AN *IN VITRO* COMPARISON OF WORKING LENGTH ACCURACY BETWEEN A DIGITAL SYSTEM AND CONVENTIONAL FILM WHEN VERTICAL ANGULATION OF THE OBJECT IS VARIABLE

by

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When I was seven years old, I explained to my parents that I wanted to be an orthodontist and drive a semi on weekends. I have yet to go over the road with anything larger than my pickup, and my dream of moving teeth has transformed into a passion for saving them, but not a bad prophecy at seven. The completion of this chapter in my life represents the efforts of so many.

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INTRODUCTION

Consistent determination of the correct working length for cleaning, shaping, and obturating root canal systems is one of many important elements in successful endodontic therapy. Working length determination is accomplished with the aid of several methods, including the use of apex locators, knowledge of canal configurations, the tactile feedback of files, and radiography. When radiographs are used to determine working length, the practitioner will utilize either digital radiography systems or conventional films. The principles for obtaining quality diagnostic radiographs for both systems are the same, but the variables affecting conventional film may present differently when compared with digital systems. One of the more common radiographic variables affecting image diagnostics is the vertical angulation of the object as it relates to the film. The consequences of changing vertical angulation are elongation or foreshortening of the image as the exposure angle changes from parallel. The image produced on film may differ from that of the sensor when exposed to x-radiation at these angles.

Working length radiographs continue to be the standard for determining the extent of cleaning, shaping, and ultimately, the length of obturation. For decades, the gold standard for dental imaging has been the use of plain film and conventional processing. Tidmarsh et al.[1] confirmed the use of plain film to be superior to that of digital radiographs and electronic apex locators in length determination. Recently, digital radiography has emerged as the new standard of imaging in dentistry.[2] Digital system advantages as compared with conventional film include image manipulation that enhances the perceived image quality, patient education, lower radiation exposure to patients, and instant imaging.[3-5] Lozano et al.[6] determined that digital radiography, despite its advantages, only approached the accuracy of Ektaspeed film when a K-type file of size 15 was used. Significant differences in the accuracy of digital images were noted in comparison for all file sizes, thus proving conventional film to be more accurate in length determination. Loushine et al.[7] determined that when digital images were enhanced with calibrated measurements, they were more accurate than uncalibrated lengths of the same images. In endodontics, the use of this accompanying software for calibrated working length measurement and interpretation has become standard practice; however, the accuracy compared with plain film is still questioned. Lamus et al.[8] compared known file lengths with Schick CDR and Ektaspeed films and found that the most accurate lengths were determined with conventional films; however, the enhanced digital film error in length determination was minimal, and images were clinically useful. This study did not change variables of exposure and utilized a modified parallel technique.

One specific variable leading to possible distortion and image degradation is the angulation of the source to the object. Proprietary computer software is used to interpret the information to make it suitable for display on the computer monitor. The variables affecting image quality with conventional film are well documented and quantifiable. These include film speed, exposure time, angulation, soft tissue interference, and bone density.[3] There is no published research concerning the response of the digital image sensor to changes in vertical angulation as the sole variable. Whereas several studies have concluded that the accuracy of digital images and conventional films are clinically similar, the exposure variables for these studies have remained constant. Vertical angulation is of particular importance in endodontics as foreshortening and elongation of the film's image will affect the determination of length. Techniques for capturing accurate images include paralleling, modified paralleling, and bisecting angle techniques. Bhakdinaronk et al.[9] determined the most accurate working length films are taken using the paralleling technique. Advantages of the paralleling technique include less distortion due to the limited vertical angulation, increased image clarity, and reproducible cone and film placement. In clinical practice, however, parallel imaging is not consistently feasible or practical. Instead, a modified parallel technique is used so the film is parallel to the central beam and angled to the long axis of the tooth.[10] The modified parallel technique poses unique distortion problems, such as increasing or decreasing angulation between the film and the objects long axis, resulting in elongation or foreshortening of the image. Conventional film and digital sensors respond to x-radiation in much the same manner; however, the active surface for the digital sensor utilizes receptor wells. Receptor wells give depth to the surface of the digital sensor and are oriented perpendicular to the sensor's surface. This topography, seen on the digital sensor, may affect the sensors ability to correctly interpret an accurate image as the angle is modified from perpendicular. The extent of distortion and accuracy when comparing these images will be investigated in this study.

PURPOSE OF THE PRESENT STUDY

The purpose of this investigation is to evaluate how changes in the vertical angulation of the object to the film affect the diagnostic working length accuracy for conventional film versus digital radiographic systems.

HYPOTHESIS

Null hypothesis: There is no significant difference in diagnostic accuracy between radiographs taken with conventional film and the Schick digital system, when the film/object vertical angulation is altered and clinically compared.

Alternative hypothesis: There is significant difference in diagnostic accuracy between radiographs taken with conventional film and the Schick digital system, when the film/object vertical angulation is altered and clinically compared.

REVIEW OF LITERATURE

HISTORY OF ENDODONTICS

As far back as 1500 B. C., the Greeks, Romans and Chinese have been focused on remedies to relieve and treat tooth pain. The Chinese first described dental caries through the tooth worm theory. Medical literature depicts inscriptions of worms atop tooth structure and its subsequent damage.[11] This theory of an outside parasite inflicting damage to the tooth prevailed as the largely accepted theory for decay and the eventual pain associated with it. Not until the age of the microscope was this long celebrated theory dismissed. Pierre Fouchard, in the "Surgical Dentist" refutes the worm theory in 1728, as he describes a method of access and removal of the offending pulpal tissue with the consequent placement of lead fillings. This historic text of the 18th century truly marks the beginning of endodontics in medicine.[12] Leonard Koecher expanded upon this idea in 1820 as he used a heated instrument to effectively cauterize the infected pulpal tissue and protect the remaining tissue with lead foil.[12, 13] Instruments specific to pulpal removal were innovative, such as Edwin Maynard's use of a filed watch spring in 1838. In 1847, Edwin Trumman introduced gutta-percha as a part of a filling material for extirpated pulps; however, it wasn't until 20 years later that G.A. Bowman used gutta-percha as a sole obturation material.[11]

Although developed solely to aid in visualization of the tooth without saliva, Barnum's 1864 use of a rubber dam has proved invaluable in achieving a contamination-free environment, an attribute that would not be appreciated until almost a century later.[12] Other advancements included the use of irrigation solutions, and in 1890, Schreier proposed the use of sodium and potassium mixed with saline to cleanse the canal prior to obturation.

The techniques, technologies, materials, and practices continued to improve with dentists performing rudimentary root canals to relieve pain and restore teeth in their patients. The year 1910 marked a shift in the paradigm of this type of treatment. Decades earlier Miller had proposed the concept that general disease was influenced by oral infection, and by extrapolation the microorganisms that cause the oral infection could disseminate from the focus to the entire body via the bloodstream.[11] This theory did not gain acceptance until an English pathologist and physician, William Hunter, gave a lecture on focal infection in 1910. His lecture, “The Role of Sepsis and Antisepsis in Medicine” halted advancement in endodontics as he accused the dentist of covering “a mass of sepsis” with gold fillings.[14] The theory gained traction throughout medicine and in the public. Physicians believed that systemic disease could now be cured by the extraction of pulpally compromised teeth. This “focal infection theory” lead to the mass extraction of teeth and crippled the advancement of endodontics for more than 20 years. C.N. Johnson, a dentist, balked at the extraction of all pulpless teeth in the 1930s and by the 1940s, laboratory research and clinical trials were sufficient to prove that devitalized teeth did not contribute to systemic disease processes.[15] Johnson’s colleague, Jasper, promoted conservation of teeth and focused on improving endodontic success as he advocated strict asepsis, standard treatment protocols, and precise root length measurement. He denounced the use of mummifying agents to fix diseased pulpal tissue and thus campaigned that all pulpal tissue must be removed. Mitchell et al.[16] in 1953 further disputed the focal infection theory by stating that supporting literature of focal infection lacked sound design, control cohorts, and appropriate bacteriological culture techniques. The focal infection theory that dominated mainstream dentistry in the early part of the 20th century lost favor and endodontics again became a viable treatment option.

As root canal therapy gained momentum in the 1940s, a group of 20 dentists seeking an organization that would serve as the steward of endodontic treatment met in Chicago in 1943. The result of their meeting was The American Association of Endodontists (AAE) and began to set the standard of endodontic treatment in dentistry. The goals of the AAE were four-fold:

1) To promote a forum in which ideas on the methods of pulp conservation and root canal therapy could be exchanged.
2) To stimulate research.
3) To establish local root canal study clubs.
4) To set a standard of care protocol as it related to root canal therapy.

These efforts in 1943 would grow to create the American Board of Endodontics in 1956. The American Dental Association validated these early efforts as endodontics was officially recognized as a specialty in 1963.

The way in which medicine and dentistry was practiced would change drastically with the influence of x-rays and their discovery by Wilhelm Roentgen in 1895.[17] At first, radiographic technique was crude and largely inefficient, often taking 30 minutes to obtain an image. The procedure would also prove deadly as both Roentgen and his wife would later die of exposure-related cancers. Despite the radiation danger, equipment and protocol improved and their use in diagnoses and treatments of disease would prove invaluable in medicine. Edmund Kells, an entrepreneur and dentist, was the first to apply the use of x-radiation to a dental setting and in 1913 marketed and sold the first x-ray machine.[11] Within five years, dentists were using the technology to visualize and enhance endodontic treatment as well as evaluate the successes of treatment.

The use of anesthesia in dentistry dates back to the 1800s. Early surgical procedures utilized sulfuric acid and chloroform as a form of pain control. In 1844, Wells suggested the use of nitrous oxide as a general anesthetic for surgery. Koller used cocaine as a topical anesthetic; however, anesthesia in this form had severe side effects, and thus its use in dentistry was imperfect.[18] The turn of the 19th century brought the use of Novocaine to dentistry and fame to Alfred Einhorn as the patriarch of the era of painless dentistry. This idea of painless dentistry brought dental procedures to the fearful masses, and the image of "Painless Parker" began to dominate the reputation of the profession. Novocaine, although effective in eliminating dental pain, came at a price. Unwanted side effects and allergy in a growing number of patients began to limit its use. Newer, amide local anesthetics eliminated the problems seen with the ester-based Novocaine and have remained the preferred methods of anesthesia.[19]

ENDODONTIC THEORY

Endodontic theory focuses the efforts of endodontic therapy on the removal of bacteria from the root canal system. This cornerstone of therapy was clearly demonstrated when Kakehashi et al.[20] showed that pulpal pathosis does not occur in the absence of bacteria. In this landmark study, notobiotic rats with pulpally exposed teeth were fed sterile diets and failed to develop pulpal pathosis. Paramount to successful root canal therapy is the efficient removal of bacteria from the canals. In every phase of endodontic treatment, including isolation, debridement, irrigation, shaping and obturation, the goal must be to decrease, eliminate, or prevent bacterial colonization of the entire root canal system. Diligent focus on each of these phases during treatment should generate a successful outcome.

In 1955 Stewart[21] outlined the phases of endodontic therapy in three distinct categories: chemomechanical preparation, microbial control, and the complete obturation of the root canal system. Stewart labeled chemomechanical preparation of the root canal system as the most important phase of treatment. In this phase, the root canal system is systematically enlarged with the use of files. As the canal is made larger, the number of viable bacteria is reduced via the physical removal of infected tissues and contaminated dentin of the canal walls. The shape and size attained, as the canal is prepared, allow for more efficient delivery of intracanal medicaments and irrigation solution. Increasing the efficiency of the irrigation solution via canal shaping allows for increased contact time of the antibacterial agents in more apical areas of the canal, while improving the solution’s ability to carry debris coronal for removal.

In 1996 Weine[22] expanded upon the treatment phases to include diagnosis as the first phase to allow for treatment planning. Weine’s definition of the objective of endodontic therapy is to restore the health and masticatory function of teeth through proper restoration. He proclaimed that one should always use a rubber dam and that the overextension of both instruments and obturation materials should be avoided. In agreement with Stewart,[23] Weine referred to the preparation of the root canal system as the most important segment of endodontic treatment. He said once the canal has been properly shaped and cleaned, the canal should be completely obturated with an inert material to allow for a hermetic seal of the canal system.

Consistent with Weine and Stewart, the chemomechanical preparation of the canal space is regarded by most clinicians to be the most important step in root canal therapy. Conversely, Keller argues that complete obturation of the root canal system is the most important step of therapy. The health of the peridontium with normal osseous tissues, intact periodontal ligament, and lamina-dura at the periapex can only be obtained through complete obturation. The ideal obturation should include a fill that seals the system at the cemento-dentinal junction and promotes new cemental deposition.

Endodontic theory and treatment protocol were expanded in 1967 by Grossman.[24] He submitted 13 principles of endodontic treatment that should be completed during any root canal procedure:

1) Use of aseptic technique.
2) Instruments should remain within the root canal.
3) Instruments should never be forced apically.
4) Canal space must be enlarged from its original size.
5) The root canal system should be continuously irrigated with an antiseptic.
6) Solutions should remain within the canal space.
7) Fistulas do not require special treatment.
8) A negative culture should be obtained before obturation of the root canal.
9) A hermetic seal of the root canal system should be obtained.
10) Obturation material should not be irritating to the periapical tissues.
11) If an acute alveolar abscess is present, proper drainage must be established.

12) Injections into infectious areas should be avoided.

13) Apical surgery may be required to promote healing of the pulpless tooth.

Grossman’s 13 principles for treatment became known as Grossman’s tenets. This treatment protocol is still used today as the standard compared with all new treatment modalities.

In the same year, Schilder[25] proposed that the ultimate objective of endodontic therapy was the elimination of diseased root canal tissue and contents to rectify periapical infection and inflammation. He proposed that the breakdown of periapical tissues can be halted only when the canal system is sealed from the periodontal ligament and surrounding bone. This is specifically achieved through the use of instruments and antiseptics followed by complete, three-dimensional filling of the root canal spaces 0.5 mm to 1 mm from the radiographic apex. Pitt-Ford[26] further expanded on the idea of three-dimensional obturation when he explained the objectives of filling as:

1) Diminishing the space available to colonizing bacteria.

2) Preventing the contamination of the apex after extirpation of the pulp.

3) Preventing the movement of bacteria along the canal walls.

Siskin stated that improperly sealed canals were prone to failure because they provide area in which tissue exudates may accumulate and stagnate allowing for the continued irritation of the periapex, which may delay or limit healing.[27] The idle tissue fluids may also serve as nidus for secondary infection.

Sealing of the root canal system from the apex to the pulp chamber results in high clinical success. However, the sealing of the pulp chamber from the oral cavity is of equal importance. Ray and Trope examined 1010 teeth with varying qualities of root canal obturation and coronal restoration.[28] Their research indicated that the quality of the coronal seal was the most important factor in determining endodontic success.

SUCCESS OF ENDODONTIC THERAPY

With the goals of endodontic theory and maintaining and improving the oral health of individual patients, it has never been more important to critically evaluate the current success and failure of root canal therapy. Current and appropriate knowledge will lead practitioners in proper decision-making when comparing alternative treatments of extraction and replacement.

The Toronto Study examined 450 endodontically treated teeth and related the preoperative diagnosis to success and outcome. The research was conducted over a period of 4 years to 6 years and all teeth were treated using the same endodontic protocol for instrumentation and obturation. The study concluded that preoperative teeth without apical periodontitis had a success of 92 percent, while those with apical periodontitis were only successful 74 percent of the time. Other factors included were the number of roots, presence of a periapical radiolucency, pulp vitality, lateral or vertical condensation of gutta-percha, and the presence of a temporary or definitive seal. In all cases, these variables were not shown to have an effect on overall success.[29]

Lazarski[30] followed 110,766 teeth over a three-and-half-year follow-up period and found that 94-percent of endodontically treated teeth remained functional. As a corollary, those teeth with intact coronal restorations were less likely to be extracted than those teeth with failing or temporary coronal restorations. Similarly, Salehrabi and Rotstein[31] found a 97-percent success rate when they followed 1,462,936 endodontically treated teeth over an eight-year period. Comparisons between root canals completed by general practitioners versus endodontic specialists, according to Alley,[32] show 89-percent and 98-percent success rates, respectively.

The success rates illustrate the importance and validity of root canal therapy as an integral part of comprehensive oral health care provided to patients. When the patients desire to retain natural dentition, and when there exists sound clinical judgment of restorative and periodontal prognosis by the clinician, root canal therapy can be expected to maintain functional natural dentition.

CANAL ANATOMY

The degree of complexity of the root canal system is often underestimated by clinicians as irregularities of the canal systems are often underinstrumented.[11] Several key anatomical and histological studies confirm complexity of the anatomy of the root canal system.[33, 34] The complexities confirmed in these studies include differences in the number, length, curvature, and diameter of root canals. In 1890, G.V. Black was one of the primary dental professionals to illustrate canal anatomy in his book, *Descriptive Anatomy of Human Teeth*.[35] Like most early studies to determine the internal configuration of canals, G.V. Black sectioned his teeth and illustrated what he observed. Still, limitations in magnification and an inability to precisely section the teeth left most of the minor variables undiscovered. The true nature of the canal systems was realized in a landmark study by Hess.[36] Hess decalcified teeth and injected, under pressure, vulcanized rubber to create impressions of their internal structure. With the conclusion of this study, it was clear that the canal structure was comprised of intricate fins, isthmuses, and irregular cross-sectional shapes and not the cylindrical canals described by G.V. Black.

In 1972 Pineda and Kuttler[37] examined 4,183 extracted teeth by taking various radiographic angles. Two of the more important conclusions of the study were that the canals have a marked reduction in diameter in older age groups and that only 3-percent of teeth studied were straight in both the mesio-distal and bucco-lingual planes; both findings illustrated the complexity found in the root canal systems. Canals are variable in their size, shape, and number. Canals develop in a multitude of directions, with divisions and fusions throughout the internal anatomy. Moreover, there are stages of development and the dental history to consider when determining the root canal anatomy. Thus, root canal anatomy is constantly evolving with age and is extremely complex. Despite the variations of the root canal system, patterns, tendencies and percentages of canal configurations can be determined.

In 1984 Vertucci introduced a classic study classifying commonly seen variations of root canal anatomy.[38] Vertucci examined 2,400 permanent extracted teeth using a dye injection technique that highlighted the canal anatomy. His result determined eight canal types that were classified as follows:

1. Type I is a single canal from the chamber to the apex.
2. Type II has two separate canals from the chamber, but joins near the apex and exits as one.
3. Type III has one canal that separates into two canals in the mid-root and rejoins and exits as one canal.

4. Type IV has two separate canals in the chamber that exit as two separate canals.
5. Type V has a single canal that divides into two separate canals.
6. Type VI has two canals in the chamber that join and then exit as two separate canals.
7. Type VII has a single canal in the chamber that divides and rejoins and then exits as two canals.
8. Type VIII has three separate canals from chamber to apex.

Walton[3] illustrates the Weine classification for canal configurations and highlights four common canal configurations:

1. Type I is a single canal from the chamber to the apex.
2. Type II has two separate canals from the chamber, but they join near the apex and exit as one.
3. Type III has two canals from chamber to apex.
4. Type IV has one canal from the chamber, but which exits as two separate canals.

Regardless of the classification system used, both studies illustrate the complex nature of root canal systems, varying in size, number, and configurations.

Some of the more variable teeth when root canal morphology is considered are human molars. Skidmore and Bjorndal[39] looked at extracted mandibular first molars. The decalcified teeth were resin-filled and assessed for the percent of canals present. The conclusion of the study was as followed:

1. 6.7 percent had two canals.

2. 64.4 percent had three canals.
3. 28.0 percent had four canals.

Due to the high percentage of molars with four canals, the authors suggested always looking for a second distal canal in mandibular molars. Hartwell[40] in his study of maxillary first molars found that in 121 molars evaluated, 70.2-percent had a fourth canal that 99-percent of the time was located in the mesiobuccal. These studies and other similar studies illustrate the value of a thorough understanding of possible variations within teeth to successfully debride, shape, and obturate teeth.

ANATOMY OF THE ROOT APEX

In deciding the terminus of root end obturation and instrumentation, the complex anatomy of the apex must be scrutinized. In the early 20th century, the common belief among dental professionals was that the dental pulp extended beyond the root apex into the periodontal tissues.[41] The root apex ends at the dentinocemental junction, an area where the dental pulp proper ceases and merges with tissue of periapical histology.[41, 42] By observing histological samples, Gorve[43] described the terminus as an area that contains only a cementum constriction.

Early studies by Coolidge[42] stated that it was of no consequence if the pulp were amputated at the apex or short of the apex by 2 mm to 3 mm. The early success of treatment led to the common philosophy of retaining medication, instrumentation, and obturation within the root canal. Kuttler[44] studied 268 teeth and determined that the ideal working length of the root canal system is measured at this apical constriction. The results of his study indicated that the constriction, on average, was 0.5 mm to 0.6 mm coronal to the anatomical apex. The anatomical diameter of the apex showed significant variation when age groups were compared showing larger diameters in older patients by 0.12 mm.

Green[45] in 1955 utilized stereomicroscopy to evaluate the apicies of 100 mandibular molars. When comparing the distance from the anatomical apex between mesial roots and distal roots, the results showed 0.45 mm and 0.52 mm, respectively. Perhaps most indicative of the root end variance in Green’s study is that the apical foramen in some teeth was measured as far as 3 mm from the anatomical apex. In 1969, Chapman’s[46] results showed similar results for anterior dentition when he examined the apical 3 mm of 120 extracted maxillary and mandibular anterior teeth. The apical constriction lies within the region of 0.5 mm to 1.0 mm from the apex in 92.5-percent of cases. An additional study conducted by Burch and Hulen[47] investigated the relation of the apical foramen to the anatomic apex in 877 teeth and found the average distance between the foramen and the anatomic root apex to be 0.59 mm. With the location of the apical constriction identified, the success and failure of endodontic therapy could now be studied as it relates to the length of obturation.

Endodontic obturation falls into one of four categories according to Kuttler:[44] 1) overfilling or obturation beyond the CDJ; 2) under-filling or obturation short of the CDJ; 3) obturation flush with the apex, and 4) obturation flush with the CDJ. Through his research, Kuttler defined the ideal obturation: “[An obturation] that thoroughly fills the dentinal portion of the canals, seals the cementodentinal junction and stimulates the obliteration of the cemental portion of the canal with new cementum deposition.”

Overfill, he concluded, would not allow for new cementum deposit and thus would leave the apical obturation unsealed.

The apical tissue reaction to root canal filling materials is documented in a study by Murazabal[48] in 1966. Murazabal found that tissue reactions to obturation materials were dependent upon the extent of the overfill and type of material in contact with tissues. In general, apical inflammation increased with increased amounts of material as expected. However, more obscure were the results for the type of material. If the material remained soft, the physiological response was to dissolve the material and elicit a more severe biological response in the periapical tissues. Conversely, hard materials were encapsulated and walled off from the remaining periapical tissues. Erausquin[49, 50] in multiple studies showed that periapical reactions were severe when root filling material was extended to the periodontal tissues. His 1970 study demonstrated that zinc, titanium, lead, and aluminum oxides; components of root filling materials, resulted in necrosis of the periodontal ligament. Further investigation showed that necrosis was not limited to the periodontal ligament, but affected the adjacent bone. Healing of the area was prolonged due to the slower healing rate of osseous tissues. Conversely, in 1972 Erausquin[50] showed that dentinal plugs instead of foreign filling materials showed significantly less inflammation and no necrosis.

Seltzer[51, 52] in two studies in the late 1960s examined the histological response to periapical tissue of overextended obturation. In one year of clinical follow-ups and radiographic exams, Seltzer found that granulomas formed in teeth with no periapical pathosis prior to initial treatment. Animal studies followed in which Seltzer[53] compared tissue reactions to under- and overfilling of root canal materials. This study was unique because pulpal and periapical inflammation was not present prior to instrumentation; therefore, inflammation present at follow-up was a direct result of endodontic instrumentation. Over a follow-up period of two to 39 weeks, Seltzer found that the inflammatory reaction to underfilling was less severe and shorter when compared with overextended obturation.

In a 20-year study, Swartz[54] identified successes and failures in his private practice. His overall success rate for root canal therapy was 89.66-percent; however, that percentage dropped to 63-percent when the canal on the radiograph was considered to be overfilled. Underfilled and flush-filled canals resulted in a success rate four times that of overfilled canals. In a similar clinical study, Bergenholtz[55] examined 556 root canals completed by dental students in Scandinavia. On follow-up exam, a full 35-percent of teeth with overfilled canals were indicated for retreatment. Furthermore, upon retreatment, the root canals showed an overall lower success rate.

While tissue inflammation and overall success rates of root canal therapy are adversely affected by overextension of filling materials, these are not the only components of root canal therapy to consider. Endodontic flare-up or an exacerbation of symptoms following root canal therapy has been shown to have an increased incidence when instrumentation and obturation occur beyond the apical foramen. Flare-ups are seen in previously asymptomatic teeth with chronic apical periodontitis. Seltzer explains that the periapical tissues in such cases have adapted to the inflammation. Disruption of this inflammatory apical periodontitis with the extrusion of filling materials can result in liquefactive necrosis and purulence. The clinical result is severe pain and swelling.

Ruccuci et al.[56, 57] examined the reaction of intracanal pulp tissues histologically in 35 patients. The study observed the health of pericapical tissues when instrumented short or long of the apical foramen. Biopsy of the apex and periapical tissues were congruent with previous studies. Over-instrumentation displayed severe inflammation and necrosis of tissues in direct contact with extruded materials. Vital pulp tissues were noted in cases where the obturation and instrumentation was confined to canal space. Ruccuci indicates that the prognosis of root-canal-treated teeth is greatly improved if “homogenous obturation to the apical constriction” is obtained.

HISTORY OF DENTAL RADIOGRAPHY

The year 1895 marked what would become one of the most important events in modern medicine with the discovery of the x-ray by Wilhelm Roentgen in Germany.[58, 59] Soon adaptations were made to the process to allow for intraoral images. Morton[59] was the first to appreciate the dental pulp chamber on images. The first experimentation with radiographs and working length determination occurred with C. Edmund Kells in 1899, with the use of a wire placed in a central incisor to help determine length. The information provided on radiograph was invaluable to practitioners seeking to increase successful treatment outcomes. With these early successes, the use of the dental radiographs taken for root canal treatment quickly became the standard of care. Practitioners like Merrit[60] were among the first to outline the use of radiographs in dental treatment. He advocated the use of radiographs for pre-operation, during instrumentation, and for postoperative exam. As the potential outcomes of endodontically treated teeth became more evident, Liebman[61] was the first to advocate a recall radiograph as he noted that root-canal-treated teeth and the surrounding peridontium often change in the month following treatment. The addition of dental radiographs in patient treatment became the standard of care not only in the dental office, but as Sweet[62] outlined in his 1938 article, “The Legal Aspect of Dental Roentgenograms,” the US legal community demanded their use. By the 1940s, as reported by Bober,[59] dental professionals agreed that radiographs were necessary in the treatment of pulpless teeth.

The use of dental radiographs, although helpful, was fraught with inconsistent images and difficulties in interpretation. Most of the inconsistencies were traced to technique and protocol. The standardization of the techniques used to obtain diagnostic images was necessary to allow a reproducible image. McCormack[63] recognized the early benefits of standard techniques in patient position, film position, and exposure perimeters and made efforts to be consistent throughout treatment for each patient. As early practitioners noted, image quality was wildly affected as orientation angles of the film and object were different. Price[64] outlined a technique for bisecting the angle between the tooth and the film along an imaginary plane with the central x-ray perpendicular. This become known as the bisecting angle technique. Throughout the middle part of the 20th century and into the 1970s, this dominated the techniques used for intraoral radiography. The technique failed to reproduce consistent images and was replaced by the right-angle technique.

Fitzgerald[65, 66] first pioneered a technique for right-angle radiography. Commonly referred to as paralleling technique, the protocol calls for film placement parallel to the long axis of the tooth to be radiographed. Coinciding with the development of the technique was the further advancement in x-ray equipment technology. The procedure required the use of more powerful radiation generators due to an increase in object-film distance. Fitzgerald recommended the use of hemostats in solid spacers to aid on film placement and enhance the predictability of the result. The limitations to the technique were, unfortunately, not rectified via more powerful x-ray generation. The increased object-film distance had the effect of blurring the image. Through experimentation the film-to-anode distance, commonly 8 inches, was increased to 14 inches and eliminated the blurring effect on the film.[65] This increase in distance yielded a sharper, more detailed image. Updegrave[67] expanded on variable cone distance, and through his 1951 experimentations, he determined 16 inches of set cone distance was determined to be optimum. To accomplish the desired cone distance, Updegrave[67] fashioned a wire extension that could be retrofitted to the standard 8 inch cone. This design was later incorporated into manufactured cone heads. In 1959, Updegrave,[68] unhappy with cone positioning variables, introduced a system of plastic guides and film holders that improved the repeatability and alignment of the film, tooth, and cone head. These film holders were the preceptor to the current XCP, manufactured by the Rinn Corp. of Dentsply USA.

RADIOGRAPHIC VARIABLES

The interpretation of dental films is ultimately up to the observer. It is a representation of anatomy that is limited in its diagnostic value if the image is inaccurate. Inaccuracies in films are due to several variables that include film-source distance, and vertical and horizontal angulations of the object and film and source, among other variables. Vertical and horizontal angulation was the subject of Thunthy's[69] 1986 research. Observers were asked to determine pulp-caries distances as well as to observe canal spaces. These are two areas of critical importance to endodontics. Evaluators frequently misdiagnosed caries exposures on vertical angle films and were unable to distinguish canal space when horizontal angles were less than ideal. When used properly, the parallel technique is a vast improvement over the distortion problems that are seen in the bisecting angle technique. However, the ideal parallel orientation is not always feasible clinically. Barr and Gron[70] demonstrated the limitation when the technique was tried in the maxilla of individuals with shallow palatal vaults. The study revealed that the parallel orientation of the films taken was only correctly oriented to the limited portions parallel to the long axis; however, the relative anatomical size was distorted. They concluded that the displayed orientation, with respect to the location of the structures was proper, but the scale was inaccurate. These inaccuracies yielded images that were elongated up to 10-percent. This is of critical importance to root canal therapy, as a 22-mm palatal root may be misrepresented by as much as 2.2 mm. Their study did attempt to rectify the inaccuracies by allowing for the film to diverge up to 20° from parallel to the long axis of the tooth, while keeping the central beam perpendicular to the film. The interesting results showed that longitudinal distortion was minimized or eliminated at the detriment to orientation of the structures. These findings suggested that although true paralleling radiography may prove impossible in the maxilla, modification of the protocol by as little as 20° yields a better diagnostic image.

A 1966 study of longitudinal distortion by Langland[71] contrasted images taken of anterior teeth with an XCP to known tooth lengths. One hundred percent of images in the study were elongated or foreshortened; however, the values of the distortion in millimeters, in most cases, was insignificant. Typically, the film represented a foreshortened image. The results suggested that films taken for endodontic diagnostic evaluation of working length and obturation be taken with an XCP for the most accurate representation of actual tooth length.

Two closely related exposure parameters that affect radiographically produced images are kilovolt peak (kVp) and milliampere-second (mAs). When voltage is applied to the x-ray tube, the resultant radiation is determined based on the peak of that voltage; the value, expressed as kilovolt peak, is variable in modern x-ray units.[11] This peak in voltage is another variable that must be anticipated when taking dental radiographs, because changes in kVp have a direct effect on the image produced. Commonly kVp is related to the image contrast and defines the quality of the x-ray beam. Contrast is the effective difference in the degree of density between two areas on the radiograph.[72] Milliampere-seconds are a unit of radiographic exposure equal to the product of the milliamperage and the exposure time in seconds, when milliamperage is the electrical current present in the x-ray tube at the time of exposure or when the kVp is applied.[72] Milliampere-seconds are commonly related to the density of the image seen on the radiograph. The relation is linear and describes the intensity of the x-ray. Density is the degree of darkness on the film.

In the infancy of dental radiographs, these exposure parameters remained constant due to limitations of the equipment. As the sophistication of the imaging equipment progressed, the ability to control the levels of kVp and mAs became clear variables in the determination of the image.

In 1978 Thunthy[73] described the effects of kVp and mAs on film resolution and film contrast in a two-part study and found that when the "film density was kept constant, the higher the kVp, the lower the resolution and image contrast percentage. Also, the higher the mAs, the higher the resolution and image contrast percentage." The second part of the experiment explored the outcome of images taken when density was not constant. The relation of kVp and contrast and density showed no significant difference from the first study; however, a slight correlation could be made for density and contrast for changing mAs when Kvp was variable. The conclusion was a "positive correlation between resolution and image contrast percentage, but a negative correlation was found between resolution and film density."[73]

Webber et al.[74] in 1968 found diagnostic consequences of varying the kVp for intraoral radiographs taken on teeth with known interproximal caries. The experiment focused on images taken with 65 kVp and 90 kVp. Subjective assessment valued 65 kVp with fewer diagnostic errors than those images taken at higher kilovoltages. In a similar 1976 study, Oishi et al.[75] looked at the effect of kVp on diagnostic image quality. He found that high areas of natural contrast like the interproximal space and the enamel of the tooth crown showed less contrast. However, more even areas of natural contrast showed an increase in contrast between the more subtle shades of gray.

DIGITAL RADIOGRAPHY

Updegrave[67] in 1951 discussed the principles of accepting a new technique, material, or equipment and has often been quoted when discussing the principles for successful addition to the armamentarium of a clinician from his article in *Oral Surgery*

Oral Medicine Oral Pathology. He stated that prior to a new technique being accepted four tenets must be observed:[67]

1. It must prove practical.
2. It must produce improved results.
3. Additional equipment must be obtainable.
4. Improvement of results must warrant the effort and expense.

In the brief history of dental radiography, there have been advancements in technique, safety, and materials. However, no improvement had such wide-ranging impact as the introduction of digital radiographic technology in the latter part of the 20th century. Although not immediately identified in 1987, the merits of digital radiography for the use in dentistry were outlined by Eikenberg and Vandre[76] in 2000 when they stated digital systems allow for greater speed in image acquisition, require no disposal for developing chemicals, fulfill the desire for electronic record keeping, and reduce patient radiation exposure. In 1987, Geneva, Switzerland showcased a black-and-white television-based system named RadioVisioGraphy by Dr. Francis Mouyen. The direct digital system was the first of its kind, but was initially limited due to the poor quality, lack of proper resolution, and gray scale of the monitors of the day. The degradation of the displayed image was due to the use of Video Graphics Array (VGA) cards, whose limitations in image resolution limited the display. VGA systems were released by the IBM Corporation in 1987 and were proprietary to IBM-defined standards. VGA systems used a resolution of 640 X 480 based on a 4-bit system. The 4-bit refers to the color that is actually displayed from a 64-color palate. The 64-color palate could also be enhanced via 256 shades of gray. Enhancement of the VGA graphics yielded Ultra-VGA (UVGA) and Super-VGA (SVGA). Unlike IBM VGA systems, SVGA systems were defined via the independent Video Electronics Standards Association (VESA) and allowed resolution of 1024 X 768 8-bit pixels.[77] Great advancements have been made since the inception of the early VGA monitors because technology in software and hardware has continued to grow at an exponential rate. These advancements have allowed image manipulation of contrast and brightness. The relation of the contrast, density, and brightness of the displayed image was once seen as a linear relation but can now be manipulated to produce a desired effect on the image.

Allowing an image to be displayed on a digital monitor was not limited solely to digital systems. The photostimulated luminescence (PSL) was first pioneered by the Fuji Corp. in 1983. The system has been modified and used with some frequency in modern medicine. This modified system utilizes a photostimulable phosphor plate (PSP). X-ray is used to excite phosphor molecules that when revealed via a processing laser known as a photomultiplier can be converted to a digital image.[78] Advantages of this system include lower cost than traditional digital systems, the ability to use existing x-ray equipment without modification, and faster processing times when compared with traditional film. However, the plates are fragile and susceptible to scratching and damage, although they can be reused and have a life of 300 to 400 images. In 1970 Savara et al.[79] showed how a phosphor screen, when attached to an optical source, can produce an image, if the phosphorous is excited via radiation. This was the first intraoral use of a phosphor screen in dental radiography. The optical connection carries the light from the phosphor screen that is produced when excited by the x-radiation. At this point, the light is organized, but too weak to form images. The light travels through an intensifier and the final image is stored and displayed.

The backbone of a digital imaging system is the sensor. Now produced in several iterations by more than two dozen companies, the concept of charged-coupled devices or CCDs was first introduced by Eugene F. Lally. His 1961 article "Mosaic Guidance for Interplanetary Travel," explained the use of optical detectors that are able to produce an image when digitally processed. Although technology was not fully developed, Lally's work was realized at AT&T Bell labs in 1969 by Willard Boyle. With input from rival companies RCA, Sony, and Texas Instruments, the first commercially available CCD was made available in 1974 for use in medical grade imaging. Current CCDs are essentially energy registers that allow for the transportation of electrical signals (analog) through capacitors that modify the signal for its intended purpose and display. The surface of the CCD is an energy (x-ray) sensitive array or pixels set in silicone.[80] The pixels are discrete boxes in which electrons produced by x-ray or light photons are deposited. This deposit can be controlled via an external circuit and can transfer the electric charge to adjacent pixels to allow for uniformity and coupling of the charge across the full active surface of the sensor.

The basic operation of the CCD in capturing images is complex. The basic CCD has two regions, the photoactive region and the transmission region. The photoactive region is the epitaxial silicone layer and transmission region comprised of the shift register.[81] The epitaxial region is excited via bombardment with x-radiation that produces an electric charge, and as the charge accumulates in each pixel, adjacent pixels are influenced and become more highly charged. This region is comprised mostly of thin silicone matrices due to its highly predictable behavior under voltage changes. These layers are stacked in a particular fashion that will allow potential wells to release their charge from one well to the next with very little decrease in overall voltage across the given length of the active surface. Although extremely thin, these wells can store up to 1 million electrons at full capacity. The electrons are stored in potential wells within the silicone layer; each well is capped via a positively charged layer of silicon dioxide that sequesters the electrons within each well. The silicone dioxide also serves as a gate for the release of the charges from one well to the next.[80] This energy is transferred to a two-dimensional array from one end of the sensor to the other until all wells have dumped their electrons to the array. The wells of the CCD are in columns, and from one layer to another, they function independently of each other. This is described as the two-dimensional parallel register of the CCD. One column is specifically dedicated to a single pixel or picture element. A pixel, located in the transferring portion of the CCD, is represented by a grouping of wells and the silicone dioxide voltage gate or gates and an electrode.[80] The gates are responsible for sensitivity to light or electrons and charge shifting. Depending upon the manufacturer, the number of these components may vary. The array or pixel transfers the electrons to the charge amplifier that converts the charge to voltage. By repeating this process from column to column, the entire digital contents of the array can be sequenced, digitized, and stored for immediate transfer to the serial register. This process is clocked in milliseconds.[81]

In contrast to the two-dimensional parallel resister, a one-dimensional serial register is need to further organize the stored electrons for use in the CCD readout. The serial register and the charged parallel register are separated via still more positively charged electrode gates that allow for one parallel column of transfer at a time. As the pixels are transferred, an increasing positive charge is built up to a point that satisfies the voltage potential of the next gate. This allows the next column to transfer to the serial register. In this way, the columns are kept in an order that is paramount to final image. Once the full charge is established in the serial register, the row of electron packets produced in the transfer progresses toward an output amplifier. The signals produced by the output amplifier are proportional to the charge in each packet and the original energy transferred to the sensor during exposure. The output amplifier converts the electric charge to voltage that can be read via an analog-digital converter. Computer software must assign a grid number to the voltage received from the output amplifier for placement into a image file. The information once analog is now digitized and can be manipulated via software to change values of each voltage-grid location per the users desired outcome; this is image processing.[82] The digitized information must then be converted back to an analog signal for display via S-VGA.[83]

CCD sensors are only as sensitive as their capability to accrue and measure the amount of photo-charge stored and released by each pixel during the time of exposure. Pixels are classified by charge storage capacitance and high dark resistance.[84] CCD imaging can differ dramatically from one sensor to another. CCD sensors are evaluated by their power of resolution, the signal to noise (garbage data) ratio of the ultimate signal, and quantum efficiency or wavelength sensitivity of the photoreceptor.[80]

Three configurations currently exist for CCDs: full frame, frame transfer, and interline transfer.[80] The three steps in image transfer are key to understanding frame transfer.[85]

- The first step of the image capture process on the CCD sensor begins with a reset of the sensor, whereby any residual charge left from the previous image is drained from each pixel.[85]

- In the second step, light is captured from the image scene. The photons hit the sensor and are converted to electrons at each pixel. Electrons accumulate in each pixel during the period in which the sensor is acquiring energy from the external source (x-ray). This period is called the integration period or shutter period.[85]

- In the third step, the integration period, the electrons that have accumulated are shifted out of the pixel and then the pixels are reset and the process starts again for the next image.

According to Adept Electronic Solutions, the difference between interline transfer, frame transfer, and full frame sensors is where "the electrons (pixel charge) are stored (if stored) before being read out of the sensor."[85] The interline transfer CCD is similar to full frame CCD, but with less image clarity. Most common sensors in use today utilize interline transfer.[86]

Nair et al.[83] looked at advancement in CCD sensor technology. He concluded that the newer systems have a smaller active area providing a less bulky sensor and lower absorption requirements, allowing for an equally efficient sensor at lower radiation exposures.

A complementary metal oxide semiconductor (CMOS) sensor is another way to acquire digital images. In imaging sensors utilizing CMOS, each pixel has its own charge-voltage conversion, amplifiers, noise correction, and digitization circuit. They are less expensive to manufacture and produce similar image results as compared with CCD sensor technology. The CMOS sensor has not gained significant traction for use in dentistry due to the bulk of the individual sensor, which does not allow for ease of intra-oral use. The active area of the sensor is also limited for a given sensor size when compared with that of the traditional CCD sensor.[83]

Farman and Farman[87] compared several different digital systems with both CMOS and CCD receptors in order to determine the diagnostic quality of these sensors compared with that of conventional film. They concluded that digital systems were of equal diagnostic quality to that of conventional film. Moreover, CMOS and CCD sensor systems showed no significant difference in special resolution, contrast, or sensitivity to exposure limits.

The resolution of an image is directly related to the image quality produced. Traditionally, resolution is expressed in line pairs per millimeter (lp/mm) whether the image is digital or on film. Film has a resolution of 16 lp/mm that can be improved with the use of magnification to over 20 lp/mm. The digital image has equivalent resolution values and depending upon hardware may even exceed film with a resolution of up to 25 lp/mm. This image size when displayed on a monitor allows for evaluation with magnification. Nair et al. studied the diagnostic value of films and digital images and found that there is no significant advantage of one system over the other.[83]

The sensitivity of the digital sensor is directly related to the pixel size as demonstrated by Giger and Doi.[88] The study evaluated pixel size differences on the basis of threshold contrast. Threshold contrast, liminal contrast, or contrast sensitivity is defined as the smallest contrast needed to determine a target object from its surroundings. Images were taken of objects of differing sizes from 0.1 mm up to 20 mm. The results indicated that 0.2 mm pixel size was adequate for visual detection of the necessary detail in digital images. Above 0.2 mm, image degradation increased dramatically.

Kassebaum et al.[89] disagreed with Giger in the results of his 1989 study. In an effort to examine the diagnostic quality of digital films, he had examiners compare film images of known pathological entities with that of digital images of the same entity. The images were periapical, bitewing, and panoramic films that were then digitized using an image transmission system. Within the group of digitized images, pixel size could be manipulated. Examiners concluded that standard film images had greater diagnostic quality regardless of pixel size utilized; however, the two studies showed similar results for pixel size. When a pixel size of less than 0.2 mm was used, examiners felt that digitized image quality approached that of film.

Webber and Stark[90] revealed that enhanced digital images could be beneficial as diagnostic aids due to the ability of the enhancements to separate familiar visual stimuli. Through the alteration of the film images, when digitized, they were able to show an appreciable advantage when examiners were asked to evaluate images. Through changes in contrast of the digitized images, complex areas of the image were shown to be more amenable to the resolution of the human eye, thus allowing for irregularities or areas of interest to become more prominent as perceived images were more discrete and detailed.

In an effort to evaluate the use of digital radiography by general dentists, Hellen-Halme et al. conducted a survey of 139 general dentists in 2007.[91] The study concluded that a majority of the dentists experienced some sort of clinical difficulty when using digital systems. Caries detection was cited as one of the most difficult interpretations to make when lesions were considered non-cavitational. Modification of the image, utilizing imaging software, was consistently used by dentists, including adjustment of contrast and brightness, as well as adjusting ambient lighting to lower levels to aid in interpretation.

In 2000 Borg et al. sought to compare the image qualities of the solid-state digital sensors to that of phosphor plate receptors. [92] The study included four solid-state detectors, including a computed dental radiography (CDR) Active Pixel Sensor from Schick (Schick Technologies Inc., Long Island, NY) and two photostimulable phosphor (PSP) systems. Conclusions of eight examiners showed that CDR had the highest image quality of those tested. When software enhancement of the images was made available to the examiners, most preferred the original images. One examiner described the computer enhanced image as a "cheating image."[92]

Tyndall et al.[93]compared Kodak Ekta-speed film with a digital system for interproximal caries detection. A total of 66 teeth and 120 interproximal surfaces were imaged with both film and digital systems. Observers were asked to assess the images for the presence or absence of interproximal caries. The digital system software allowed for image enhancement. The study concluded that Ekta-speed and non-enhanced digital images were of equal diagnostic quality in interproximal caries detection. Enhanced images were of lesser diagnostic quality.

Imaging of a vertical root fracture (VRF) is historically one of the more difficult images to obtain. A 2007 study in *Oral and Maxillofacial Radiology* evaluated the diagnostic ability of CCD and conventional film to detect VRF in single canal teeth with previous endodontic treatment. The authors, Tsesis et al.,[94] concluded that neither CCD nor conventional film provided a significant advantage in detection of VRF, but digital films were preferred by the examiners employed in the study.

In early medical imaging, one of the technological hurdles was storage of the images once obtained. Full image sizes infringed upon the capacity of the computers used to store the information and limited "teleradiography" or image sharing via an internet connection. Dental digital radiographic images as a set can be in excess of 20 MB to 50 MB in file size, so that image compression is beneficial in limiting the size of the file while stored on digital media like DVD or on the users hard-drive. There are several types of compression; however, data compression of digital images effectively reduces redundancy of the image data in order to allow storage or transmittal of the data in an efficient form. The lack of redundancy yields a decrease in the size of image files. The degree of the image compression is expressed in a ratio of the uncompressed file size to that of the compressed image.[95]

Two broad categories of compression methods are applied to medical images, lossy and lossless compression. Lossless compression methods use statistical redundancy within the data profile of an image to reproduce the exact image that was stored. Its reproducibility, however, is at the cost of limited compression ratios. According to Koff, in 2006, lossless image compression can only reduce image size two-to-four-fold.[96] In contrast, lossy compression methods decrease file sizes by much larger ratios. The larger file compressions, however, are yielded at the expense of the quality of the reproduced image. In short, the reproduction of an image compressed via lossy methods will not be an exact reproduction of the original. Lossy compression is used if some loss of image fidelity is acceptable.[96]

Debate among the medical community continues about the effects of lossy compression on the diagnostic value of images stored as such. A common concern of lossy compression may be realized clinically with misdiagnosis because subtle findings may not be represented when the image is reproduced. Several studies refute this and cite the use of reasonable compression levels to avoid non-diagnostic images. Dr. Bak, in the 2006 newsletter of The Society for Computer Applications in Radiology, published a literature review of scientific data collected in over 120 research papers on the subject of the use of lossy compression in medical imaging and concluded that "based on scientific studies, irreversible compression is a clinically acceptable option for the compression of medical images."[97] Southard[98] looked at lossy compression specifically for dental radiographs that are stored in a digital video format. He was able to validate the use of digital media to reproduce images that examiners found equal in quality to the original films.

The two most common ways to store a medical digital image in compression is JPEG (Joint Photographic Expert Groups) and JPEG2000. JPEG is most useful at lower compression ratios due to "blockiness," an artifact seen on images with highly compressed JPEGs. In an effort to streamline compression and reproducibility, an upgrade to JPEG2000 offers a new compression method, using wavelet technology that allows for much higher compression ratios (smaller file size) with limited artifact.

Interestingly, the staggering technological advancement for dental digital imaging systems on the market has come with some drawbacks. The consequence of the rapid evolution has limited the number of viable studies undertaken to evaluate these systems.

In a literature review conducted in late 2005, Wenzel looked at the use of digital radiography and caries diagnosis with the use of digital systems.[99] Through an extensive Medline search, articles were produced from 1999 to 2005 with different types of evidence from questionnaires to clinical *in vivo* studies. Wenzel concluded that in most instances a “conclusive judgment may not be possible for digital systems” due to the fact that digital systems were rapidly updated and constantly changing, not allowing research to keep pace with advancement.

WORKING LENGTH DETERMINATION

In a 1918 article concerning the location of the apical foramen, Custer[100] quipped, “Pulp canals have been half filled and overfilled for want of accurate knowledge of root length.” Working length determination is often the result of measurement of preoperative radiographs or operative radiographs with instruments of known length relation within the canals of teeth. Blayney[41] stated that the length of the canal system could be determined through the use of assorted measuring wires being placed within the canals and radiographed. He stated that the length given by the wires was not always accurate and that the length of the shadow produced by the wire on the film would have to be taken into account when determining the exact length. Over the years, the use of grids plastered to the outside of patients’ faces and other bizarre methods proved impractical and inexact. However, the length to which practitioners would go to determine proper working length during endodontic procedures displayed the importance of this one variable in successful treatment.

The proprietary software that accompanies most digital radiographic systems allows for a cursor to be extended between two fixed points on an image and then yields value expressed in millimeters. Recent iterations of the software allow for multiple point-to-point placements of the cursor lines to aid in the accuracy of the working length around curvature. Although calculations are somewhat different among manufacturers, the principle is similar; the distance is calculated via the number of pixels between the two chosen points. The measurement is not only a function of the software, but also the specific pixel size found on the sensor's active surface.[82] Digital images are not immune to errors in projection geometry and thus distortion, elongation, and foreshortening are still common setbacks. The software tools used to measure length will yield erroneous values if these distortions are not corrected with calibration. Calibration typical of digital software requires that an object of a known dimension be captured in the image. The software will prompt the user to enter the measurement of the known object and thus calibrates the entire image. Calibration allows for a more accurate estimate of the distance being measured.

Bregman[101] reported a simple mathematical formula that would allow for working length determination on films. He described a method whereby an instrument is placed a known distance into the canal and radiographed. He then measured the length of the file and the length of the tooth on the radiograph. When the real length of the file and imaged length of the file were compared, a proportion was realized and could be applied to the radiographed length of the tooth to arrive upon the real length of the tooth.

The relation of the measurements is represented in this simple formula as:

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

(Where the CAD is apparent tooth length, as seen on radiograph; CRI is real instrument length; CAI is apparent instrument length as seen on radiograph, and CRD is the real tooth length.)

Ingle's method of file length determination utilized two radiographs.[102] One diagnostic radiograph is obtained and the tooth length is measured. Then, another radiograph is taken with the instrument inserted to that length. The length of the file is then adjusted if long or short by adding or subtracting that distance. This simple method of working length determination is still used and taught today.

Best et al.[103, 104] described a technique that did not require a file or instrument be placed within the canal of a tooth. His method describes placement of a 10-mm steel pin affixed parallel with the long axis of the tooth with soft wax. A radiograph was exposed and placed on a measurement scale-gauge, which would indicate the tooth's length. This method was evaluated at a 95-percent success rate when compared with actual lengths of teeth once extracted.

The electroconductometer, an early version of the modern electronic apex locator, was proposed by Sunada.[103] The use of three electrodes, two attached to the patients' cheeks and one attached to the instrument inserted into the canal, yields a closed electric circuit. When the resistance of the circuit is measured, at 40mA, the apical section of the tooth has been reached. Once reached, the instrument length is marked via a rubber stopper at a repeatable reference point, withdrawn, and measured. This measurement, according to Sunada, can be confirmed via radiograph.

Bramante and Berbert[105] sought to determine the most accurate methods of determining working length of those discussed above. The study examined the methods of Best, Bregman, Ingle, and Sunada for determining tooth length in 224 teeth. The two-radiograph method proposed by Ingle was the most accurate. Sunada's apex locator, although somewhat variable in accuracy, performed better than both the Best and Bergman methods, and in palatal roots, was the most accurate.

The Everett and Fixott[106] method was developed from an approach to evaluate the height of alveolar bone loss over time. Radiographs were overlaid with a plexiglass-gold grid of known dimensions to determine alveolar ridge changes between two radiographs. Although used primarily in periodontics, the same methods were described by the authors in determination of tooth and endodontic instrument length.

One shortcoming of the file and tooth length measurements when using radiographs is the difficulty of reproducing an anatomically accurate image. With this in mind, Forsberg exposed working length films of several teeth and compared paralleling, modified paralleling, and bisecting-angle radiographic techniques.[10] The purpose was to determine which method was most accurate. A 0.3-mm diameter wire simulating an endodontic file was fixed at one of three distances in relation to the anatomical apex: 2 mm beyond the apex, flush with the apex, and 2 mm short of the apex. Exposure parameters were constant while all teeth with the fixed wires were radiographed in all three of the above methods. The study concluded that the paralleling technique was the most accurate in the reproduction of the distance from the file to the apex of the tooth. The bisecting-angle technique was found to be accurate if vertical angulation was minimal. However, inherent difficulty in determining the degree of angulation in a clinical setting limits the viability of the technique.

Variations in projection geometry, depending upon their nature, can result in image distortion and magnification. Loushine et al.[7] suggested several techniques to combat distortion when taking working length films. He explained a simple, effective method of calibration using an opaque object of known dimension placed within the radiographic field. This object then serves as the calibration object to set up a simple yet accurate conversion for precise length measurements. Calibrated images were more accurate than non-calibrated images.

Zulqarnain et al.[107] studied the effect of x-ray beam vertical angulation on radiographs taken of the alveolar ridge. Radiographic assessment of the alveolar crest was completed on five human mandibles at several different vertical angulations, including 10°, 0°, and -10°. They found gross over- and under-estimates of the actual height of the alveolar crest with values that ranged from 1.84 mm to 3.70 mm for individual sites. Zulqarnain stated that the incorrect values were "directly related to the angle of the beam."

Hausmann et al.[108] published a similar result in the *Journal of Periodontal Research* in 1989. He stated that the "degree of inaccuracy is related to the angle of the angular deviation." In a second part of the study, Hausmann compared the average angles of periapical films and bitewing films when taken by clinicians. He found that more significant changes in vertical angulation were seen with periapical films, and as a corollary, an increase in distortion was seen. Both studies illustrate the significant effects of vertical angulation of the central beam and the object when assessing measurements taken from the image.

Guneri et al.[109] utilized new subtraction software for digital images in an effort to eliminate angulation errors. A maxillary right molar was imaged using standard projection geometry of 0° of vertical and horizontal angulation. Several images were then taken with differing vertical angulations. Subtraction software was then used to subtract the standard images from that of the images taken with angular modification. The results indicate that subtraction software was able to tolerate vertical angulations up to 10° from perpendicular. Guneri suggests if vertical angulation is kept under 10°, subtraction software may prove valuable in determining changes in the objects imaged over time.

Garcia et al.[110] investigated the challenges that vertical angulation poses when determining the working length of endodontically treated teeth. Digital radiographs and Ekta-speed films were taken of single-rooted teeth at three vertical angulations, 0°, 15° and 30°, and then compared. The results indicated that no significant difference was observed between the images taken at 0° and 15° for either the digital or conventional images. The 30-degree films for both types of image resulted in the impression of a shortened image equating to 1.5 mm when measured by observers.

In an early study to compare conversional film and the first digital system for working length accuracy, Griffiths et al. found radiovisiography to be grossly inaccurate when compared with that of conventional film.[111]

Hedrick et al.[112] compared two direct digital radiographic systems with regard to working length determination, Trophy and Regam, with conventional E-speed films.

Working length films were taken in a limited number of teeth with the use of a jig that allowed for standardization of the projection geometry. Despite trends towards more accurate readings with conventional films, the results were not statistically significant overall.

At Indiana University, Leddy et al.[113] compared working length accuracy using either RadioVisioGraphy or Kodak E-speed conventional films. Examiners were asked to evaluate working length for both positive and negative digital images and conventional films. No difference between positive and negative images with regard to accuracy was observed. Moreover, no statistical difference was found between digital images and conventional film for working length determination.

In a study entitled an "Evaluation of a Digital Radiography to Estimate Working Length," Almenar, Garcia, and Navarro evaluated direct and indirect techniques of obtaining working length with both conventional and digital films.[114] In addition to perpendicular films, two vertical angulations were taken at 15° and 30° for both methods. They concluded no statistical difference among the methods used with the exception of the film taken at 30° of vertical angulation. This amount of angulation resulted in shortened values in excess of 1 mm when the indirect method was used.

A comparison of the working length accuracy between the Dexis digital system and D-speed film was the focus of Eikenberg and Vandre.[76] Their conclusions indicated that digital measurements were slightly more accurate than those measurements taken on plain film. 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.

Melius et al.[115] used a stereomicroscope to determine the accuracy of Schick CDR and E-speed film. Teeth with single canals were negotiated with a 15 K-type file to the minor foramen as seen under a stereomicroscope. Both digital and conventional films were then exposed with the files in place. There were no alterations in projection geometry between the groups. Evaluation of the radiographic distance between the file tip and the radiographic apex was measured using the digital software and a millimeter-calibrated ruler. They found that there was no clinically significant difference between the conventional film and digital images.

Walton suggested the use of a file size greater than a 10 K-type endodontic file for determining radiographic working length on conventional films. He stated that "number 8 and 10 files should not be used [as the] small tips fade out and are usually not visible (on radiographs)."[3] Friedlander et al.[116] evaluated the image clarity of size 06 K-type files on phosphor-plate digital images and conventional radiographs. The files were placed in extracted human mandibular molars short of the working length, to ensure dentin completely surrounded the file tip. The findings show that the 06 files, when digitally imaged, were non-diagnostic due to lack of clarity and the examiners' inability to decipher the terminus of the file.

There have also been a number of other methods of localizing the elusive apical foramen, which have not utilized radiographs. In 1907, Kells described the dangers of radiation exposure in the dental setting. [117] These dangers coupled with the inherent inaccuracy of the two-dimensional image produced on radiographs spawned the search for new ways to determine the length of root canal systems. Custer[100] outlined an electrical method of finding the apical foramen using electrical conduction. He stated that a voltage difference between a "dry pulp canal and the tissues just beyond the apical foramen" could be quantified. Custer employed a crude method using dry cell batteries, an ammeter, and a negative electrode to determine the location of the apical foramen. This method, although crude and sometimes shocking, proved somewhat accurate in determining the length of the tooth.

Suziki[118] years later expanded upon the concepts set forth by Custer in 1918. His study evaluated the use of what he termed "iontophoresis." Suzuki felt that consistent electrical resistance between an instrument in a root canal system and an electrode in contact with the oral mucosa could be measured more accurately than Custer's early study, making it viable for working length determination. His 1948 experiments on canines concluded that a consistent resistance of 6.5 kΩ between the oral mucosa and the periodontal membrane could be applied to a device used to measure that specific resistance and thus locate the length of the tooth.

Sunada[103] developed a resistance-type apex locator in 1962. His study consisted of two parts. First, he looked to recreate the earlier Suzuki study, and second, to determine, radiographically, if those readings correlated to the instruments being at the working length of the tooth. Sunada successfully recreated Suzuki's 6.5 kΩ resistance. He found that when an instrument was placed within a canal until a reading of 6.5 kΩ was reached, radiographically, this correlated to the length of the canal nine out of 11 times.

Inoue[119] in 1971 departed from sole resistance-type locators, and with the addition of sound waves, created the Sono-explorer. As the instrument is advanced into the canal, the audible pitch of the Sono-explorer changes according to the resistance. A low-pitch sound was emitted when the instrument was in the coronal aspect of the tooth, and higher pitch sounds emanated as the instrument was advanced until a predetermined sound was heard when the apex was reached.

Another type of apex locator is the impedance type. Impedance is a quantifiable measurement of the opposition to the flow of an alternating current.[120] The locator works on the theory that there is greater impedance along canal walls in the coronal third as opposed to more apical areas, due to dentin wall thickness. An example of an impedance type locator is the Root ZX (J. Morita, US).

Ingle[18] classified the major types of apex locators and placed them into first- through fourth-generation locators, based on how the apex locator worked.

- First-generation apex locators are resistance-type apex locators. They measure opposition to the flow of direct current. A reading of 6.5 kΩ (current 40 mA) coincides with the tip of the instrument reaching the apex in the canal.
- Second-generation locators are impedance-type apex locators.
- Third-generation apex locators are more complex frequency-dependent impedance devices. Due to the constant comparing of impedance signals inherent in the design, this type is also known as “comparative impedance.”
- Fourth-generation apex locators by Sybron Endo are ratio-type locators that determine the impedance at several frequencies.

Studies of the accuracy of modern apex locators show an improvement in accuracy over introductory attempts. Tselnik et al.[121] studied the accuracy of the Root ZX (J. Morita, US) and the Elements (SybronEndo, CA) apex locators, third and fourth generation devices, respectively. Both apex locators were more than 90-percent accurate to within 1 mm of the minor constriction of the apex. No significant difference was seen between the two units.

McDonald discussed the advantages of apex locators in determining working length for endodontic therapy as an adjunct to digital radiography.[120] He stated that, "Digital imaging systems provide the clinician with the ability to manipulate, enhance, and store radiographic images for immediate recall, an ability unique for radiography… [Therefore, apex locators] do not replace radiographs completely in treatment." Radiographs are an important piece of data, and a means by which the clinician gleans important information on the overall shape, curvature, and anatomy of teeth. These data give the clinician a good guide and provide a baseline from which to use an apex locator. Current generation apex locators have degrees of accuracy that range from 83.0-percent to 93.4-percent.[120]

Shabahang et al.[122] studied the accuracy of the Root ZX apex locator in an *in-vitro* study and found that it was 96-percent accurate to within +/-0.5 mm of the apical foramen. Nguyen et al.[123] looked at the accuracy of apex locators with enlarged canals and found that the Root ZX was able to identify the narrowest canal diameter in the absence of apical constriction. Ounsi et al.,[124] in an *in-vitro* study, showed that the apex locators are only accurate in the measurement when in contact with the periapical tissues. The study concluded that electronic apex locators were unable to detect the 0.5 mm from the foramen with any accuracy. Ibarrola et al.[125] looked at the effects of canal instrumentation prior to using an apex locator for working length determination. The study demonstrated that if the coronal portion of the canal was flared prior to use of the apex locator, an increased efficiency was observed.

Brunton et al.[126] evaluated if a true decrease in radiation exposure was evident in cases that utilize apex locators for working length determination. Significant reduction in radiation exposure was realized and attributed to a lack of film retakes. Moreover, the working lengths of teeth that used both EALs and radiographs were more accurate.

RADIATION SAFETY

The early careless use of x-radiation would prove to have significant health risks for those individuals in proximity to the radiation source. As imaging evolved, the effects of exposure become more evident as studies published the potential risk of overexposure and the need to limit its frequency. The dosage of ionizing radiation is relatively small in medical imaging. However, there have been several reports that indicate the risks may in fact be higher than once believed. The risks are monitored via the Committee of Biological Effects of Ionizing Radiations (BEIR V) and are outlined in the committee's 1990 publication. The United Nations Scientific Committee on Exposure and Atomic Radiation (UNSCEAR) also monitors and evaluates radiation variables to give recommendation for usage and protection. Diagnostic radiation for the purpose of medical imaging accounts for approximately 11-percent of all annual radiation, a number currently falling due to advancement in equipment and the use of digital systems. When radiation exposure is limited to dental specialists, the 11-percent plummets below 0.5-percent per year.[113] To effectively determine the risk associated with radiation exposure, the dosage of radiation must be defined. In 1990 the International Commission on Radiological Protection (ICRP) defined such a term as the effective dose (ED). In doing so, the ICRP has become the most accepted source in radiation dosage and safety.

Effective dose can be difficult to define, as one component of effective dosage is stochastic. Stochastic risk is a term used to describe a situation in which the outcomes are exceedingly difficult to predict, and therefore, a certain level of allowance is made and reflected in the outcome. In radiation exposure, the stochastic risks are carcinogenesis and hereditary effects. The more acute responses to radiation that display a direct cause-and-effect relation, like erythema radiation sickness and death, are not measured via stochastic means. Effective dose is a comparison of the stochastic risk of non-uniform exposure with the risk of uniform exposure to the whole body. The effective dose was created out of the knowledge that radiation exposure and its risks are not the same throughout the body. Living tissues whose cellular turnover is high are considerably more sensitive to changes induced via radiation than more sessile cellular lineages. The effective dose can be calculated via a weighted average of the equivalent dose with the weighting factors designed to account for the radiosensitivities of the tissue. Once calculated the effective dose is expressed in sieverts (Sv).[127]

Since 1990, studies to determine the detrimental effects of radiation dosage have used the effective dose as defined by the ICRP. Unfortunately, no specific weighting was given to the specific tissues unique to the oral cavity. The effective dosage numbers were updated in 2007, when ICRP revised effective dose calculations based on the latest available information for radiation exposure and the newest tissue sensitivities. The debut of salivary gland tissue, oral mucosa, and extra-thoracic tissues on the sensitivity lists allowed for a more precise calculation of associated risks. The updates proved invaluable when studies that utilized the ICRP protocol from 1990 were recalculated with the new 2007 guidelines. The risk associated with dental radiography was deemed 32-percent to 422-percent higher than the estimates from the 1990 ICRP guidelines. [128] Significantly adjusted sensitivities were seen for salivary gland tissue and the oral mucosa as they received the highest equivalent doses of all tissues reexamined. A completed full-mouth series with D-speed film and round collimation resulted in the largest effective dose according to the ICRP.[128] The ICRP is recommended the following to reduce patient exposure in the 2007 guidelines:

- F-speed film, PSP and charge-coupled device (CCD) sensors should be used rather than E-speed film.
- Rectangular collimation should be used for periapical and bitewing radiographs.
- Clinical examination and patient needs should dictate radiographic selection.

In an effort to determine differences in radiation sensitivity, Greer[129] examined the effect of increasing experimental radiation exposure on several distinct areas of the head and neck. He concluded that some anatomical areas were more sensitive to increasing kVp. Those areas with increased sensitivity were the submandibular tissues, base of the tongue, and sella turcica, whose absorbed dose increased in proportion with the kVp.

In a series of articles in 1989 and 1990, Danforth and Torabinejad evaluated exposure levels of radiation during endodontic procedures, and more specifically, which tissues seemed most susceptible to the radiation. In the first article, Torabinejad et al.[130] investigated the specific risks to tissue via the use of a phantom head and neck with the use of a human skull, cervical vertebrae, and complete dentition embedded in a tissue-equivalent material representative of human soft tissue in density values. In addition, dosimeters were also embedded. Exposures were made at 70 kVp and 90 kVp using the paralleling technique without lead protection on the phantom. They concluded that radiation dosage is low when compared with that of medical therapeutic dosages and other medical imaging processes. Differences in kVp demonstrated that 90 kVp traveled farther through the tissues to deposit radiation beyond that of the targeted radiation site. As a follow up, Danforth and Torabinejad[131] assessed the relative risk of adverse effects of the radiation exposures studied in the first study. Using dose/exposure models for the effective dose, they determined that 90 kVp correlated to an estimated 1 in 7.69 million chance of developing leukemia, a 1 in 667,000 chance of thyroid gland neoplasia, and a 1 in 1.35 million risk of salivary gland neoplasia. As expected, the lower dosage associated with 70 kVp reduced these risks.

Kaeppler et al.[132] sought to determine the most effective means to lower dose radiation. By adjustment of two variables, Kaeppler evaluated an increase in the tube potential setting (and a decrease of milliampere seconds from 90 kVp to 60 kVp) by an additional attenuation (use of lead foils) of the x-ray beam behind the film plane or by the use of digital radiography. Changes in tube potentials did not affect the dosage absorption of the phantom tissues as significantly as expected. In one part of the experiment, lead backing of the films was increased. In general, when tube potential settings were increased, the dose reduction decreased. The absorbed dose was reduced to 52-percent when a digital phosphor plate was used instead of a film at 60 kVp. The use of three lead foils behind the film plane instead of one resulted in a 14.0-percent reduction of the absorbed dose at 60 kVp. His study ultimately concluded that effective dose is more readily reduced via the use of digital radiographic methods.

The use of digital radiography in dentistry in effectively lowering radiation dosages has been well documented. Farmen et al.[133] evaluated the absorbed dose during endodontic treatment of both E- and D-speed film and a digital system. Results indicated that significant reduction in radiation dosage is realized with the use of digital radiography. Reduction in dosage over D-speed film was 94-percent and 90-percent for E-speed film.

Even now, with the lower risk associated with digital dental radiography and E-speed film, the use of protective measures is mandatory. This includes the use of lead patient aprons and thyroid collars and prudent exposure protocol in an effort to limit radiation exposure for the patient and operator alike.

METHODS AND MATERIALS

SELECTION OF TEETH

Twelve human teeth were selected for this study. All teeth were collected from the Oral Health Department under IUPUI/Clarian IRB study number 112456. All teeth were stored in a sealed container with sterile water and kept at a temperature of 37° C. Specific criteria were met for tooth selection. Radiographs were taken in buccal-lingual direction to confirm that a canal system is present with typical morphology representative of the type of tooth selected. Teeth selected consisted of a maxillary central incisor, a maxillary canine, a single rooted maxillary premolar, three maxillary first molars, a mandibular central incisor, a mandibular canine, a single root mandibular premolar, and three mandibular first molars. All canals selected were Walton type I configuration, namely, a single orifice with a single apical foramen. Teeth with abnormal canal anatomy or abnormal root morphology, including obvious lateral canals, extensive caries, or root fracture were discarded. Once the teeth had been selected, 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 6-percent sodium hypochlorite (Chlorox Co., Oakland, CA) for 30 minutes.

SPECIMEN PREPARATION

Selected teeth were then accessed using Brassler Endodontic access bur blocks in accordance with ideal access guidelines set forth by Walton for each individual tooth type.[3] The mesial-buccal canal of the maxillary molar was selected. The distal canal of the mandibular first molar was selected. A #15 K-type endodontic file (Kerr, Remulus, MI) was inserted into the root canal and advanced out the apical foramen of all teeth to ensure canal patency. All teeth with canals that could not be negotiated with a #15 K-type endodontic file were excluded from the study and replaced with a tooth of the same type.

CANAL LENGTH DETERMINATION

Canal length determination was accomplished by passing a #10 K-type endodontic file into the root canal until the file is visually flush at the apical foramen with the aid of a dental operating microscope at X20 magnification (Figure 2). This canal length was recorded for each tooth. An identical #15 K-type endodontic file was then advanced to a distance of either 0.5 mm, 1 mm and 1.5 mm short of the canal length for each individual tooth. Each tooth selected had one of these marked files randomly selected and placed to a length determined by the rubber stopper. This file and canal relation remained constant throughout the study for all teeth selected.

MOUNTING OF TEETH

Only the researchers knew the exact length of the file in each tooth. The files were affixed in place with Super Glue (Super Glue Corp., Rancho Cucamonga, CA.) and 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 (Figure 3). In this way, 12 teeth were mounted in plaster with a known canal/file length relationship (Figure 4).

IMAGE ACQUISITION

Mounted specimens were then subjected to radiographic exposure using Siemens (Charlotte, NC) (Figure 5) conventional Ultra-speed Kodak dental films (Kodak, Rochester, NY) and a Schick digital imaging system using CDR dicom software (Schick Technologies, Long Island City, NY) (Figure 6) for Microsoft Windows. A custom fabricated mounting jig ensured consistency of physical exposure parameters (Figure 7). The mounting jig was fabricated to except the Ultra-speed film (Figure 8) and the digital sensor (Figure 9). The mounting jig also allowed for accurate manipulation of the angulation of the long axis of the object as it related to a fixed and mounted film or sensor. Changes in the angulation were controlled via a rotational mount accurate to 1° (Figures 10 and 11). The distance between the film/sensor and the most posterior aspect of the object remained constant at 5 mm with the collimator fixed at 4 cm to the film surface. The mAs/exposure time was determined at 0.12 ms for the Schick system and 0.25 ms for the Ultra-speed films. These parameters were based on findings of a pilot study. Using the paralleling technique, all teeth were radiographed at 90 ° to their long axis. Secondly, all teeth were radiographed using the modified paralleling technique by taking vertical angled films in 5-degree increments to 20° from perpendicular and subsequently increased to 10-degree increments to a maximum of 40°. These angled modifications took place at both negative and positive values from perpendicular. Therefore, films of varying vertical angulations were taken at 50°, 60°, 70°, 75°, 80°, 85°, 90°, 95°, 100°, 105°, 110°, 120°, and 130° for all teeth in the sample set and with both Ultra-speed film and Schick CDR. In this way, each tooth was imaged 26 times with 13 digital and 13 conventional films exposed. Conventional films were then processed and coded for tracking and evaluation purposes (Figures 12 and 13).

Four dental professionals with experience in working length determination for conventional film and Schick CDR digital software were selected. The examiners selected were two private practice endodontists and two first-year endodontic residents with a minimum of two post-doctorate years of experience. These examiners had no prior knowledge of the file lengths for the individual teeth radiographed. The examiners were given a tutorial on how to operate the software measurement application as well as how to measure the lengths on the conventional films (Figures 14 and 15). Examiners were instructed to determine the distance from the end of the file to the radiographic apex of the tooth. For conventional film, examiners were asked to use magnification of X4 and a graded ruler accurate to 0.5 mm (Figures 15 and 16). All figures not given in 0.5-mm increments were rounded to the nearest 0.5 mm. Films were viewed using a conversional radiograph viewing light box under dim lighting conditions to enhance contrasts. Examiners were limited to 10 seconds for evaluation of individual images. For Schick CDR images, the examiners were asked to calibrate each image and employ the measuring tool bar integrated to the Schick software. The 2-mm blank on the shank of the utilized K-type files was used for individual digital images calibration. Evaluation of the digital images was completed under dim lighting conditions similar to that used for Ultra-speed film evaluations. Examiners were informed that the length of the file in each film was not constant and that the distance from the end measurement was manually recorded.

INTRACLASS CORRELATION COEFFICIENT

Ten randomly selected images were chosen and the examiners were asked to repeat their measurements two weeks after their initial measurements to assess intra-examiner reliability (IER). See Figure 1 for summary of experimental design.

GROUPS

- Group 1: Utilized the Schick CCD sensor and CDR digital software images, for a total of 130 films.
- Group 2: Utilized Ektaspeed Kodak films, for a total of 130 films.

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 film type, angle, and the interaction of angle with film type. 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 a separate 10 randomly selected conventional films were scored a second time by each examiner. The intraclass 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). A mixed model with fixed effects for type of image, angle, and the interaction of the two were used to model working length. Random tooth and examiner effects were also included to incorporate into the model the correlation induced by repeated measurements of the same tooth. Comparisons of the model estimates of mean working length for digital and conventional images were conducted while holding the distance and exposure power constant. A Sidak adjustment was used to control the type 1 error.

Each examiner repeated 10 randomly selected measurements of working length. These were used to measure each examiner's repeatability. Paired t-tests were used to test for no difference. The intraclass correlation coefficient (ICC) was calculated.

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

RESULTS

Several aspects of the error in working length were scrutinized. First, the overall error in the difference between conventional film and digital images was calculated for each tooth and compared among image types. The error in the working length was not significantly different between digital and conventional film images (p = 0.402). The 0.4-mm value indicated that digital film was slightly more accurate from angle to angle, but clinically insignificant due to the small scale of less than 0.5 mm. The significance level for the p-value was set at 0.5 to equate for 0.5 mm in human eye resolution.

In an effort to isolate variables, the error associated with the different angles for each image was excluded. After adjusting for angle, the error in the working length from the digital image was only 0.02 mm greater (95-percent CI: -0.03, 0.06) than the conventional film. This represents a clinically insignificant difference.

Lastly, the images were compared for each tooth at each specific angle. There was no significant difference among the different angles (p = 0.246) for all teeth in the test set. Furthermore, there was no statistical difference seen among image types and the angle (p = 0.149). When tooth type was corrected for, there was not enough variability to make a statistical comparison.

As a secondary conclusion, the ICC measured a significant difference in the examiner repeatability for film types. Digital films were significantly (p = 0.50) easier to evaluate consistently among all examiners.

FIGURES AND TABLES

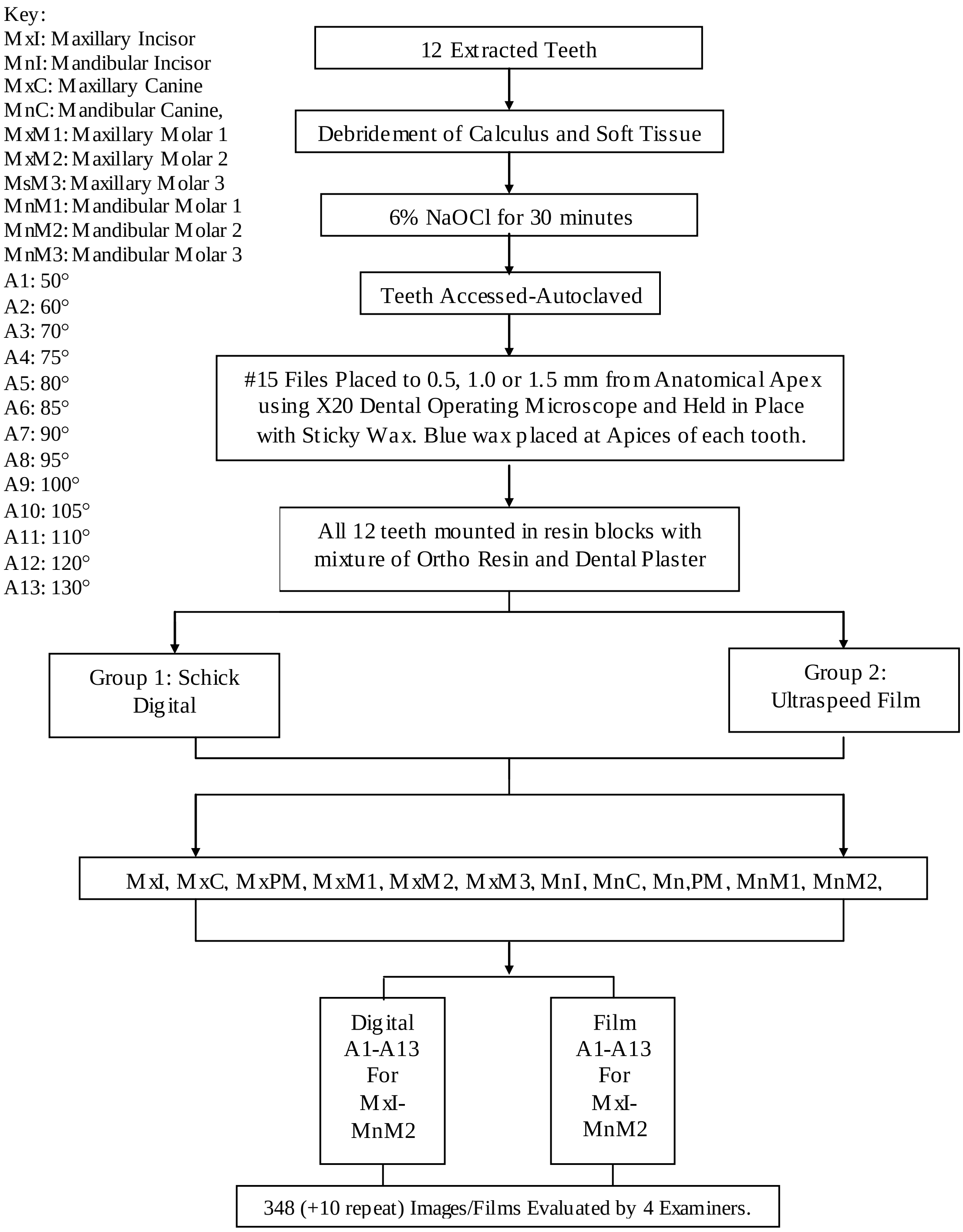


FIGURE 1. Summary of experimental design.

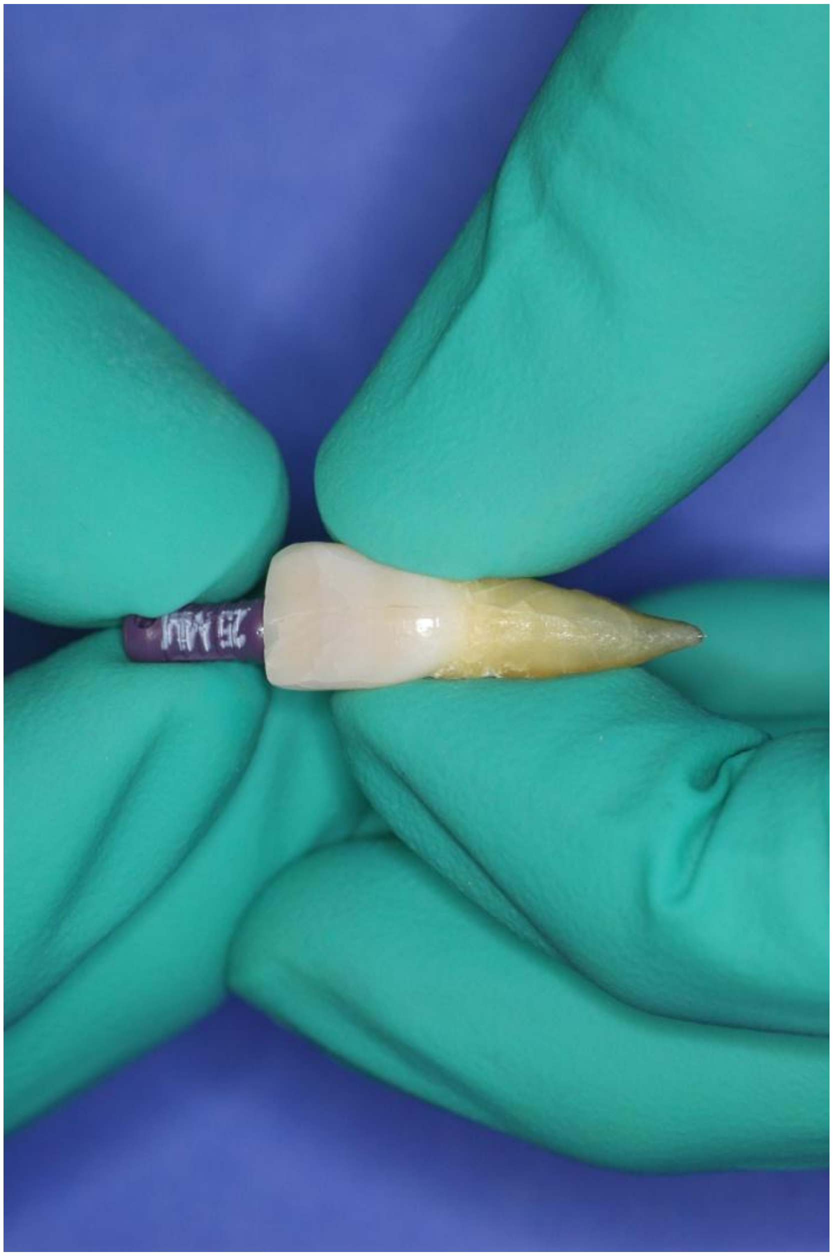


FIGURE 2. Working length determination.

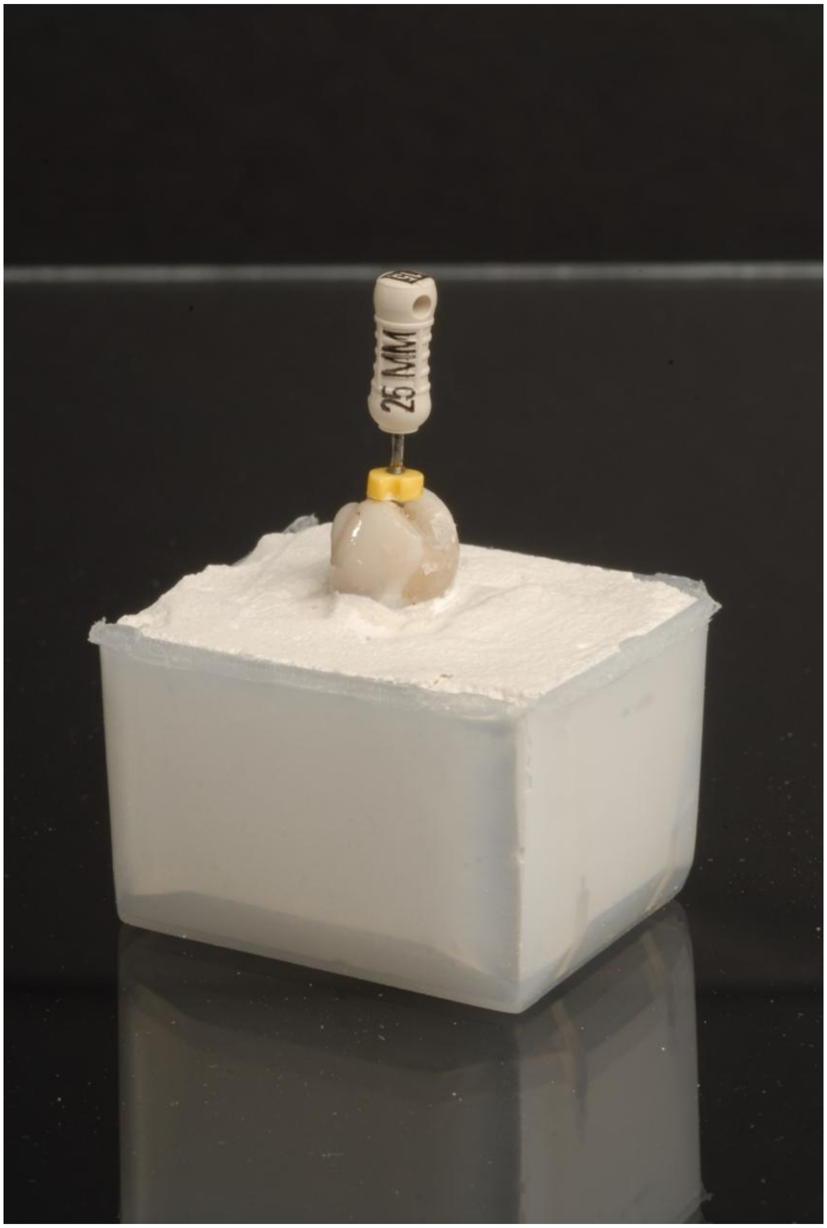


FIGURE 3. Mounted specimen.

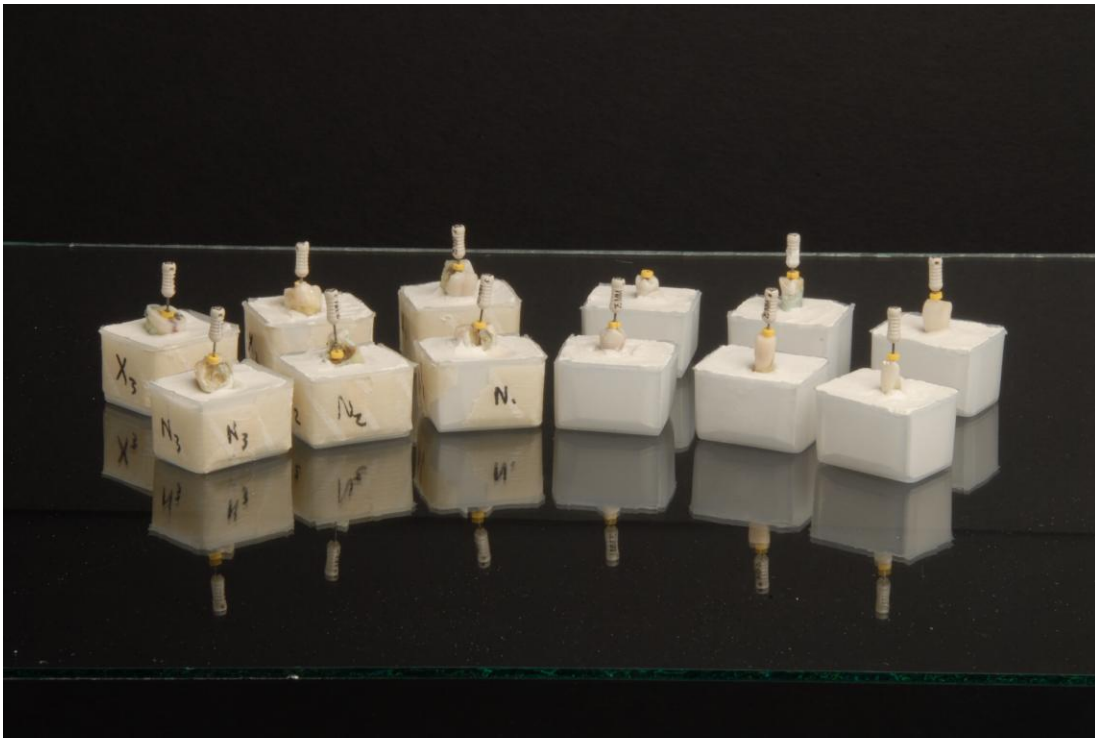


FIGURE 4. Twelve mounted specimens.

FIGURE 5. X-ray head unit.

FIGURE 6. Schick digital sensor.

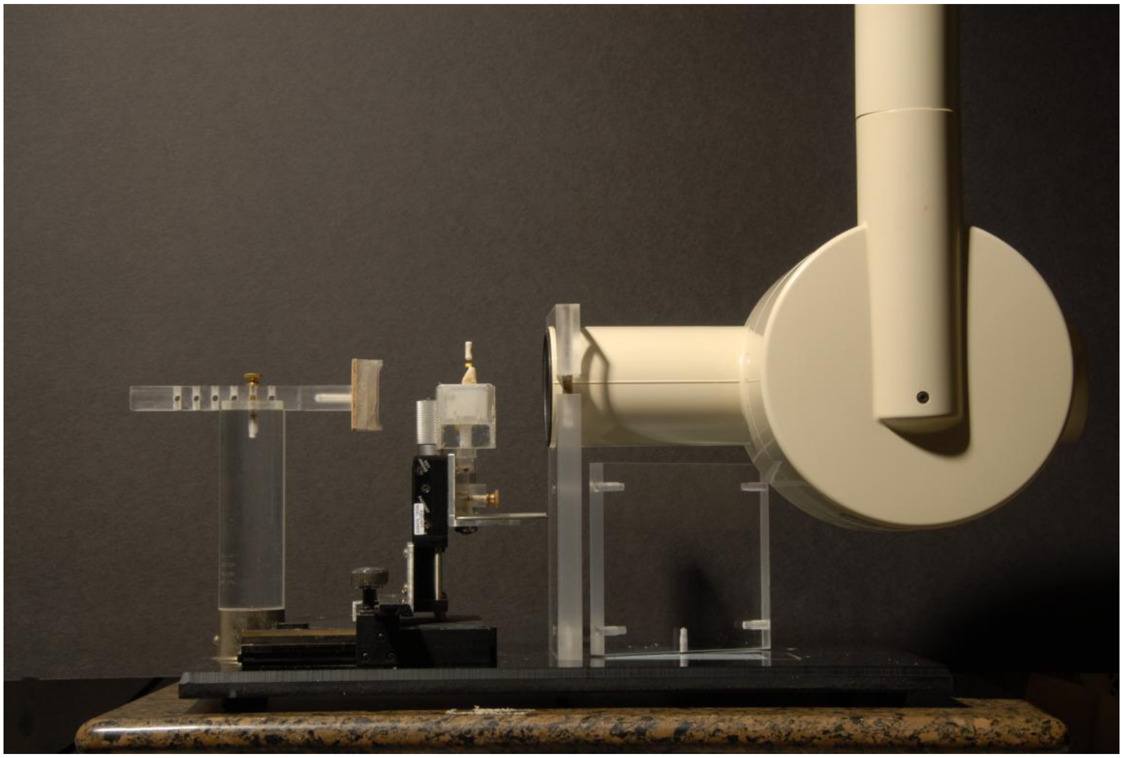


FIGURE 7. Jig setup.

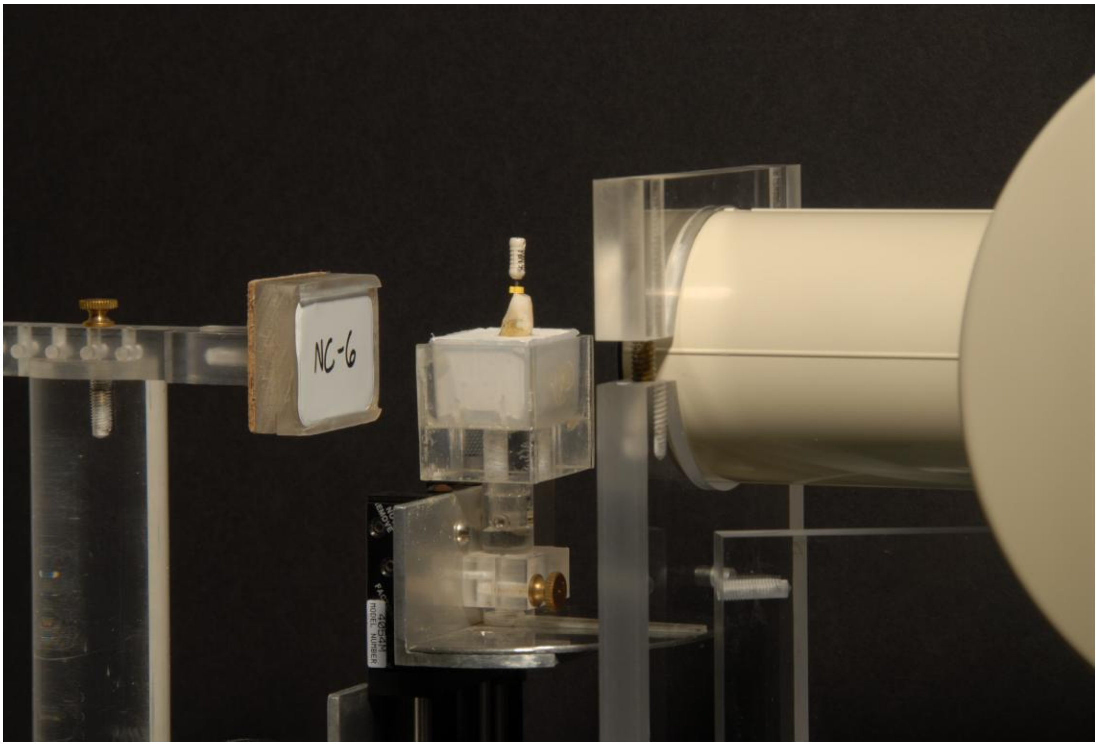


FIGURE 8. Conventional film jig set up.

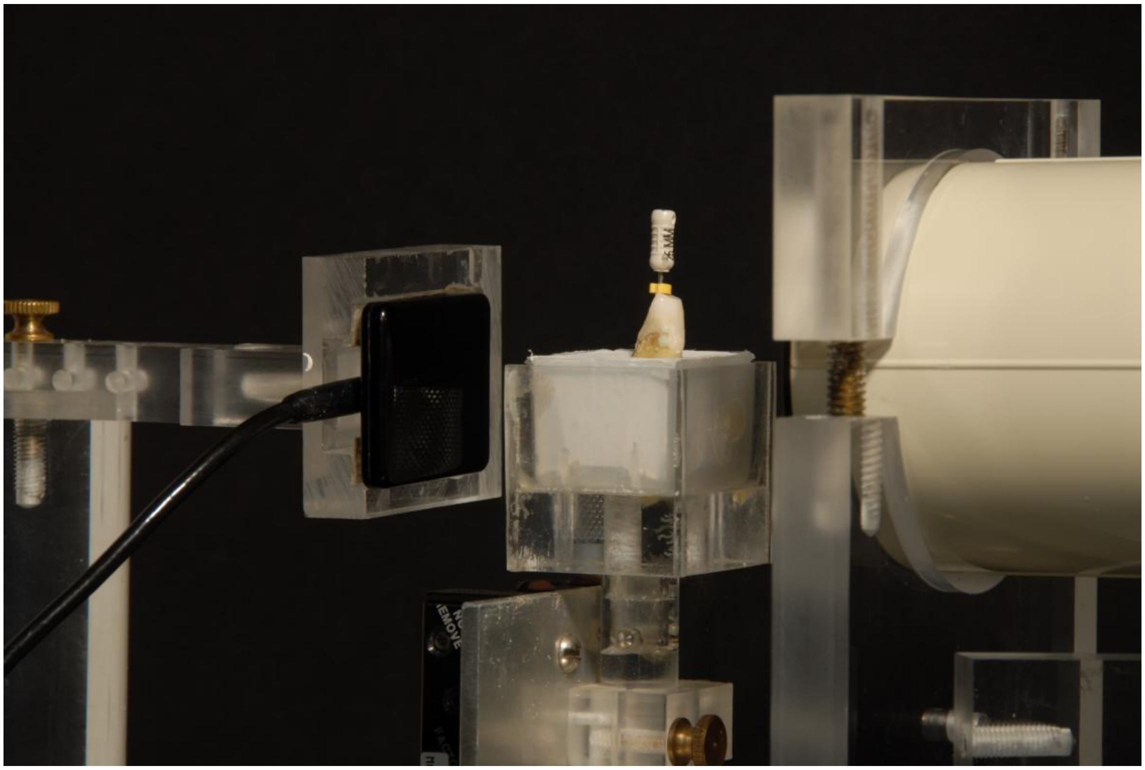


FIGURE 9. Mounted specimen for digital exposure.

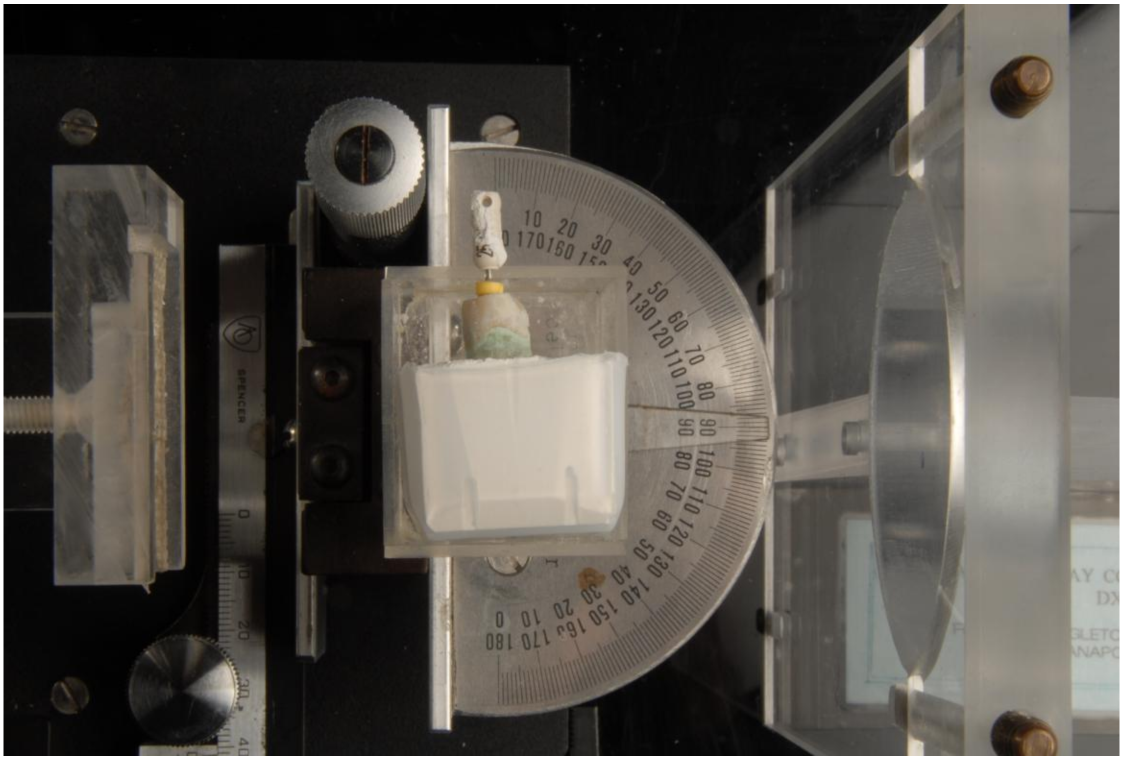


FIGURE 10. Perpendicular specimen in mounting jig.

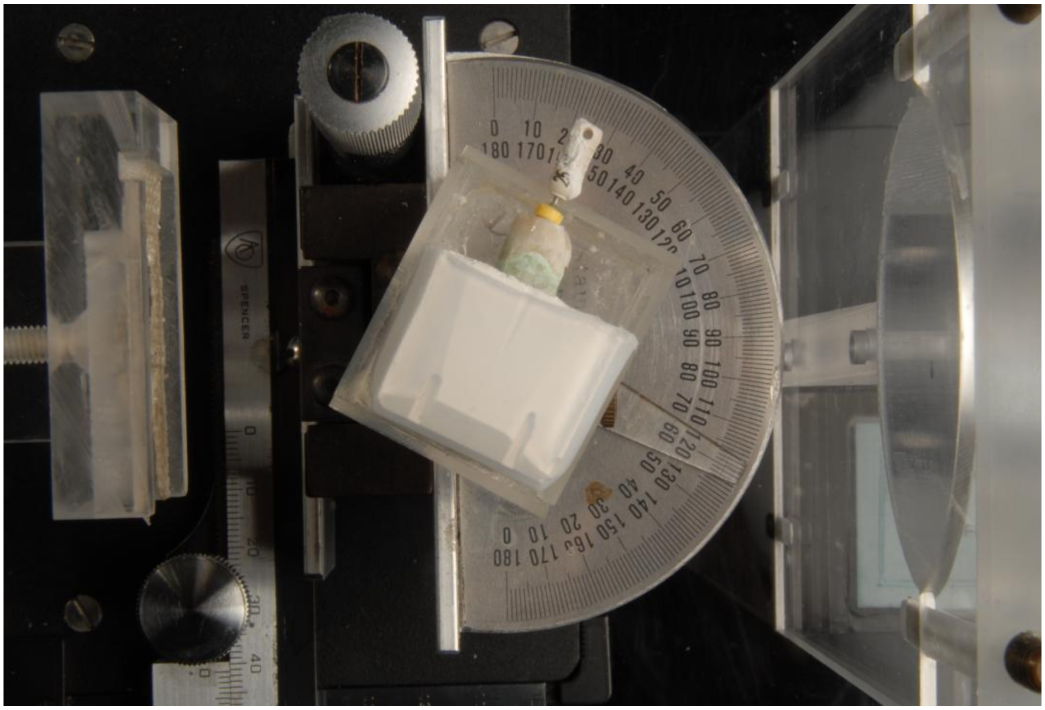
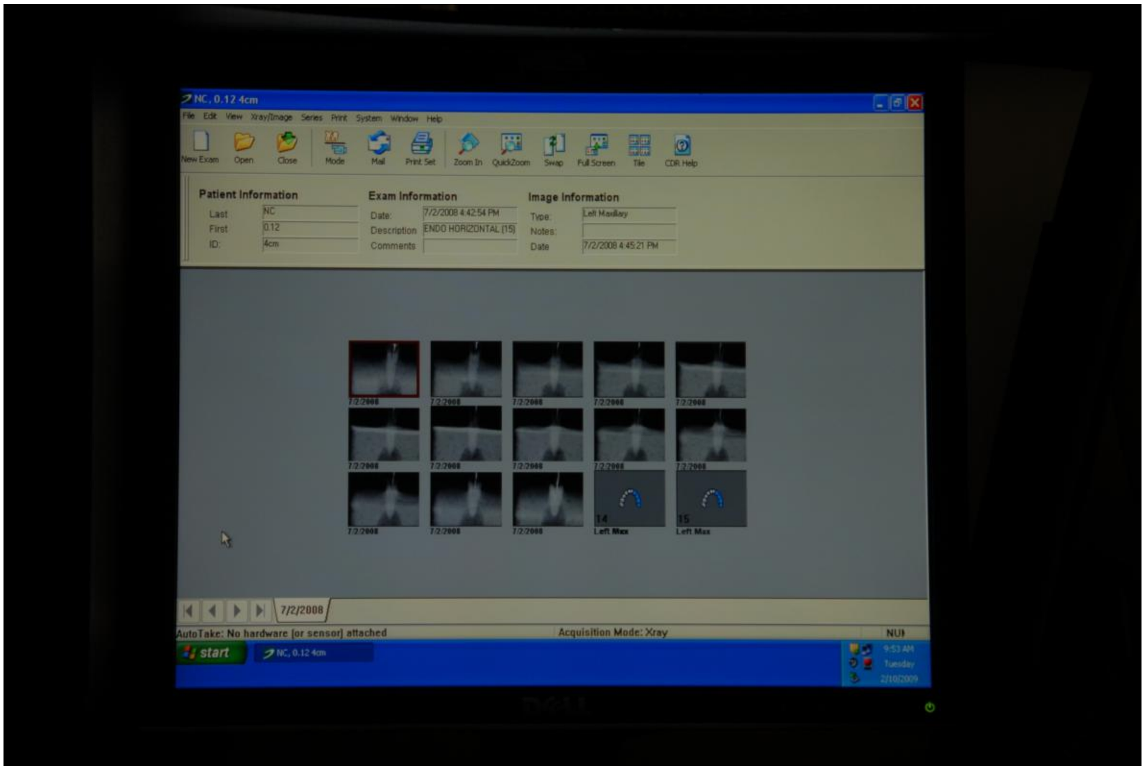


FIGURE 11. Angled specimen in mounting jig.



Patient Information

Last: NC
First: 0.12
ID: 4cm

Exam Information

Date: 7/2/2008 4:42:54 PM
Description: ENDO HORIZONTAL (15)
Comments:

Image Information

Type: Left Maxillary
Notes:
Date: 7/2/2008 4:45:21 PM

AutoTake: No hardware [or sensor] attached

Acquisition Mode: Xray

NUI

FIGURE 12. Randomized digital images.

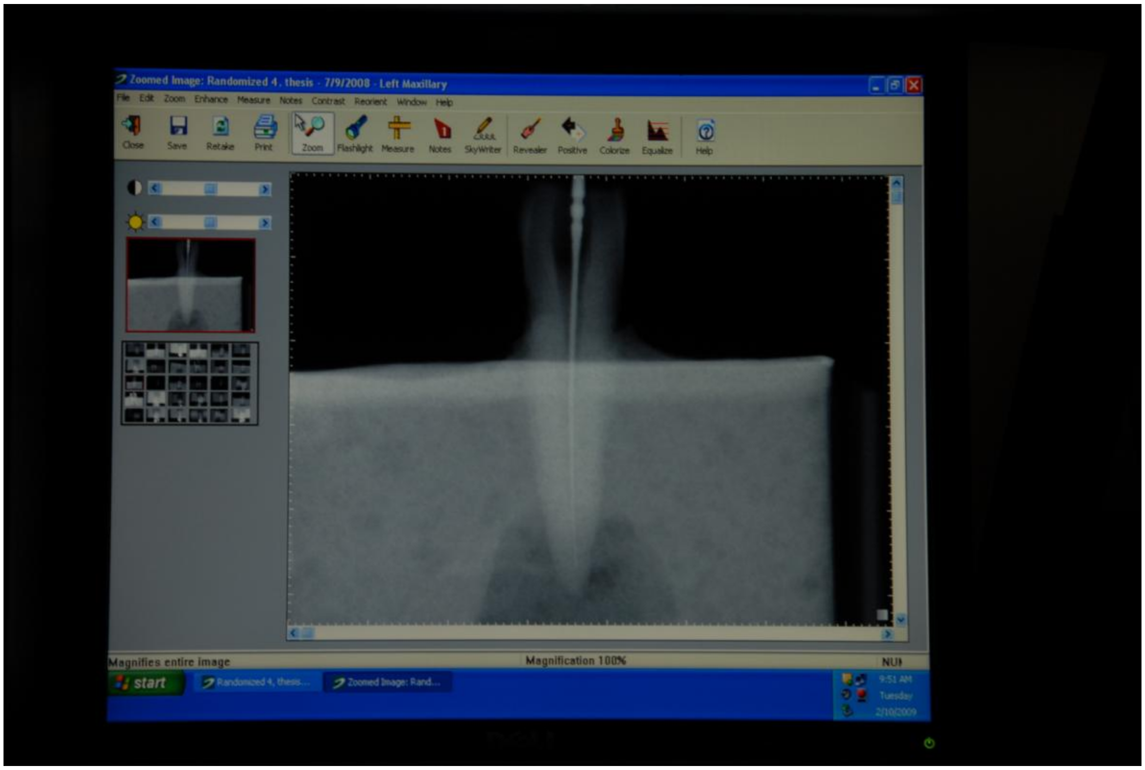
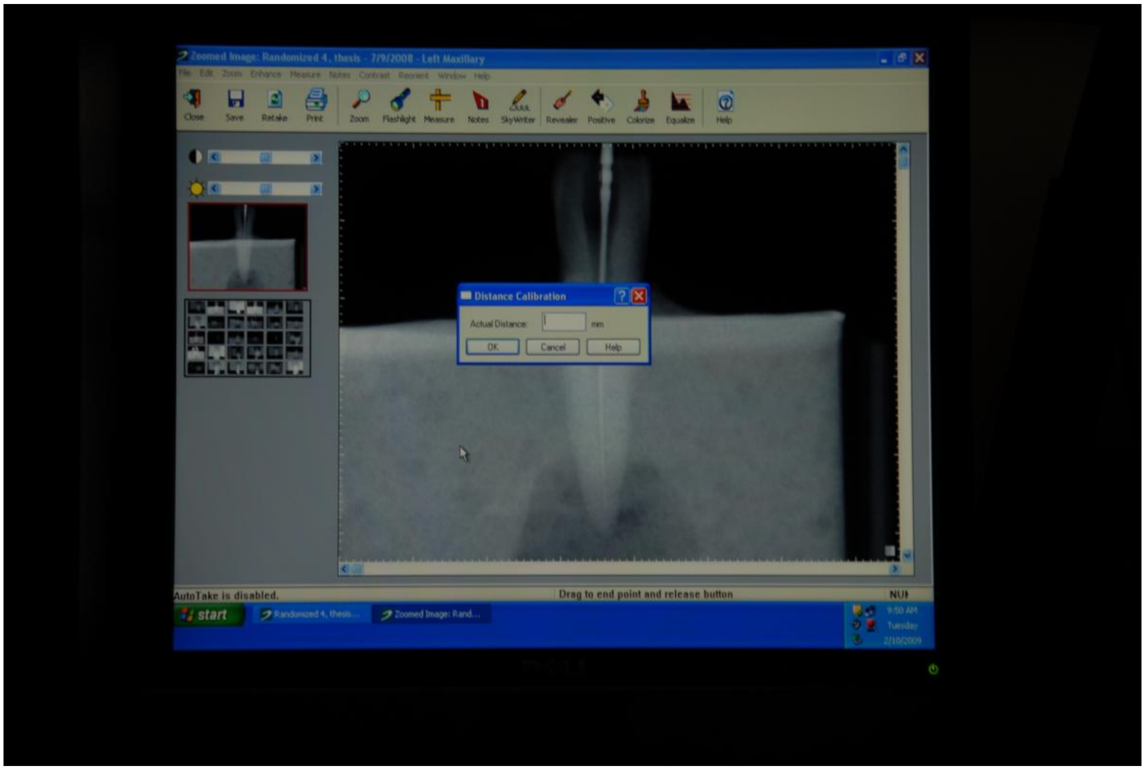


FIGURE 13. Schick CDR typical image.



AutoTake is disabled.

Drag to end point and release button

FIGURE 14. Calibration of digital image.

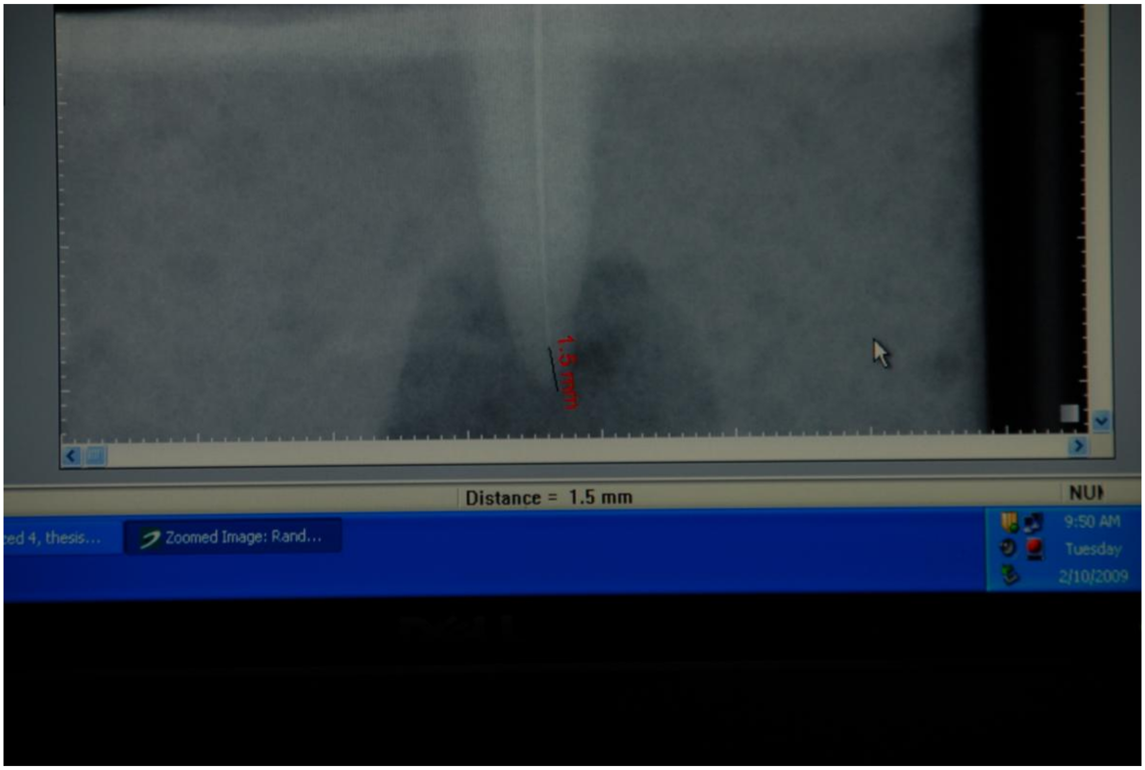


FIGURE 15. Measurement of digital image.

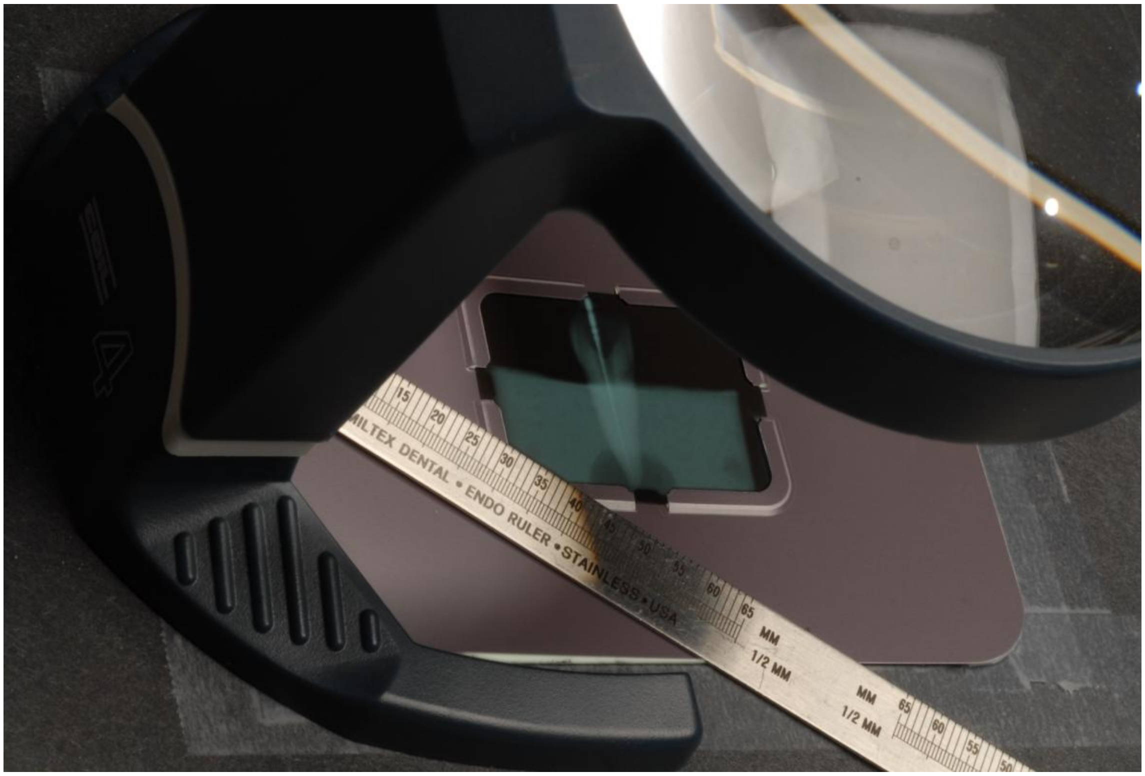


FIGURE 16. Conventional film measurement setup.

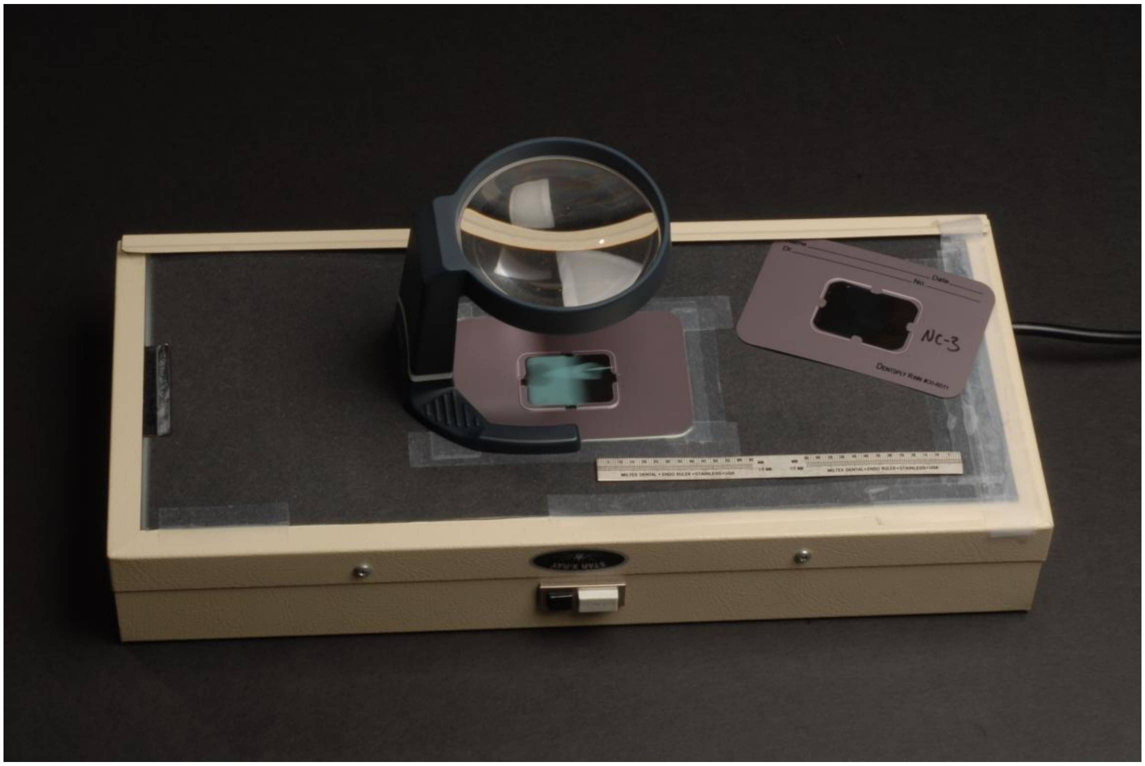


FIGURE 17. Conventional film measurement setup.

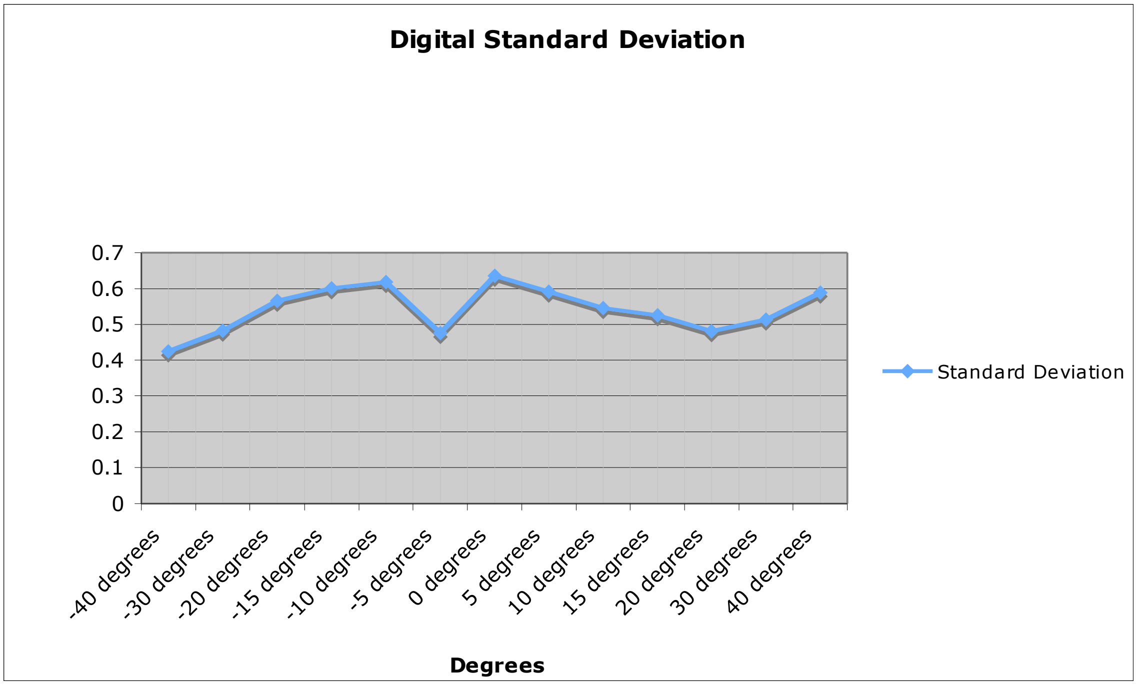


FIGURE 18. Standard deviation of digital images for all teeth.

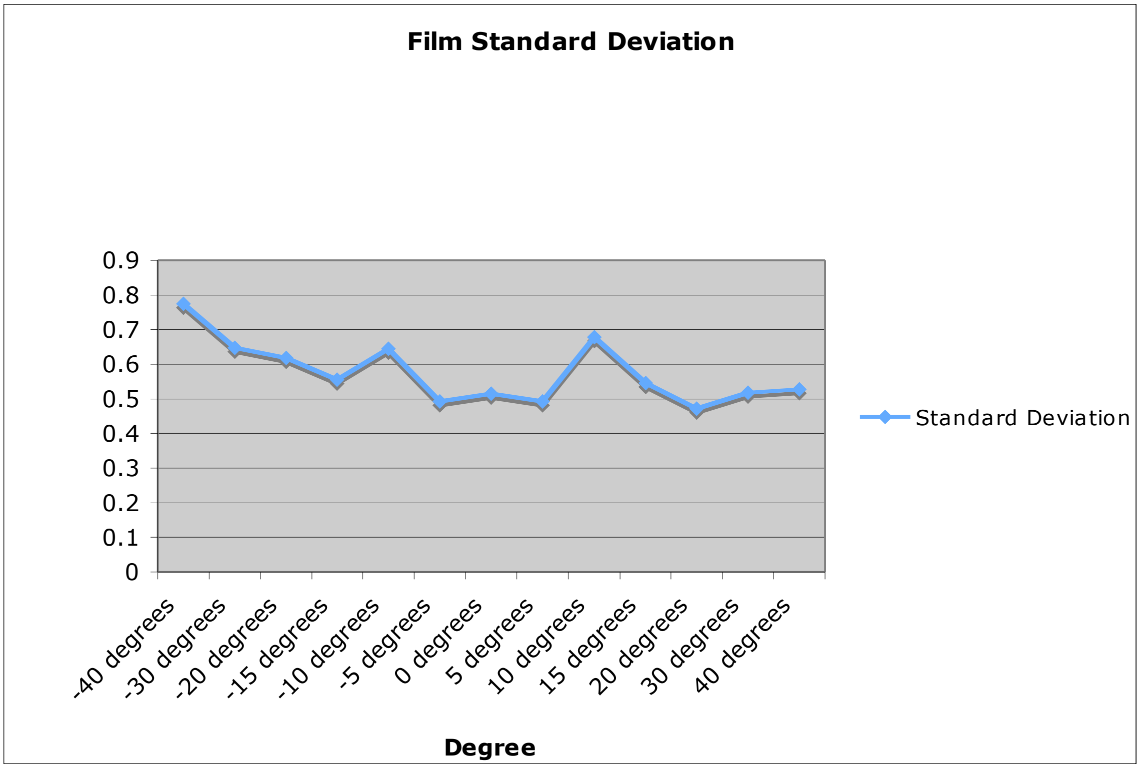


FIGURE 19. Standard deviation of conventional film radiographs for all teeth.

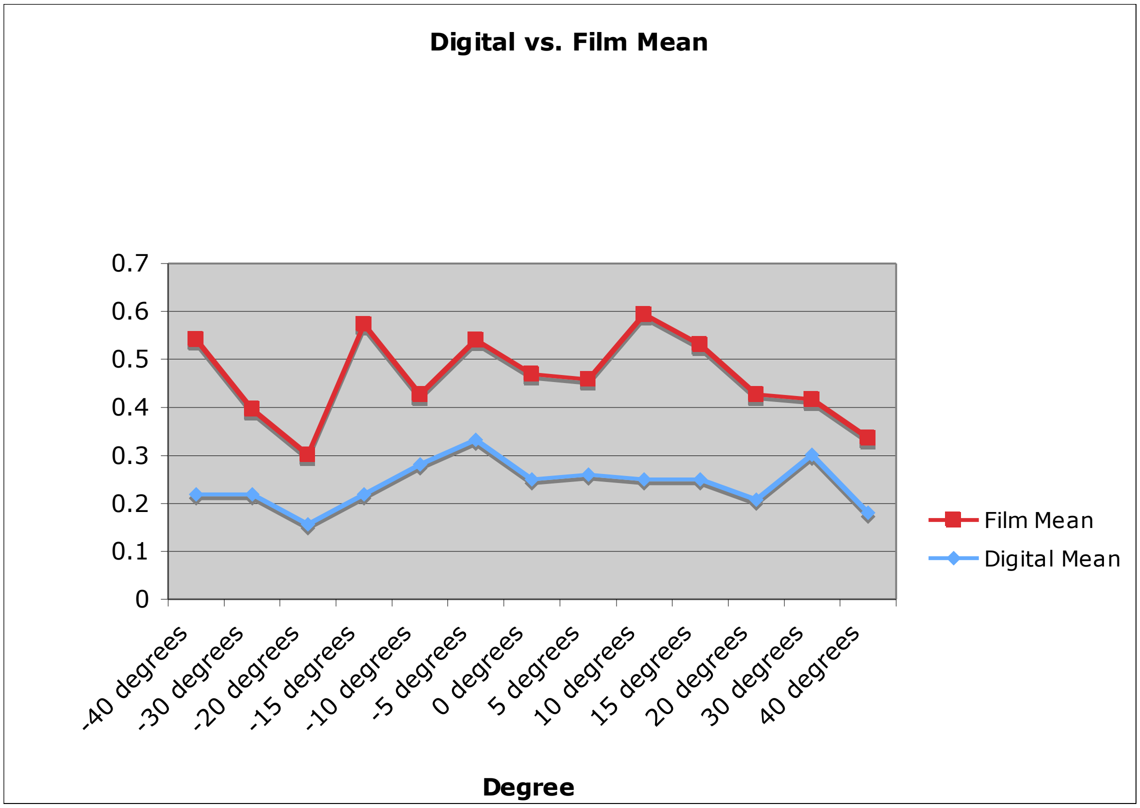


FIGURE 20. Mean error for digital images and conventional films for all teeth.

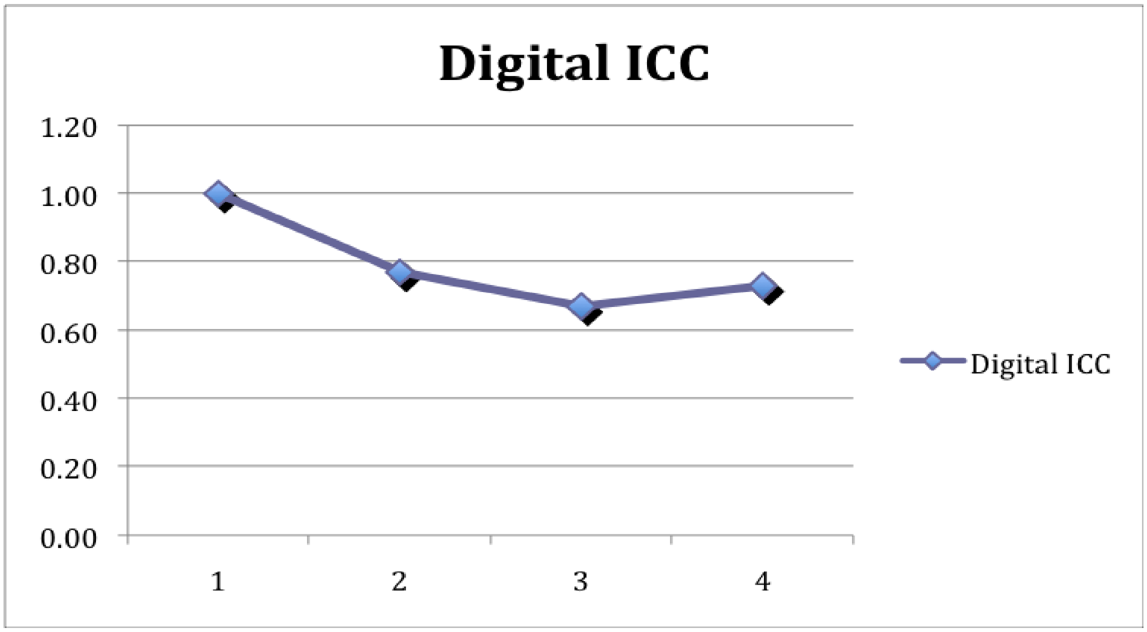


FIGURE 21. Intraclass correlation for digital images with four observers.

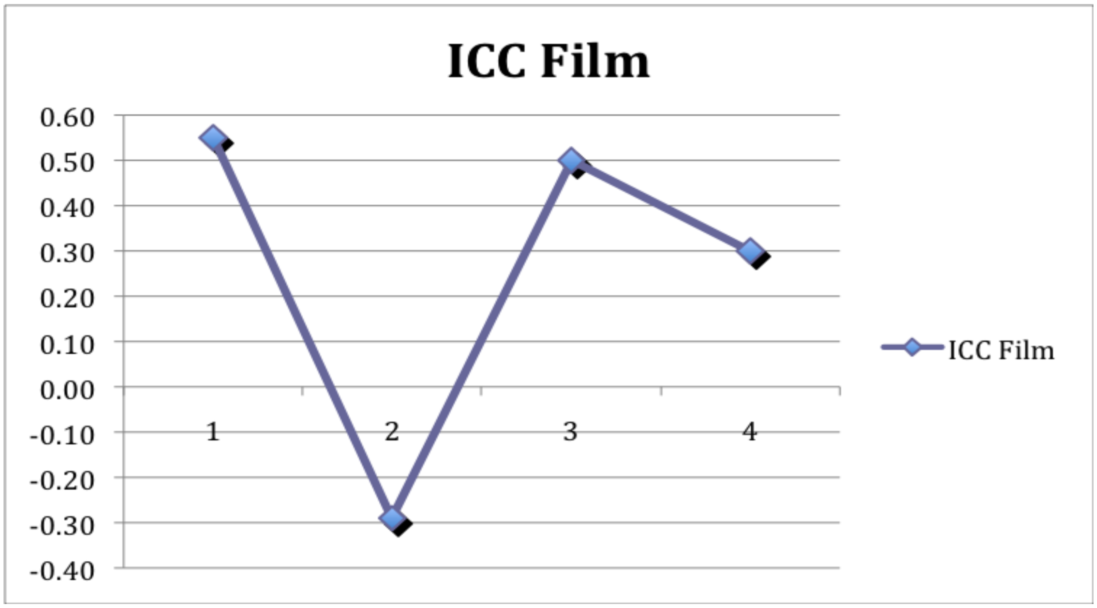


FIGURE 22. Intraclass correlation for conventional film with four observers.

TABLE I

Intraclass correlation of digital images and conventional film

	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

TABLE II

Mean and standard deviation for all vertical angles

Analysis Variable Error in reading (mm)							
Angle	Film image	N Obs	Mean	Std Dev	Coeff of Variation	Minimum	Maximum
50 degrees	Digital	48	0.219	0.424	193.87	-0.5	1.5
	Film	48	0.323	0.775	240.066	-0.5	3
60 degrees	Digital	48	0.219	0.483	220.685	-0.5	1
	Film	48	0.177	0.648	366.016	-1	1.5
70 degrees	Digital	48	0.156	0.566	362.497	-1	1.5
	Film	48	0.146	0.618	424.111	-0.5	1.5
75 degrees	Digital	48	0.219	0.601	274.554	-1	1.5
	Film	48	0.354	0.555	156.717	-0.5	1.5
80 degrees	Digital	48	0.281	0.618	219.75	-1	1.5
	Film	48	0.146	0.644	441.448	-1.5	2
85 degrees	Digital	48	0.333	0.476	142.918	-0.5	1.5
	Film	48	0.208	0.493	236.571	-1	1.5
90 degrees	Digital	48	0.25	0.636	254.324	-1	2
	Film	48	0.219	0.515	235.311	-0.5	1.5
95 degrees	Digital	48	0.26	0.592	227.487	-1	2
	Film	48	0.198	0.492	248.511	-0.5	1.5
100 degrees	Digital	48	0.25	0.546	218.311	-0.5	1.5
	Film	48	0.344	0.678	197.113	-1	2
105 degrees	Digital	48	0.25	0.526	210.369	-1	1.5
	Film	48	0.281	0.545	193.729	-0.5	1.5
110 degrees	Digital	48	0.208	0.482	231.333	-1	1.5
	Film	48	0.219	0.472	215.589	-0.5	1.5
120 degrees	Digital	48	0.302	0.513	169.827	-0.5	1.5
	Film	48	0.115	0.518	452.226	-0.5	1.5
130 degrees	Digital	48	0.181	0.589	325.044	-1	1.5
	Film	48	0.156	0.528	337.601	-1	2

TABLE III

Mandibular molar 1 mean error and standard deviation for all vertical angles

Angle	Film image	N Obs	Mean	Std Dev	Coeff of Variation	Min.	Max.
50 degrees	Digital	4	1.125	0.479	42.552	0.5	1.5
	Film	4	2.375	0.629	26.491	1.5	3
60 degrees	Digital	4	0.75	0.289	38.49	0.5	1
	Film	4	1.125	0.479	42.552	0.5	1.5
70 degrees	Digital	4	1.375	0.25	18.182	1	1.5
	Film	4	1.375	0.25	18.182	1	1.5
75 degrees	Digital	4	1	0.408	40.825	0.5	1.5
	Film	4	1.25	0.289	23.094	1	1.5
80 degrees	Digital	4	1	0	0	1	1
	Film	4	1.625	0.25	15.385	1.5	2
85 degrees	Digital	4	1	0.408	40.825	0.5	1.5
	Film	4	1	0.577	57.735	0.5	1.5
90 degrees	Digital	4	1	0	0	1	1
	Film	4	1.5	0	0	1.5	1.5
95 degrees	Digital	4	0.875	0.25	28.571	0.5	1
	Film	4	1	0.408	40.825	0.5	1.5
100 degrees	Digital	4	1.25	0.289	23.094	1	1.5
	Film	4	1.75	0.289	16.496	1.5	2
105 degrees	Digital	4	1.125	0.479	42.552	0.5	1.5
	Film	4	1.25	0.289	23.094	1	1.5
110 degrees	Digital	4	1.125	0.25	22.222	1	1.5
	Film	4	1.25	0.289	23.094	1	1.5
120 degrees	Digital	4	1.25	0.289	23.094	1	1.5
	Film	4	1.25	0.289	23.094	1	1.5
130 degrees	Digital	4	1.25	0.289	23.094	1	1.5
	Film	4	1	0.408	40.825	0.5	1.5

TABLE IV

Mandibular molar 2 mean error and standard deviation for all vertical angles

Angle	Film image	N Obs	Mean	Std Dev	Coeff of Variation	Min.	Max.
50 degrees	Digital	4	0	0	.	0	0
	Film	4	-0.125	0.25	-200	-0.5	0
60 degrees	Digital	4	-0.5	0	0	-0.5	-0.5
	Film	4	-0.625	0.25	-40	-1	-0.5
70 degrees	Digital	4	-0.5	0.408	-81.65	-1	0
	Film	4	-0.5	0	0	-0.5	-0.5
75 degrees	Digital	4	-0.625	0.25	-40	-1	-0.5
	Film	4	-0.25	0.289	-115.47	-0.5	0
80 degrees	Digital	4	-0.75	0.289	-38.49	-1	-0.5
	Film	4	-0.875	0.479	-54.71	-1.5	-0.5
85 degrees	Digital	4	-0.5	0	0	-0.5	-0.5
	Film	4	-0.25	0.289	-115.47	-0.5	0
90 degrees	Digital	4	-0.75	0.289	-38.49	-1	-0.5
	Film	4	-0.375	0.25	-66.667	-0.5	0
95 degrees	Digital	4	-0.25	0.645	-258.199	-1	0.5
	Film	4	-0.125	0.25	-200	-0.5	0
100 degrees	Digital	4	-0.5	0	0	-0.5	-0.5
	Film	4	-0.5	0.408	-81.65	-1	0
105 degrees	Digital	4	-0.5	0.408	-81.65	-1	0
	Film	4	-0.125	0.25	-200	-0.5	0
110 degrees	Digital	4	-0.25	0.289	-115.47	-0.5	0
	Film	4	0.75	0.5	66.667	0.5	1.5
120 degrees	Digital	4	0	0	.	0	0
	Film	4	0	0	.	0	0
130 degrees	Digital	4	0	0	.	0	0
	Film	4	0	0	.	0	0

TABLE V

Mandibular molar 3 mean error and standard deviation for all vertical angles

Angle	Film image	N Obs	Mean	Std Dev	Coeff of Variation	Min.	Max.
50 degrees	Digital	4	0.625	0.25	40	0.5	1
	Film	4	0.25	0.645	258.199	-0.5	1
60 degrees	Digital	4	0.75	0.289	38.49	0.5	1
	Film	4	0.5	0.707	141.421	-0.5	1
70 degrees	Digital	4	0.5	0	0	0.5	0.5
	Film	4	0.625	0.25	40	0.5	1
75 degrees	Digital	4	1.125	0.25	22.222	1	1.5
	Film	4	0.5	0	0	0.5	0.5
80 degrees	Digital	4	0.75	0.645	86.066	0	1.5
	Film	4	0.5	0	0	0.5	0.5
85 degrees	Digital	4	0.875	0.25	28.571	0.5	1
	Film	4	0.625	0.25	40	0.5	1
90 degrees	Digital	4	0.5	0.408	81.65	0	1
	Film	4	0.5	0	0	0.5	0.5
95 degrees	Digital	4	0.25	0.5	200	-0.5	0.5
	Film	4	0.75	0.289	38.49	0.5	1
100 degrees	Digital	4	0.375	0.479	127.657	0	1
	Film	4	0.375	0.25	66.667	0	0.5
105 degrees	Digital	4	0.75	0.5	66.667	0.5	1.5
	Film	4	0.25	0.5	200	-0.5	0.5
110 degrees	Digital	4	0.25	0.289	115.47	0	0.5
	Film	4	0.375	0.25	66.667	0	0.5
120 degrees	Digital	4	0.25	0.289	115.47	0	0.5
	Film	4	-0.125	0.25	-200	-0.5	0
130 degrees	Digital	4	0.125	0.25	200	0	0.5
	Film	4	-0.125	0.25	-200	-0.5	0

TABLE VI

Mandibular premolar mean error and standard deviation for all vertical angles

Angle	Film image	N Obs	Mean	Std Dev	Coeff of Variation	Min.	Max.
50 degrees	Digital	4	0.25	0.289	115.47	0	0.5
	Film	4	0.25	0.289	115.47	0	0.5
60 degrees	Digital	4	-0.125	0.25	-200	-0.5	0
	Film	4	-0.125	0.479	-382.971	-0.5	0.5
70 degrees	Digital	4	-0.125	0.25	-200	-0.5	0
	Film	4	-0.25	0.289	-115.47	-0.5	0
75 degrees	Digital	4	0	0	.	0	0
	Film	4	0.375	0.25	66.667	0	0.5
80 degrees	Digital	4	0	0.408	.	-0.5	0.5
	Film	4	-0.125	0.25	-200	-0.5	0
85 degrees	Digital	4	0	0.408	.	-0.5	0.5
	Film	4	0	0	.	0	0
90 degrees	Digital	4	0	0.408	.	-0.5	0.5
	Film	4	0.125	0.25	200	0	0.5
95 degrees	Digital	4	-0.125	0.25	-200	-0.5	0
	Film	4	-0.25	0.289	-115.47	-0.5	0
100 degrees	Digital	4	-0.375	0.25	-66.667	-0.5	0
	Film	4	0	0	.	0	0
105 degrees	Digital	4	-0.125	0.25	-200	-0.5	0
	Film	4	-0.25	0.289	-115.47	-0.5	0
110 degrees	Digital	4	-0.625	0.25	-40	-1	-0.5
	Film	4	0	0	.	0	0
120 degrees	Digital	4	-0.25	0.289	-115.47	-0.5	0
	Film	4	-0.125	0.25	-200	-0.5	0
130 degrees	Digital	4	-0.5	0.408	-81.65	-1	0
	Film	4	-0.5	0	0	-0.5	-0.5

TABLE VII

Mandibular canine mean error and standard deviation for all vertical angles

Angle	Film image	N Obs	Mean	Std Dev	Coeff of Variation	Min.	Max.
50 degrees	Digital	4	0	0	.	0	0
	Film	4	0.25	0.289	115.47	0	0.5
60 degrees	Digital	4	0.375	0.479	127.657	0	1
	Film	4	0.375	0.75	200	-0.5	1
70 degrees	Digital	4	0	0	.	0	0
	Film	4	0	0	.	0	0
75 degrees	Digital	4	0.75	0.289	38.49	0.5	1
	Film	4	0.125	0.25	200	0	0.5
80 degrees	Digital	4	1.25	0.289	23.094	1	1.5
	Film	4	-0.125	0.479	-382.971	-0.5	0.5
85 degrees	Digital	4	0.375	0.479	127.657	0	1
	Film	4	-0.25	0.289	-115.47	-0.5	0
90 degrees	Digital	4	1.375	0.75	54.545	0.5	2
	Film	4	0.25	0.289	115.47	0	0.5
95 degrees	Digital	4	1.5	0.408	27.217	1	2
	Film	4	-0.25	0.289	-115.47	-0.5	0
100 degrees	Digital	4	1	0	0	1	1
	Film	4	0.25	0.289	115.47	0	0.5
105 degrees	Digital	4	0.625	0.25	40	0.5	1
	Film	4	-0.125	0.25	-200	-0.5	0
110 degrees	Digital	4	0.25	0.289	115.47	0	0.5
	Film	4	0.125	0.25	200	0	0.5
120 degrees	Digital	4	0.75	0.289	38.49	0.5	1
	Film	4	0	0	.	0	0
130 degrees	Digital	4	0	0	.	0	0
	Film	4	0	0	.	0	0

TABLE VIII

Mandibular incisor mean error and standard deviation for all vertical angles

Angle	Film image	N Obs	Mean	Std Dev	Coeff of Variation	Min.	Max.
50 degrees	Digital	4	0	0	.	0	0
	Film	4	0.25	0.289	115.47	0	0.5
60 degrees	Digital	4	0.375	0.479	127.657	0	1
	Film	4	0.375	0.75	200	-0.5	1
70 degrees	Digital	4	0	0	.	0	0
	Film	4	0	0	.	0	0
75 degrees	Digital	4	0.75	0.289	38.49	0.5	1
	Film	4	0.125	0.25	200	0	0.5
80 degrees	Digital	4	1.25	0.289	23.094	1	1.5
	Film	4	-0.125	0.479	-382.971	-0.5	0.5
85 degrees	Digital	4	0.375	0.479	127.657	0	1
	Film	4	-0.25	0.289	-115.47	-0.5	0
90 degrees	Digital	4	1.375	0.75	54.545	0.5	2
	Film	4	0.25	0.289	115.47	0	0.5
95 degrees	Digital	4	1.5	0.408	27.217	1	2
	Film	4	-0.25	0.289	-115.47	-0.5	0
100 degrees	Digital	4	1	0	0	1	1
	Film	4	0.25	0.289	115.47	0	0.5
105 degrees	Digital	4	0.625	0.25	40	0.5	1
	Film	4	-0.125	0.25	-200	-0.5	0
110 degrees	Digital	4	0.25	0.289	115.47	0	0.5
	Film	4	0.125	0.25	200	0	0.5
120 degrees	Digital	4	0.75	0.289	38.49	0.5	1
	Film	4	0	0	.	0	0
130 degrees	Digital	4	0	0	.	0	0
	Film	4	0	0	.	0	0

TABLE IX

Maxillary molar 1 mean error and standard deviation for all vertical angles

Angle	Film image	N Obs	Mean	Std Dev	Coeff of Variation	Min.	Max.
50 degrees	Digital	4	-0.375	0.25	-66.667	-0.5	0
	Film	4	-0.375	0.25	-66.667	-0.5	0
60 degrees	Digital	4	-0.5	0	0	-0.5	-0.5
	Film	4	-0.5	0	0	-0.5	-0.5
70 degrees	Digital	4	-0.625	0.25	-40	-1	-0.5
	Film	4	-0.375	0.25	-66.667	-0.5	0
75 degrees	Digital	4	-0.5	0	0	-0.5	-0.5
	Film	4	-0.5	0	0	-0.5	-0.5
80 degrees	Digital	4	-0.5	0	0	-0.5	-0.5
	Film	4	-0.5	0	0	-0.5	-0.5
85 degrees	Digital	4	0	0	.	0	0
	Film	4	-0.375	0.479	-127.657	-1	0
90 degrees	Digital	4	-0.25	0.289	-115.47	-0.5	0
	Film	4	-0.5	0	0	-0.5	-0.5
95 degrees	Digital	4	-0.5	0	0	-0.5	-0.5
	Film	4	-0.375	0.25	-66.667	-0.5	0
100 degrees	Digital	4	-0.125	0.25	-200	-0.5	0
	Film	4	-0.5	0.408	-81.65	-1	0
105 degrees	Digital	4	-0.125	0.25	-200	-0.5	0
	Film	4	-0.375	0.25	-66.667	-0.5	0
110 degrees	Digital	4	0.125	0.25	200	0	0.5
	Film	4	-0.25	0.289	-115.47	-0.5	0
120 degrees	Digital	4	0	0.408	.	-0.5	0.5
	Film	4	-0.5	0	0	-0.5	-0.5
130 degrees	Digital	4	0.25	0.289	115.47	0	0.5
	Film	4	0.125	0.25	200	0	0.5

TABLE X

Maxillary molar 2 mean error and standard deviation for all vertical angles

Angle	Film image	N Obs	Mean	Std Dev	Coeff of Variation	Min.	Max.
50 degrees	Digital	4	0.125	0.25	200	0	0.5
	Film	4	0.375	0.25	66.667	0	0.5
60 degrees	Digital	4	0.375	0.25	66.667	0	0.5
	Film	4	0.125	0.25	200	0	0.5
70 degrees	Digital	4	0.5	0	0	0.5	0.5
	Film	4	0.125	0.25	200	0	0.5
75 degrees	Digital	4	0	0	.	0	0
	Film	4	0.5	0	0	0.5	0.5
80 degrees	Digital	4	0.125	0.25	200	0	0.5
	Film	4	0.25	0.289	115.47	0	0.5
85 degrees	Digital	4	0.375	0.25	66.667	0	0.5
	Film	4	-0.125	0.25	-200	-0.5	0
90 degrees	Digital	4	0.125	0.25	200	0	0.5
	Film	4	0.125	0.25	200	0	0.5
95 degrees	Digital	4	0	0	.	0	0
	Film	4	0.125	0.25	200	0	0.5
100 degrees	Digital	4	0	0	.	0	0
	Film	4	0.5	0.408	81.65	0	1
105 degrees	Digital	4	0	0.408	.	-0.5	0.5
	Film	4	0.75	0.5	66.667	0	1
110 degrees	Digital	4	0	0	.	0	0
	Film	4	0.25	0.289	115.47	0	0.5
120 degrees	Digital	4	0.375	0.479	127.657	0	1
	Film	4	-0.125	0.25	-200	-0.5	0
130 degrees	Digital	4	0.125	0.25	200	0	0.5
	Film	4	0	0	.	0	0

TABLE XI

Maxillary molar 3 mean error and standard deviation for all vertical angles

Angle	Film image	N Obs	Mean	Std Dev	Coeff of Variation	Min.	Max.
50 degrees	Digital	4	0	0	.	0	0
	Film	4	-0.125	0.25	-200	-0.5	0
60 degrees	Digital	4	0	0	.	0	0
	Film	4	-0.25	0.289	-115.47	-0.5	0
70 degrees	Digital	4	0	0	.	0	0
	Film	4	-0.125	0.25	-200	-0.5	0
75 degrees	Digital	4	-0.375	0.25	-66.667	-0.5	0
	Film	4	0	0	.	0	0
80 degrees	Digital	4	0	0	.	0	0
	Film	4	0	0	.	0	0
85 degrees	Digital	4	0.25	0.5	200	0	1
	Film	4	0.125	0.25	200	0	0.5
90 degrees	Digital	4	-0.125	0.25	-200	-0.5	0
	Film	4	0.125	0.25	200	0	0.5
95 degrees	Digital	4	-0.125	0.25	-200	-0.5	0
	Film	4	0	0.408	.	-0.5	0.5
100 degrees	Digital	4	0	0	.	0	0
	Film	4	-0.125	0.25	-200	-0.5	0
105 degrees	Digital	4	0.125	0.25	200	0	0.5
	Film	4	0	0	.	0	0
110 degrees	Digital	4	0	0	.	0	0
	Film	4	0	0	.	0	0
120 degrees	Digital	4	0.5	0.408	81.65	0	1
	Film	4	0.125	0.25	200	0	0.5
130 degrees	Digital	4	-0.25	0.289	-115.47	-0.5	0
	Film	4	-0.125	0.25	-200	-0.5	0

TABLE XII

Maxillary premolar mean error and standard deviation for all vertical angles

Angle	Film image	N Obs	Mean	Std Dev	Coeff of Variation	Min.	Max.
50 degrees	Digital	4	0	0	.	0	0
	Film	4	0.75	0.289	38.49	0.5	1
60 degrees	Digital	4	0.125	0.25	200	0	0.5
	Film	4	0.875	0.75	85.714	0	1.5
70 degrees	Digital	4	0.125	0.25	200	0	0.5
	Film	4	0.625	1.031	164.924	-0.5	1.5
75 degrees	Digital	4	0.375	0.25	66.667	0	0.5
	Film	4	0.75	0.645	86.066	0	1.5
80 degrees	Digital	4	0.5	0	0	0.5	0.5
	Film	4	0.125	0.479	382.971	-0.5	0.5
85 degrees	Digital	4	0.5	0	0	0.5	0.5
	Film	4	0.375	0.25	66.667	0	0.5
90 degrees	Digital	4	0.5	0.408	81.65	0	1
	Film	4	0	0	.	0	0
95 degrees	Digital	4	0.5	0	0	0.5	0.5
	Film	4	0.375	0.25	66.667	0	0.5
100 degrees	Digital	4	0.5	0	0	0.5	0.5
	Film	4	0.375	0.25	66.667	0	0.5
105 degrees	Digital	4	0.25	0.289	115.47	0	0.5
	Film	4	0.375	0.25	66.667	0	0.5
110 degrees	Digital	4	0.25	0.289	115.47	0	0.5
	Film	4	0	0	.	0	0
120 degrees	Digital	4	0.5	0	0	0.5	0.5
	Film	4	-0.125	0.25	-200	-0.5	0
130 degrees	Digital	4	1.125	0.479	42.552	0.5	1.5
	Film	4	0.375	0.25	66.667	0	0.5

TABLE XIII

Maxillary canine mean error and standard deviation for all vertical angles

Angle	Film image	N Obs	Mean	Std Dev	Coeff of Variation	Min.	Max.
50 degrees	Digital	4	0.5	0	0	0.5	0.5
	Film	4	0.375	0.479	127.657	0	1
60 degrees	Digital	4	0.5	0	0	0.5	0.5
	Film	4	0.375	0.25	66.667	0	0.5
70 degrees	Digital	4	0.625	0.25	40	0.5	1
	Film	4	-0.125	0.479	-382.971	-0.5	0.5
75 degrees	Digital	4	0.375	0.629	167.774	-0.5	1
	Film	4	0.5	0.408	81.65	0	1
80 degrees	Digital	4	0.625	0.25	40	0.5	1
	Film	4	0.375	0.25	66.667	0	0.5
85 degrees	Digital	4	0.625	0.25	40	0.5	1
	Film	4	0.5	0	0	0.5	0.5
90 degrees	Digital	4	0.5	0.408	81.65	0	1
	Film	4	0.5	0	0	0.5	0.5
95 degrees	Digital	4	0.5	0	0	0.5	0.5
	Film	4	0.625	0.25	40	0.5	1
100 degrees	Digital	4	0.25	0.5	200	-0.5	0.5
	Film	4	1.25	0.289	23.094	1	1.5
105 degrees	Digital	4	0.625	0.25	40	0.5	1
	Film	4	0.75	0.289	38.49	0.5	1
110 degrees	Digital	4	0.625	0.25	40	0.5	1
	Film	4	-0.25	0.289	-115.47	-0.5	0
120 degrees	Digital	4	0.5	0.408	81.65	0	1
	Film	4	0.875	0.25	28.571	0.5	1
130 degrees	Digital	4	0.125	0.25	200	0	0.5
	Film	4	0.5	0.408	81.65	0	1

TABLE XIV

Maxillary incisor mean error and standard deviation for all vertical angles

Angle	Film image	N Obs	Mean	Std Dev	Coeff of Variation	Min.	Max.
50 degrees	Digital	4	0	0	.	0	0
	Film	4	0.25	0.289	115.47	0	0.5
60 degrees	Digital	4	0.125	0.25	200	0	0.5
	Film	4	0.25	0.289	115.47	0	0.5
70 degrees	Digital	4	0.125	0.479	382.971	-0.5	0.5
	Film	4	0	0.408	.	-0.5	0.5
75 degrees	Digital	4	0.125	0.25	200	0	0.5
	Film	4	0.25	0.645	258.199	-0.5	1
80 degrees	Digital	4	0.125	0.25	200	0	0.5
	Film	4	0.375	0.25	66.667	0	0.5
85 degrees	Digital	4	0.375	0.25	66.667	0	0.5
	Film	4	0.5	0.408	81.65	0	1
90 degrees	Digital	4	0.125	0.25	200	0	0.5
	Film	4	0.25	0.289	115.47	0	0.5
95 degrees	Digital	4	0.25	0.289	115.47	0	0.5
	Film	4	0.25	0.289	115.47	0	0.5
100 degrees	Digital	4	0.375	0.25	66.667	0	0.5
	Film	4	0.375	0.25	66.667	0	0.5
105 degrees	Digital	4	0.25	0.289	115.47	0	0.5
	Film	4	0.625	0.25	40	0.5	1
110 degrees	Digital	4	0.25	0.289	115.47	0	0.5
	Film	4	0.375	0.25	66.667	0	0.5
120 degrees	Digital	4	0.125	0.25	200	0	0.5
	Film	4	0.375	0.25	66.667	0	0.5
130 degrees	Digital	4	0.5	0	0	0.5	0.5
	Film	4	0.375	0.25	66.667	0	0.5

DISCUSSION

Endodontic success in root canal therapy is directly related to the accuracy of working length used for cleaning, shaping, and ultimately, obturation of the root canal system. Several studies have concluded that overestimation of canal length results in the poorest success rates. Swartz et al.[54] realized a significant drop in success rates of root canals completed with overfilled canals. Bergenholtz et al.[134] realized a 35-percent failure rate on teeth that have been overfilled. Underfilled canal systems also appreciated a decline in overall success rates of endodontic therapy when compared with obturations extended to the CDJ and the minor constriction. The methods of working length determination have been varied, and often, more than one is used in determination to gain a more accurate estimation.

Dental radiographs have been one method of working length determination among practitioners. The accuracy of conventional film for working length determination has been well established. In recent years the use of digital imaging has becoming increasingly popular for use in endodontics among private practitioners and accredited endodontic programs. Early studies concluded a clear accuracy advantage to conventional film over digital systems as demonstrated by Griffiths 1992 efforts.[111] As digital systems evolved; however, the accuracy of the rendered image improved and most current studies conclude that digital systems are as accurate as their conventional predecessor.[112] Our study found similar results, as no significant difference was measured in the accuracies of the two systems.

One drawback of imaging with x-radiation is the susceptibility of the system to errors in the final image as projection geometries are altered. Elongation or foreshortening of the image will result in inaccurate working lengths if it is not corrected. Thunthy et al.[69, 130] found that the effects of vertical angulation on caries diagnosis resulted in inaccurate evaluations. Barr and Gron[70] showed significant discrepancies between actual root length and radiographic root length when vertical angulation allows for elongated images. Their findings showed up to a 10-percent difference in length; therefore, a 20-mm root may be misrepresented by up to 2 mm.

Ours is the only study to date that attempted to use several changes in vertical angulation in an effort to compare relative accuracies of digital and conventional films. Moreover, our study endeavored to find a point at which vertical angulation became too great and thus rendered a non-diagnostic image. In our study, despite the similarly observed distortion of the image as seen in other studies, the relative distance of the file tip to the radiographic apex remained accurate even when vertical angles were less than ideal. This was evident when the mean error in working length for both systems was compared among the different angles. No statistically significant difference was seen in working length determination for digital and conventional images taken at extreme angles (+/-40°) and those taken at perpendicular (0°). This finding supports the null hypothesis.

One clue for this unexpected outcome may be explained by Loushine et al.[7] His study showed that calibrated digital images are more accurate that non-calibrated images. In our study design, examiners used calibration software on all digital images, perhaps negating any effect of elongation or foreshortening. Obviously, conventional films cannot be calibrated, but statistical analysis of the mean error shows a trend of less accurate measurements associated with extreme-angle films.

Techniques for standardizing the projection geometries have been proposed to increase the accuracy of the representing image as well as to allow for more precise interpretation. The paralleling technique, described by Fitzgerald,[135] requires that the film/sensor be placed parallel to the long axis of the tooth and has been shown to yield the most dimensionally accurate image. Forsberg exposed working length films of several teeth and compared paralleling, modified paralleling, and bisecting-angle radiographic techniques.[10] The study concluded that the paralleling technique was the most accurate in the reproduction of the distance from the file to the apex of the tooth. Similarly, our study showed that the examiners were minimally more accurate in working length determination when the vertical angulation was ideal; however, the results were not statistically significant.

Few studies have been completed observing the effects of vertical angulation on digital working length films. Most studies concerning vertical angulation with digital systems evaluate the height of the alveolus. Zulqarnain et al.[107] used a digital system to evaluate the effects of vertical angulation in assessing changes in alveolar bone height. He examined the difference between 0 and +/- 10 ° of vertical angulation. His results support the hypothesis that larger vertical angulations result in significantly limiting the observer from proper evalution of true distances. In a congruent study of alveolar bone height, Hausmann et al.[108] concluded similar findings. Garcia et al.[114] did evaluate estimates of working length when vertical angulation was modified for a digital and conventional system. His study concluded a trend of increasing error for larger vertical angles (30°). The study, however, only used three different degrees of vertical angulation. No attempt was made to mimic typical vertical angles for the type of tooth.

One drawback of the study were the poor ICC numbers seen among the examiners. The ICC for conventional film indicated that only 29-percent of radiographs were successfully read with the same length twice. The ICC was calculated without bias of film angulation, because images were chosen at random. Evaluation of the ICC images revealed a variable that was not controlled for; the proportion of images in the random sample that represented angles greater than 30° was 70-percent. The ICC was poor due to the inherent difficulty in reading extreme-angle films. Therefore, the ICC was an assessment of difficult image evaluation and not the repeatability that was desired. The ICC for digital images was significantly better with a mean value of 70-percent. The stark difference in ICC values for digital and conventional systems shows that observers found the digital system to be more consistent in working length determination. Other factors considered in evaluating the ICC outcome were examiner fatigue and the order of the observed images. In all cases examiners evaluated all 348 images in one sitting; both eye and mental fatigue may have contributed to the poor ICC numbers. Moreover, in all cases digital images were evaluated first, immediately followed by conventional film evaluation. This, too, may have contributed to the poor ICC.

CONCLUSION AND SUMMARY

Our study was the first to apply commonly used vertical projection geometries to different imaging systems. This *in-vitro* study used smaller increments of vertical angulation and a larger range of angles in an effort to mimic the subtle differences commonly seen clinically. The results from the study indicated that there is no statistically significant difference between conventional film and Schick digital CDR with regard to working length when the vertical angle of the object and the film/sensor is changed. The examiners ability to reliably repeat the measurements for each conventional film was poor. The ICC was poor due to the inherent difficulty in reading extreme-angle films. Therefore, the ICC was an assessment of difficult image evaluation. The ICC for digital images was significantly better with a mean value of 70-percent. Due to the poor ICC of conventional film images, a comparison of the two imaging methods is inconclusive.

When film type was considered independently, the accuracy of the working lengths obtained for conventional film and digital images, regardless of tooth type and angle, was good, with the average error in working length to be less than 0.5 mm. An interesting trend emerged when the mean error was averaged for each angle. The expected outcome of a more accurate working length determination was seen for angles at or near perpendicular (90°). Although the difference in working length between the angles was not statistically significant in this study, the trend suggests that more accurate working length measurements are recorded when the vertical angulation is ideal. Given the dramatic increase in the use of digital media, software, and imaging systems used for endodontic radiography, and given the difficulties compounded by the inherent variations in projections geometries, evaluation of the accuracy in digital working length films must continually be compared with conventional films, the standard for accurate working length images.

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ABSTRACT

AN *IN VITRO* COMPARISON OF WORKING LENGTH ACCURACY BETWEEN A DIGITAL SYSTEM AND CONVENTIONAL FILM WHEN VERTICAL ANGULATION OF THE OBJECT IS VARIABLE

by

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Accurate determination of working length during endodontic therapy is critical in achieving a predictable and successful outcome. Working length is determined by the use of electronic apex locators, tactile perception, knowledge of average tooth lengths and dental radiography. Due to the increasing use of digital radiography in clinical practice, a comparison with conventional film in working length determination is justified. The purpose of this study is to determine if there is a difference between Schick digital radiography and Kodak Ultra-speed film in the accurate determination of working lengths when vertical angulation of the object is variable.

Twelve teeth with #15 K-flex files at varying known lengths from the anatomical apex were mounted in a resin-plaster mix to simulate bone density. A mounting jig for the standardization of projection geometries allowed for exact changes in vertical angulation as it related to the object (tooth) and the film/sensor. Each tooth was imaged using Schick CDR and Kodak Ultra-speed film at varying angles with a consistent source-film distance and exposure time. Four dental professionals examined the images and films independently and measured the distance from the tip of the file to radiographic apex and recorded their results.

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, vertical angulation, and the interaction of angle and film type. Tooth type and examiner were included in the model as random effects assuming a compound symmetry covariance structure. The repeatability of each examiner, for each film type, was assessed by estimating the intra-class correlation coefficient (ICC). The ICC was determined when 12 randomly selected images and radiographs were reevaluated 10 days after initial measurements.

The repeatability of each examiner for Schick CDR was good with ICCs ranging from 0.67 to 1.0. Repeatability for the conventional film was poor with ICCs varying from -0.29 to 0.55. We found the error in the working length was not significantly different between film types ($p = 0.402$). After adjusting for angle, we found that error in the working length from the digital image was only 0.02 mm greater (95-percent CI: -0.03, 0.06) than the conventional film. Furthermore, there was not a significant difference among the angles (p = 0.246) nor in the interaction of image type with angle (p = 0.149).

Based on the results of our study, we conclude that there is not a statistically significant difference in determining working length between Schick CDR and Kodak Ektaspeed film when vertical angulation is modified.

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