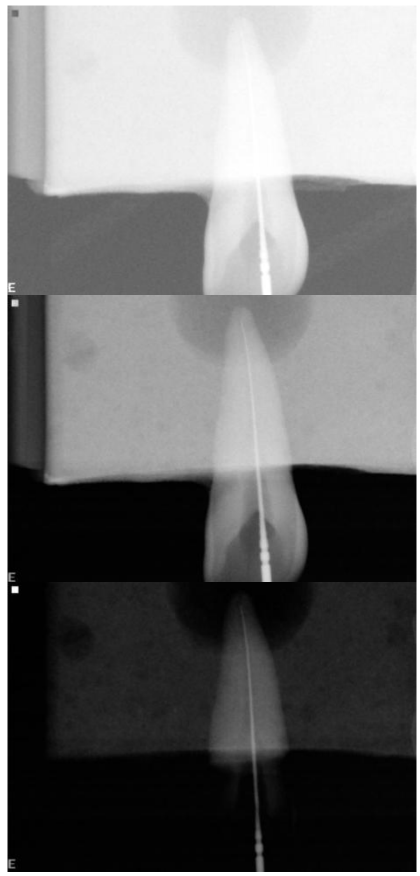

Figure 14. Under-, ideally and overexposed radiographs of a maxillary incisor.

TABLE I

Repeatability results[a]

	DIGITAL			CONVENTIONAL FILM		
Examiner	**ICC**	**95% CI**		**ICC**	**95% CI**	
1	1.00	Ne		0.55	-0.05	0.86
2	0.77	0.34	0.94	-0.29	-0.74	0.38
3	0.67	0.14	0.90	0.50	-0.12	0.85
4	0.73	0.26	0.92	0.30	-0.34	0.76

[a]ICC = intra-class correlation coefficient.
95% CI = 95% confidence interval.
Ne = not estimable.

TABLE II

Analysis variable

ANALYSIS VARIABLE : ERROR IN READING (MM)								
Dist (cm)	Exp time (mAs)	Film image	N Obs	Mean	Std Dev	Lower 95%CL for Mean	Upper 95%CL for Mean	Pr > |t|
4	0.06	Digital	48	0.063	0.522	-0.089	0.214	0.4111
	0.08	Film	48	0.188	0.522	0.036	0.339	0.0164
	0.12	Digital	48	0.24	0.536	0.084	0.395	0.0033
	0.25	Film	48	0.323	0.551	0.163	0.483	0.0002
	0.20	Digital	48	0.224	0.508	0.066	0.382	0.0067
	0.40	Film	48	0.292	0.534	0.137	0.447	0.0004
8	0.06	Digital	48	0.177	0.489	0.035	0.319	0.0156
	0.08	Film	48	0.219	0.601	0.044	0.393	0.0151
	0.12	Digital	48	0.115	0.486	-0.027	0.256	0.1093
	0.25	Film	48	0.344	0.612	0.166	0.521	0.0003
	0.20	Digital	48	0.219	0.525	0.066	0.371	0.0059
	0.40	Film	48	0.25	0.555	0.089	0.411	0.0031
12	0.06	Digital	48	0.177	0.56	0.014	0.34	0.0335
	0.08	Film	48	0.323	0.606	0.147	0.499	0.0006
	0.12	Digital	48	0.171	0.46	0.037	0.304	0.0133
	0.25	Film	48	0.24	0.555	0.078	0.401	0.0044
	0.20	Digital	48	0.146	0.472	0.009	0.283	0.0376
	0.40	Film	48	0.26	0.536	0.105	0.416	0.0015

TABLE III

Mean error and standard deviation[a]

	DIGITAL		FILM	
	Mean Error (mm)	Std (mm)	Mean Error (mm)	Std (mm)
Light ($p > 0.05$)	0.139	0.524	0.243	0.576
Ideal ($p > 0.05$)	0.224	0.489	0.389	0.564
Dark ($p > 0.05$)	0.222	0.517	0.271	0.545
Combined ($p = 0.001$)	0.17	0.506	0.271	0.564

[a]Mean error and standard deviation for digital versus film with light, ideal or dark radiographs. Overall mean error and standard deviation for digital versus film.

TABLE IV

Analysis variable by tooth type

ANALYSIS VARIABLE : ERROR IN READING (MM)									
Tooth	Dist (cm)	Exp time (mAs)	Film image	N	Mean	Std Dev	Lower 95%CL for Mean	Upper 95%CL for Mean	Pr > |t|
Mandibular Molar 1	4	Short	Digital	4	1.25	0.289	0.791	1.709	0.0032
			Film	4	0.875	0.479	0.113	1.637	0.0354
		Medium	Digital	4	1.25	0.289	0.791	1.709	0.0032
			Film	4	1.25	0.289	0.791	1.709	0.0032
		Long	Digital	4	0.925	0.15	0.686	1.164	0.0011
			Film	4	1.125	0.479	0.363	1.887	0.0182
	8	Short	Digital	4	1.25	0.289	0.791	1.709	0.0032
			Film	4	1.375	0.25	0.977	1.773	0.0016
		Medium	Digital	4	1.25	0.289	0.791	1.709	0.0032
			Film	4	1.25	0.289	0.791	1.709	0.0032
		Long	Digital	4	1.375	0.25	0.977	1.773	0.0016
			Film	4	1.375	0.25	0.977	1.773	0.0016
	12	Short	Digital	4	1.25	0.289	0.791	1.709	0.0032
			Film	4	1	0.707	-0.125	2.125	0.0663
		Medium	Digital	4	1.125	0.25	0.727	1.523	0.0029
			Film	4	1.375	0.25	0.977	1.773	0.0016
		Long	Digital	4	1	0	.	.	.
			Film	4	1.375	0.25	0.977	1.773	0.0016
Mandibular Molar 2	4	Short	Digital	4	-0.625	0.25	-1.023	-0.227	0.0154
			Film	4	-0.5	0.408	-1.15	0.15	0.0917
		Medium	Digital	4	-0.625	0.25	-1.023	-0.227	0.0154
			Film	4	-0.25	0.289	-0.709	0.209	0.1817
		Long	Digital	4	-0.575	0.538	-1.431	0.281	0.122
			Film	4	-0.5	0	.	.	.
	8	Short	Digital	4	-0.375	0.25	-0.773	0.023	0.0577
			Film	4	-0.625	0.25	-1.023	-0.227	0.0154
		Medium	Digital	4	-0.5	0.408	-1.15	0.15	0.0917
			Film	4	-0.5	0	.	.	.
		Long	Digital	4	-0.25	0.289	-0.709	0.209	0.1817
			Film	4	-0.5	0	.	.	.
	12	Short	Digital	4	-0.625	0.25	-1.023	-0.227	0.0154
			Film	4	0.375	0.854	-0.984	1.734	0.4444
		Medium	Digital	4	-0.5	0	.	.	.
			Film	4	-0.5	0	.	.	.
		Long	Digital	4	-0.625	0.25	-1.023	-0.227	0.0154
			Film	4	-0.75	0.289	-1.209	-0.291	0.0138

(continued)

TABLE IV

(continued)

MANDIBULAR MOLAR 3	4	SHORT	DIGITAL	4	0.125	0.25	-0.273	0.523	0.391
			Film	4	0.5	0.408	-0.15	1.15	0.0917
		Medium	Digital	4	0.625	0.25	0.227	1.023	0.0154
			Film	4	0.875	0.25	0.477	1.273	0.006
		Long	Digital	4	0.5	0	.	.	.
			Film	4	1	0.408	0.35	1.65	0.0163
	8	Short	Digital	4	0.25	0.289	-0.209	0.709	0.1817
			Film	4	0.75	0.5	-0.046	1.546	0.0577
		Medium	Digital	4	0.125	0.25	-0.273	0.523	0.391
			Film	4	0.625	0.25	0.227	1.023	0.0154
		Long	Digital	4	0.375	0.25	-0.023	0.773	0.0577
			Film	4	0.5	0	.	.	.
	12	Short	Digital	4	0.5	0.577	-0.419	1.419	0.1817
			Film	4	0.5	0	.	.	.
		Medium	Digital	4	0.5	0	.	.	.
			Film	4	0.625	0.25	0.227	1.023	0.0154
		Long	Digital	4	0.5	0.408	-0.15	1.15	0.0917
			Film	4	0.5	0	.	.	.
Mandibular Canine	4	Short	Digital	4	0.125	0.25	-0.273	0.523	0.391
			Film	4	-0.375	0.25	-0.773	0.023	0.0577
		Medium	Digital	4	0.375	0.25	-0.023	0.773	0.0577
			Film	4	0.625	0.479	-0.137	1.387	0.0796
		Long	Digital	4	0.375	0.479	-0.387	1.137	0.2152
			Film	4	0.75	0.289	0.291	1.209	0.0138
	8	Short	Digital	4	0.5	0	.	.	.
			Film	4	0	0.408	-0.65	0.65	1
		Medium	Digital	4	-0.125	0.25	-0.523	0.273	0.391
			Film	4	0.5	0	.	.	.
		Long	Digital	4	0	0.408	-0.65	0.65	1
			Film	4	0.5	0	.	.	.
	12	Short	Digital	4	0	0	.	.	.
			Film	4	0.375	0.25	-0.023	0.773	0.0577
		Medium	Digital	4	0.375	0.25	-0.023	0.773	0.0577
			Film	4	0	0.408	-0.65	0.65	1
		Long	Digital	4	0	0	.	.	.
			Film	4	0.625	0.25	0.227	1.023	0.0154

(continued)

TABLE IV

(Continued)

MANDIBULAR INCISOR	4	SHORT	DIGITAL	4	-0.25	0.289	-0.709	0.209	0.1817
			Film	4	0	0	.	.	.
		Medium	Digital	4	0.125	0.25	-0.273	0.523	0.391
			Film	4	0.125	0.25	-0.273	0.523	0.391
		Long	Digital	4	0.375	0.25	-0.023	0.773	0.0577
			Film	4	0.25	0.289	-0.209	0.709	0.1817
	8	Short	Digital	4	0.125	0.25	-0.273	0.523	0.391
			Film	4	0	0	.	.	.
		Medium	Digital	4	0.25	0.289	-0.209	0.709	0.1817
			Film	4	0	0	.	.	.
		Long	Digital	4	0.375	0.25	-0.023	0.773	0.0577
			Film	4	0.25	0.289	-0.209	0.709	0.1817
	12	Short	Digital	4	0.5	0	.	.	.
			Film	4	0.625	0.946	-0.881	2.131	0.2783
		Medium	Digital	4	0.375	0.25	-0.023	0.773	0.0577
			Film	4	0.25	0.289	-0.209	0.709	0.1817
		Long	Digital	4	0.125	0.25	-0.273	0.523	0.391
			Film	4	0.125	0.25	-0.273	0.523	0.391
Mandibular Premolar	4	Short	Digital	4	-0.25	0.289	-0.709	0.209	0.1817
			Film	4	0.375	0.25	-0.023	0.773	0.0577
		Medium	Digital	4	0	0	.	.	.
			Film	4	0	0	.	.	.
		Long	Digital	4	-0.125	0.25	-0.523	0.273	0.391
			Film	4	-0.125	0.25	-0.523	0.273	0.391
	8	Short	Digital	4	-0.125	0.25	-0.523	0.273	0.391
			Film	4	0.125	0.25	-0.273	0.523	0.391
		Medium	Digital	4	-0.125	0.25	-0.523	0.273	0.391
			Film	4	-0.25	0.289	-0.709	0.209	0.1817
		Long	Digital	4	-0.125	0.25	-0.523	0.273	0.391
			Film	4	0.125	0.25	-0.273	0.523	0.391
	12	Short	Digital	4	0	0	.	.	.
			Film	4	-0.375	0.25	-0.773	0.023	0.0577
		Medium	Digital	4	-0.125	0.25	-0.523	0.273	0.391
			Film	4	0	0	.	.	.
		Long	Digital	4	-0.125	0.25	-0.523	0.273	0.391
			Film	4	0.25	0.289	-0.209	0.709	0.1817

(continued)

TABLE IV

(continued)

MAXILLARY MOLAR 1	4	SHORT	DIGITAL	4	-0.5	0	.	.	.
			Film	4	-0.125	0.479	-0.887	0.637	0.6376
		Medium	Digital	4	-0.5	0	.	.	.
			Film	4	-0.5	0	.	.	.
		Long	Digital	4	-0.375	0.25	-0.773	0.023	0.0577
			Film	4	-0.25	0.289	-0.709	0.209	0.1817
	8	Short	Digital	4	-0.375	0.25	-0.773	0.023	0.0577
			Film	4	-0.25	0.289	-0.709	0.209	0.1817
		Medium	Digital	4	-0.375	0.25	-0.773	0.023	0.0577
			Film	4	-0.5	0	.	.	.
		Long	Digital	4	-0.5	0	.	.	.
			Film	4	-0.625	0.25	-1.023	-0.227	0.0154
	12	Short	Digital	4	-0.5	0	.	.	.
			Film	4	-0.5	0.408	-1.15	0.15	0.0917
		Medium	Digital	4	-0.45	0.1	-0.609	-0.291	0.0029
			Film	4	-0.375	0.479	-1.137	0.387	0.2152
		Long	Digital	4	-0.5	0	.	.	.
			Film	4	-0.125	0.25	-0.523	0.273	0.391
Maxillary Molar 2	4	Short	Digital	4	0.25	0.5	-0.546	1.046	0.391
			Film	4	0.625	0.629	-0.376	1.626	0.1411
		Medium	Digital	4	0.375	0.25	-0.023	0.773	0.0577
			Film	4	0.625	0.479	-0.137	1.387	0.0796
		Long	Digital	4	0.375	0.479	-0.387	1.137	0.2152
			Film	4	0	0	.	.	.
	8	Short	Digital	4	0.125	0.25	-0.273	0.523	0.391
			Film	4	0	0.408	-0.65	0.65	1
		Medium	Digital	4	0	0	.	.	.
			Film	4	0.25	0.289	-0.209	0.709	0.1817
		Long	Digital	4	0.125	0.25	-0.273	0.523	0.391
			Film	4	0	0	.	.	.
	12	Short	Digital	4	0.25	0.289	-0.209	0.709	0.1817
			Film	4	0.75	0.289	0.291	1.209	0.0138
		Medium	Digital	4	0.125	0.25	-0.273	0.523	0.391
			Film	4	0.125	0.25	-0.273	0.523	0.391
		Long	Digital	4	0.125	0.25	-0.273	0.523	0.391
			Film	4	0.25	0.289	-0.209	0.709	0.1817

(continued)

TABLE IV

(continued)

MAXILLARY MOLAR 3	4	SHORT	DIGITAL	4	0	0	.	.	.
			Film	4	0	0	.	.	.
		Medium	Digital	4	0	0	.	.	.
			Film	4	0	0	.	.	.
		Long	Digital	4	.	.	.	.	.
			Film	4	0	0	.	.	.
	8	Short	Digital	4	0.125	0.25	-0.273	0.523	0.391
			Film	4	0.375	0.25	-0.023	0.773	0.0577
		Medium	Digital	4	0.125	0.25	-0.273	0.523	0.391
			Film	4	0.75	0.289	0.291	1.209	0.0138
		Long	Digital	4	0	0.408	-0.65	0.65	1
			Film	4	0	0	.	.	.
	12	Short	Digital	4	-0.375	0.25	-0.773	0.023	0.0577
			Film	4	0.25	0.289	-0.209	0.709	0.1817
		Medium	Digital	4	0	0	.	.	.
			Film	4	0	0	.	.	.
		Long	Digital	4	0.125	0.25	-0.273	0.523	0.391
			Film	4	0	0	.	.	.
Maxillary Canine	4	Short	Digital	4	0.375	0.25	-0.023	0.773	0.0577
			Film	4	0.625	0.25	0.227	1.023	0.0154
		Medium	Digital	4	0.75	0.289	0.291	1.209	0.0138
			Film	4	0.75	0.289	0.291	1.209	0.0138
		Long	Digital	4	0.5	0	.	.	.
			Film	4	0.5	0	.	.	.
	8	Short	Digital	4	0.5	0.408	-0.15	1.15	0.0917
			Film	4	0.875	0.629	-0.126	1.876	0.0689
		Medium	Digital	4	0.375	0.25	-0.023	0.773	0.0577
			Film	4	0.875	0.25	0.477	1.273	0.006
		Long	Digital	4	0.5	0	.	.	.
			Film	4	0.75	0.5	-0.046	1.546	0.0577
	12	Short	Digital	4	0.625	0.25	0.227	1.023	0.0154
			Film	4	0.5	0	.	.	.
		Medium	Digital	4	0.5	0	.	.	.
			Film	4	0.75	0.289	0.291	1.209	0.0138
		Long	Digital	4	0.5	0	.	.	.
			Film	4	0.625	0.25	0.227	1.023	0.0154

(continued)

TABLE IV

(continued)

MAXILLARY INCISOR	4	SHORT	DIGITAL	4	0	0	.	.	.
			Film	4	0.25	0.5	-0.546	1.046	0.391
		Medium	Digital	4	0.125	0.25	-0.273	0.523	0.391
			Film	4	0.25	0.289	-0.209	0.709	0.1817
		Long	Digital	4	0.25	0.354	-2.927	3.427	0.5
			Film	4	0.375	0.25	-0.023	0.773	0.0577
	8	Short	Digital	4	0.125	0.25	-0.273	0.523	0.391
			Film	4	0	0	.	.	.
		Medium	Digital	4	0.25	0.289	-0.209	0.709	0.1817
			Film	4	0.5	0	.	.	.
		Long	Digital	4	0.5	0.408	-0.15	1.15	0.0917
			Film	4	0.5	0	.	.	.
	12	Short	Digital	4	0.125	0.25	-0.273	0.523	0.391
			Film	4	0.25	0.645	-0.777	1.277	0.495
		Medium	Digital	4	0.125	0.25	-0.273	0.523	0.391
			Film	4	0.25	0.289	-0.209	0.709	0.1817
		Long	Digital	4	0.25	0.289	-0.209	0.709	0.1817
			Film	4	0	0	.	.	.
Maxillary Premolar	4	Short	Digital	4	0.25	0.289	-0.209	0.709	0.1817
			Film	4	0	0	.	.	.
		Medium	Digital	4	0.375	0.25	-0.023	0.773	0.0577
			Film	4	0.125	0.25	-0.273	0.523	0.391
		Long	Digital	4	0.25	0.289	-0.209	0.709	0.1817
			Film	4	0.375	0.25	-0.023	0.773	0.0577
	8	Short	Digital	4	0	0.408	-0.65	0.65	1
			Film	4	0	0	.	.	.
		Medium	Digital	4	0.125	0.25	-0.273	0.523	0.391
			Film	4	0.625	0.946	-0.881	2.131	0.2783
		Long	Digital	4	0.25	0.289	-0.209	0.709	0.1817
			Film	4	0.125	0.25	-0.273	0.523	0.391
	12	Short	Digital	4	0.375	0.25	-0.023	0.773	0.0577
			Film	4	0.125	0.25	-0.273	0.523	0.391
		Medium	Digital	4	0	0	.	.	.
			Film	4	0.375	0.479	-0.387	1.137	0.2152
		Long	Digital	4	0.375	0.25	-0.023	0.773	0.0577
			Film	4	0.25	0.289	-0.209	0.709	0.1817

(continued)

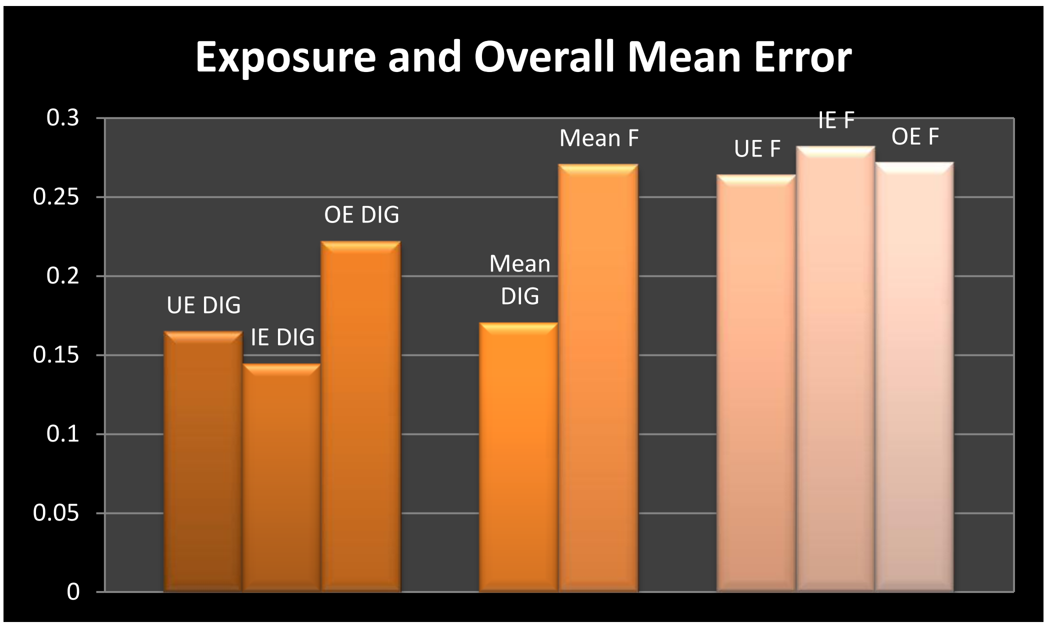

FIGURE 15. Mean error comparison of under-, ideally, and overexposed images and films.

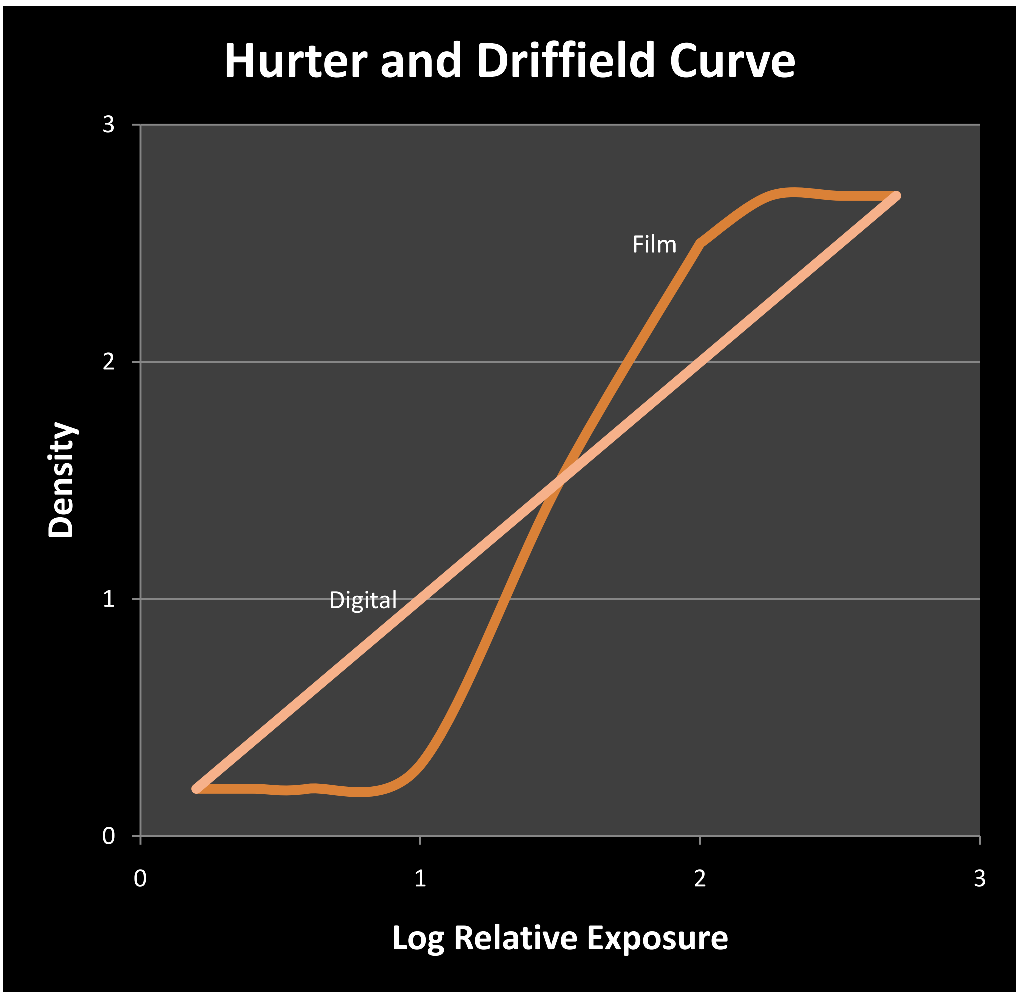

FIGURE 16. Hurter and Driffield characteristic curve.

FIGURE 17. Mean error comparison between digital and film with regard to distance.

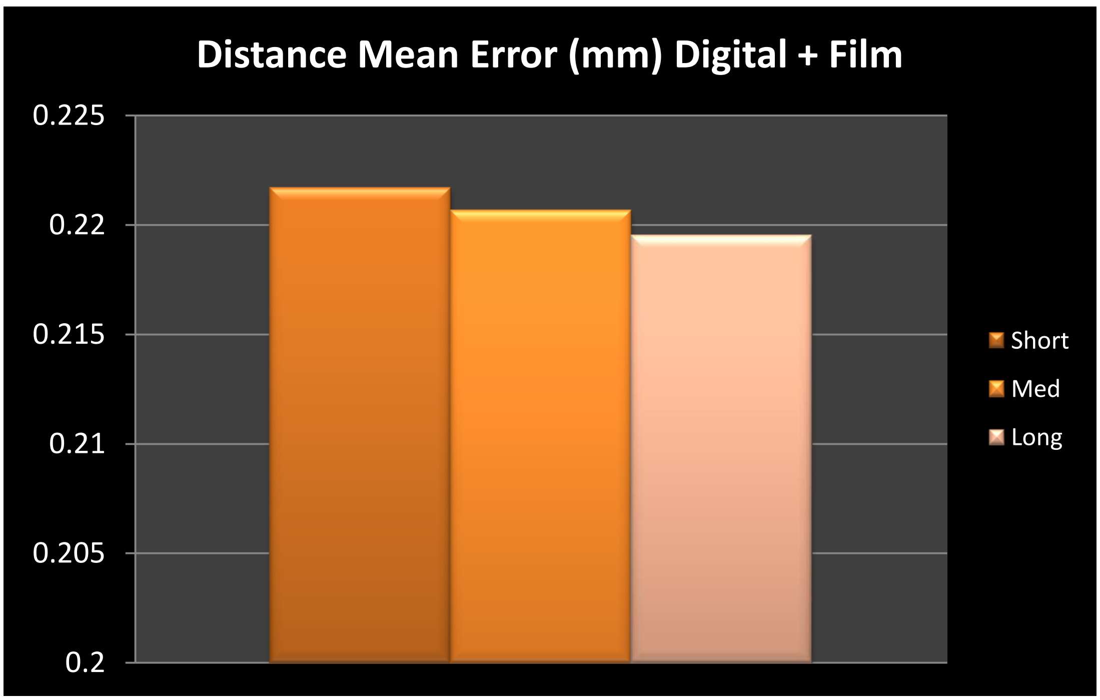

FIGURE 18. Mean error comparison of distances for digital and film combined.

DISCUSSION

There were no statistically significant differences in mean error between under-, over- or ideally exposed radiographs (Figure 14 and 15). Berkhout et al. had similar findings in which digital images required less exposure time than film to achieve diagnostically acceptable images. This is in contrast to Sheaffer et al., who found there was more error with underexposed films versus overexposed films. One possible explanation for the differences between digital and film can be found with the correlations found on the Hurter and Driffield curve (Figure 16). This plot shows that digital radiography and conventional radiography have different characteristic curves. The digital radiography shows a linear curve with increasing density as log exposure increases. However, film shows a less consistent increase in density showing an “S” curve with a steeper slope as log exposure increases. This indicates that films have a much narrower range of exposures to produce a diagnostically acceptable image. Digital radiography has a wider range in which to produce a diagnostically acceptable image. This shows that digital images not only require less radiation to produce diagnostically acceptable images, but are also less sensitive to alterations in exposure parameters such as exposure time.

Overall, independent of exposure time and distance, digital images resulted in less error (0.1 mm, $p = 0.001$) than films (Table 1; Figure 15). Eikenberg and Vandre also found that digital images had fewer measurable errors than films. In contrast, Hedrick et al. demonstrated that film was more accurate (0.27 mm) than digital images.

Both of these studies used ideal conditions with fixed exposure parameters. As with this study, the results are not clinically significant.

With regard to specific exposure variables, exposure time and source-film/image distance did not affect working length determination alone, nor did it differ between digital or conventional film. The ICCs for conventional films was poor (0.27), which likely affected the results of the study. However, within the limits of this study, digital images resulted in more repeatable readings (0.78) than conventional films. Differences in magnification could have affected ICCs in that X4.0 magnification was used for film compared with X6 magnification of the image on the computer monitor. The digital images were also aided by the use of the calibration tool. It is possible that the readings for digital would be less accurate had the calibration tool not been used. The films and images that were selected for re-examination were a true random sample. Non-ideal radiographs could have skewed the ICCs. More examiners or a larger random sample could have also improved the ICC. The films were evaluated after the images; consequently, examiner eye fatigue could have contributed to the poor results of film.

When examining the affect of distance on mean error, digital images show predictably less mean error and as the source-sensor distance increases (Figure 17). This can be explained by the decrease in the amount of magnification as the source is moved further from the object. As the source-object distance increases, the x-rays that pass through the object become more parallel and less diverging, giving a more accurate representation of the objects actual size on the film. The film showed the opposite trend (Figure 17) likely due to the difficulty the examiners had in reading the films and not from any scientific reasoning. However, when the data from films and images are combined, this expected trend is again observed (Figure 18).

SUMMARY AND CONCLUSIONS

It was the aim of this study to determine if there was a difference between Schick digital radiography and Kodak Insight conventional film in accurately determining working lengths when modifying exposure time and source-film/sensor distance. Twelve human teeth were accessed and working lengths set at random. All teeth were exposed radiographically by using either Schick digital radiography or Kodak Insight conventional film. The object film/sensor distance, milliamperage, and kilovoltage remained constant for each radiograph. The exposure time and source film/sensor distance was varied. Four examiners were asked to measure the distance between the file tip and the radiographic apex for all films and images. Each digital image was calibrated and the measuring tool was used to estimate the working length. Each film was examined under X4 magnification using a light box in a dimly lit room.

Within the limits of this *in vitro* study, it can be concluded that although there is a statistically significant difference, there is no clinically significant difference between Schick digital radiography and Kodak Insight film when estimating endodontic working length. Schick CDR digital images and Kodak Insight film are affected equally by changes in exposure time and source-film/sensor distance.

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ABSTRACT

AN *IN VITRO* COMPARISON OF WORKING LENGTH DETERMINATION

BETWEEN A DIGITAL SYSTEM AND CONVENTIONAL FILM

WHEN SOURCE-FILM/SENSOR DISTANCE AND

EXPOSURE TIME ARE MODIFIED

by

Paul J. Ley

Indiana University School of Dentistry
Indianapolis, Indiana

Accurate determination of working length during endodontic therapy is a crucial step in achieving a predictable outcome. This is determined by the use of electronic apex locators, tactile perception, and knowledge of average tooth lengths and/or dental radiography whether digital or conventional is utilized. It is the aim of this study to determine if there is a difference between Schick digital radiography and Kodak Insight conventional film in accurately determining working lengths when modifying exposure time and source-film/sensor distance.

Twelve teeth with size 15 K-flex files at varying known lengths from the anatomical apex were mounted in a resin-plaster mix to simulate bone density. Each tooth was radiographed while varying the source-film/sensor distance and exposure

time. Four dental professionals examined the images and films independently. Ten images and 10 films were selected at random and re-examined to determine each examiner's repeatability. The error in working length was calculated as the observed value minus the known working length for each tooth type. A mixed-effects, full-factorial analysis of variance (ANOVA) model was used to model the error in working length. Included in the ANOVA model were fixed effects for type of image, distance, exposure time, and all two-way and three-way interactions. The repeatability of each examiner for each film type was assessed by estimating the intra-class correlation coefficient (ICC). The repeatability of each examiner on digital film was good with ICCs ranging from 0.67 to 1.0. Repeatability on the conventional film was poor with ICCs varying from -0.29 to 0.55.We found there was an overall difference between the conventional and digital films ($p < 0.001$). After adjusting for the effects of distance and exposure time, the error in the working length from the digital image was 0.1 mm shorter (95% CI: 0.06, 0.14) than the error in the working length from the film image. There was no difference among distances ($p = 0.999$) nor exposure time ($p = 0.158$) for film or images. Based on the results of our study we conclude that although there is a statistically significant difference, there is no clinically significant difference between digital radiography and conventional film when exposure time and source-film/sensor distance are adjusted.