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A COMPARISON OF SCANNED LATERAL CEPHALOGRAMS TO CORRESPONDING ORIGINAL RADIOGRAPHS

by

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Abstract

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Scanning a radiograph is an inexpensive method for acquiring a digital image. However, the scanned image dimensional integrity has not been tested for use in diagnostic applications. The purpose of this investigation was to evaluate distortion associated with scanning an analog lateral cephalogram into a digital format, as well as assessing the accuracy of the digital radiograph in performing cephalometric analysis, superimposition, and hardcopy printout duplication. Thirty subjects were selected from the active patients at Case Western Reserve University, Department of Orthodontics with pre-treatment and post-treatment cephalograms. All sixty films were indexed with eight fiducial marks and scanned into digital format using a commercial scanner at 150 dpi. Hardcopies of the thirty initial digital images were made with a laser printer. Dolphin Imaging software was used for digitization of landmarks and corresponding cephalometric analysis and superimposition. The original radiographs were manually traced and superimpositions completed for all thirty subjects.

Comparison of distortion between the original cephalograms and the digital images showed a vertical enlargement of 0.8 mm and a horizontal reduction of 0.4 mm. Comparison of the original and hardcopy images demonstrated a net enlargement of 1.1 mm vertically and 0.4 mm horizontally. All measurements were found statistically significant. Comparison of the hand-traced cephalometric analysis and the computer-generated analysis showed statistically significant differences in six of twenty-three cephalometric measurements. Additionally, four of these six measurements showed statistically significant differences when comparing the computer-generated analysis and the digital hardcopy. All significant measurements contained the landmarks Po and Or (Frankfort-horizontal plane). No differences were found comparing original to hardcopy cephalometric measurements. No statistically significant differences were noted when evaluating manually-traced superimpositions to the computer generated superimpositions.

Although distortion was found, the clinical significance may be inconsequential based on the relatively small amount of discrepancy noted. Landmark identification errors may have contributed to the differences noted for the cephalometric analysis comparisons. Therefore, scanning cephalograms into a digital format can be considered as accurate as the original radiograph; however, caution must be taken when determining Po and Or.

DEDICATION

To Mom, Dad, and Tracy
Thank you for your faith, inspiration, guidance, and support

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INTRODUCTION

Since the inception of cephalometrics by Broadbent (1931), the lateral cephalogram has played an essential role in the diagnosis and monitoring of skeletal and dental changes in the craniofacial region of orthodontic patients. Cephalometry is an important tool in orthodontics allowing craniofacial morphology to be incorporated into orthodontic diagnosis, treatment planning, and evaluation of treatment effect and growth. Cephalometric analysis using landmark identification by manual tracing on radiographic film has been the gold standard for many years. However, new methods for obtaining radiographic images and cephalometric analysis using digital technology have emerged in orthodontic case planning. Proponents of digitally acquired cephalometric imaging cite numerous advantages over traditional cephalometrics including improved landmark identification through image enhancement techniques, faster cephalometric data acquisition and analysis, efficient storage and archiving, ease and cost of duplication of radiographs, and teleradiology of images to distant sites (Baskin & Cisneros 1997; Forsyth et al. 1996a; Rogers 2002). Furthermore, three-dimensional imaging of dentofacial records is quickly developing as a realistic diagnostic tool. Digital images of the lateral and frontal cephalogram are an integral part of this promising technology (Hans et al. 2001).

Radiographs can easily be scanned into a digital format using a relatively inexpensive, consumer-grade flatbed scanner equipped with a transparency adapter.

Ruess (2001) demonstrated that this type of scanner can provide images of equal diagnostic accuracy to the original hardcopy when digitizing chest radiographs. A variety of computer programs are now available to digitally capture scanned lateral cephalometric radiographs and perform numerous orthodontic related functions including cephalometric landmark analysis, superimposition of sequential radiographs and printing of hardcopies. An implicit question, therefore, arises: "Can these digitally scanned radiographic images accurately represent the original radiograph and thereby replace traditional radiographic hardcopy film?" In other words, how accurate is the process of scanning a lateral headfilm into a digital image, and can this digital format be effective in reliably accomplishing the functions served by a cephalogram including cephalometry, superimposition and hardcopy printout? This question is vital to both young orthodontists with limited finances, as well as established practitioners, who, while concerned about maintaining precise diagnosis and treatment, aspire to convert their practice to use more modern and efficient systems. If scanning of radiographs into a digital format can be proven accurate in all considerations, orthodontists could be provided with an inexpensive, efficient means of updating their practice to the current digital standard.

LITERATURE REVIEW

Digital Imaging

The traditional cephalogram is a radiographic image stored as analog data. Analog forms of communication are based on continuous sinusoidal waves and are limited by physical properties of the media on which they are recorded. For example, a conventional analog cephalogram records an image of the head on silver halide crystals attached to acetate film. The silver halide crystals are approximately 0.05 mm in size and have a range of approximately 10,000 shades of gray (Hans et al. 2001). The smallest detail detectable by the human eye is 0.1 mm by 0.1 mm (Forsyth 1996b). Thus, the accuracy of visual landmark identification is limited by a static representation of an image and is constrained by the physical properties of the radiographic film (Hans et al. 2001). In contrast, a computer stores digital information in a binary code as a specific series of "1"s and "0"s called bits (binary digit) that form words of eight or more bits in length called bytes (Parks & Williamson 2002). A digital image is created by forming a rectangular array of numbers (stored as bits) representing gray values from the radiographic film image. The units of this array are called picture elements (pixels). Each pixel of a gray scale image is controlled by a predetermined number of bits whose compounded values characterize the gray intensity in a logarithmic fashion (i.e., 12 bits = 2^{12} = 4,096 possible gray shades ranging black to white, where 0 represents black and 4,096

represents white). The image display of the computer system converts these numbers into a video picture (Eppley & Sadove 1991). As an image is digitized, the information is segmented into discrete units (pixels). The limiting factor in the resolution of the digital image is the size and number of the pixels available (Hans et al. 2001). Once an image is digitized with a given pixel size, its unrecorded detail is lost forever.

An important variable that must be considered when analyzing the digital format is the actual process involving the transfer of information into a digital image. A digital format of a radiograph may be produced through two different methods; direct digitization and indirect digitization including phosphor-coated plates, digital camera/videocamera image capture, and flatbed scanning.

Direct Digital Imaging

X-ray or light sensitive pixel-based sensors, charge-coupled devices (CCD), are used to directly capture radiographic information, transmitting an image into a computer for instantaneous viewing, transmission, or printing (Parks & Williamson 2002). At present, these systems are relatively new, very expensive and increase patient radiation exposure over conventional radiography, yet offer an immediate digital image with rather straightforward operator use. CCD-based digital imaging provides higher spatial resolution than phosphor plates, which should lead to higher detail conspicuity (Wenzel & Gotfredsen 2002). However, there is no definitive consensus on the resolution needed for cephalometric radiography.

Indirect Digital Imaging

Photostimulable phosphor-coated plates. Photostimulable phosphor-coated plates are used to capture analog radiographic information and store the energy from the radiation as a latent image. The plates are processed directly into the computer through a drum scanner, converting the analog information into a digital representation of the latent image, without the intermediate step of producing a conventional radiographic film (Cromer 2002). Although this method requires additional processing steps and time for digital image retrieval, it allows existing radiographic equipment to be used, significantly decreasing the cost when compared to direct digital imaging. Moreover, a reduction in radiation dosage is a cited advantage of digital x-ray capture. Kogutt et al. (1988) conducted a study to assess image quality and the reduction in radiation dose using digital x-ray capture compared to conventional radiographs in pediatric chest imaging. Even with an 85% reduction in radiation dosage to the patient, the study reported 94% of the digital images were determined to be satisfactory compared to the conventional film.

Digital Camera/Videocamera Image Capture. Digital camera and digital videocamera technology captures an image on a CCD array through the optics of a hand-held photographic camera or videocamera (Davidson et al. 2001). Through a videocamera, the image is grabbed as a frame of a videoimage. With both devices, the image can then be downloaded into a computer for analysis and storage. One of the shortcomings of this technique is that a grayscale image is captured in a color image format, resulting in many images that appear blue. Additionally, the file size may be three times the size of the same image captured in a gray scale format (Parks

& Williamson 2002). Although relatively inexpensive, this method of digital imaging can be quite cumbersome and technique sensitive requiring variable film positioning, lens adjustments, and/or zooming procedures.

Flatbed Scanning. A flatbed scanner is a common, relatively inexpensive and easy to use peripheral used for multiple applications in today's computer industry. Flatbed scanners must be equipped with a transparency adapter that fits over the bed of the scanner in order to scan radiographs (Rogers 2002). An image is scanned as a light bar passes across the image, projects light onto the image, and a CCD measures the intensity of the light that is reflected from the image converting it to an analog voltage. Computer software translates the scanned analog sampling into a digital representation. Unlike digital camera video recording, the scanning system does not require any zooming or adjustment in film position to acquire reproducible digital images (Chen & Hollender 1995).

Ruess et al. (2001) conducted a study comparing "low-cost, off-the-shelf" technology for digitizing chest radiographs. The research compared forty pediatric chest radiographs, each with a single abnormality, to digitized representations of the original radiographs. Digital images were acquired by a commercial film digitizer and two low cost methods, a digital camera and a flatbed scanner with a transparency adapter. Abnormality identification with the flatbed scanner image was nearly identical to the identification on the original radiograph. Lesion identification from images acquired by flatbed scanners also demonstrated significantly higher accuracy than did images from the digital camera. Further results showed that, although rated lower than original film image quality, flatbed scanner images were subjectively rated

higher in overall image quality than the two other digitizing methods with a significant difference ($p < 0.05$) between each technique. Ruess et al. concluded that a low-cost flatbed scanner with transparency adapter could produce digital images that were significantly superior to digital camera images and equivalent in diagnostic accuracy as the original radiograph.

A similar study conducted by Davidson et al. (2001) compared the quality of radiographic images digitized from four separate devices; a commercial-grade scanner, consumer-grade scanner, commercial-grade digital camera, and consumer-grade digital camera. Selections of medically related radiographs were digitized using each modality and tested against the original radiograph and each other. Subjective analysis compared image quality while optical density response was evaluated objectively using a grayscale test pattern. An analysis indicated that there was no significant differences in subjective quality among images digitized with the commercial-grade scanner, consumer-grade scanner, and commercial-grade digital camera. Objective tests showed similar results with all four devices closely resembling the ideal optical density versus grayscale response curve. All four methods followed the curve very closely at the two ends of the grayscale spectrum proving that lesser quality devices can compete in grayscale image reproduction at the extremes of the grayscale. However, what separated the devices was how well they followed the ideal curve in the middle grayscale values where most of the deviations were observed. This middle grayscale area often contains the important shades necessary for tissue contrast. Therefore, these results imply that the type of digitization equipment can affect the diagnostic quality of digital images, although the

study did not address this issue. The authors concluded that, for the purpose of viewing images on a computer monitor, a consumer-grade desktop scanner can produce digital images of similar quality to those produced by more expensive commercial-grade scanners and digital cameras and provides a cost-effective means to digitize radiographic films.

Resolution and Grayscale

The scanning process changes the nature of an image from an analog to a digital format by dividing the information content into pixels based on scanner spatial resolution and grayscale settings (Hans et al. 2001). These two parameters directly affect the quality of the scanned image. Spatial resolution refers to the image quality based on the fidelity of the finest details of the image content; therefore, it is the ability to record separate images of minute objects that are placed closely together. With scanning, spatial resolution is based on the number of pixels representing the image in the vertical and horizontal dimension. When spatial resolution is low, two adjacent spatial features may be blurred together appearing as a single entity rather than two separate objects. Resolution can be characterized in various ways such as pixel size (i.e., 0.1 mm), line pairs per mm (i.e., 5 lp/mm), dots per inch (i.e., 245 dpi), or horizontal and vertical pixel dimensions (i.e., 1536 pixels X 1024 pixels). However stated, spatial resolution in digital radiography is dependent on the number of small carriers (pixels) of image information representing the image content. The number of pixels is directly proportional to the amount of image detail; the smaller the pixel size, the more detail in the image, and therefore the greater the resolution. Thus, when scanning a radiograph at a given resolution, a specific number of pixels

must be determined that will be needed to sufficiently capture the information contained in the original image (Hans 1993). Images that contain a large amount of detail depend more on the number of pixels rather than the gray scale value (Forsyth et al. 1996b).

A radiograph consists of image content represented by a wide range of shades of gray. The scanning process must convert these static gray values into digital image carrier units that represent the original range of gray shades as close as possible in order to reproduce an accurate portrayal of the complex patterns of a lateral cephalogram. For this conversion to take place, each available pixel is coded with area-specific gray shade information, which, once compiled through computer software, recreates the analog information into a digital image. Each pixel is represented by a determined number of bits whose value controls the gray intensity of the specific image segment via a logarithmic fashion (i.e., 12 bits = 2^{12} = 4,096 possible gray shades ranging black to white, where 0 represents black and 4,096 represents white) (Eppley & Sadove 1991). The human eye can only discern approximately 64 gray levels at one time, but can pick these 64 shades out of as many as 10,000 possible gray levels actually present on an analog cephalometric radiograph (Hans et al. 2000). As for cephalometric scanning, if a landmark feature is in a region with relatively slow and/or subtle changes in grayscale values, then too few gray levels during gray level sampling can obscure the landmark or change its apparent location. Unfortunately, no equations or accepted standards exist to calculate grayscale values or pixel number requirements. Generally, the maximum number of gray levels available is used. Some compensations can be made since grayscale level

and number of pixels are independent. For example, at 512 gray levels, the number of horizontal and vertical pixels might be adequate; yet at 64 gray levels, an enhanced spatial resolution might compensate for the loss of grayscale resolution. However, this trade-off between spatial and grayscale resolution has limitations. Increasing the spatial resolution for an image that has too few gray levels cannot compensate for the loss of information content (Hans et al. 2000). Again, no set standard or equation are available for this determination.

Although there is a lack of accepted criterian for spatial resolution or grayscale settings regarding the digitization of orthodontic lateral cephalograms, some recommendations have been made through various research endeavors. In a recent project, Held et al. (2001) set out to determine the minimum allowable resolution, grayscale, and color settings of digital images without compromising the accuracy of cephalometric landmark identification. Researchers scanned lateral cephalograms into a computer at six different resolution settings [75 dpi black and white (default scanner setting), 200 dpi black and white, 400 dpi black and white, 600 dpi black and white, 75 dpi color, 200 dpi color] with a 256 (8-bit) image setting. Subjective analysis consisted of participants identifying landmarks and rating radiograph quality for each group. Objective analysis compared mean distance of error between settings. Their analysis showed that the scanner settings used in the digitization process did not matter significantly when standard setting were used. No statistical significance among any of the groups was found and standard settings at 75 dpi black and white with 256 grayscale resolution tended to show better landmark accuracy than all other settings tested. Thus, the authors suggested a lower resolution

without color might be the best combination of scanner settings for lateral cephalogram digitization. Color images are generally considered more useful than black and white images, as the human eye can discriminate more shades of color than it can shades of gray. For this reason, Dolphin Imaging (2003) recommends a scanning resolution of 150 dpi and 24-bit color descreening for radiograph scanning. Rogers (2002) in an article demonstrating the efficiency of scanning radiographs for duplication purposes also recommends a scanner resolution setting of 75 dpi for adequate radiograph digitization. Hans et al. (2000) suggest a spatial resolution of 0.1 mm along with a grayscale resolution of 12 bits (4096 gray shades) to adequately capture the useful information on cephalograms.

O'Callaghan (1993) examined the spatial resolution requirements necessary to use digital representations of lateral cephalograms. Twenty-five cephalograms were photographed and transferred to a photographic compact disk. Five images, viewed at three different spatial resolutions (256 pixels X 384 pixels, 768 pixels X 512 pixels, and 1024 pixels X 1536 pixels) and 8-bit grayscale were randomly selected for subjective comparison. Twenty-eight judges viewed the images to decide whether there were any discernible differences between grades of resolution. Subjective analysis showed no difference between perceived image quality at medium resolution (512 pixels X 768 pixels) and high resolution (1536 pixels X 1024 pixels). Therefore, O'Callaghan suggested the optimum spatial resolution for viewing digital images of lateral cephalometric radiographs to be 786 pixels X 512 pixels to obtain adequate diagnostic information. Results from a subsequent landmark identification comparison of the original film and corresponding digital representations (512 pixels

X 768 pixels) of the film displayed on monitors, demonstrated a comparable accuracy between both methods. Individually, some landmarks were more precisely found on the computer monitor, while others were more accurately located on the tracing. With these inaccuracies in mind, coupled with an uncertainty of the effect gray scale resolution could play in the resolution requirements, the author recommended an image acquisition resolution of 1536 pixels X 1024 pixels to preserve the measurement accuracy of traditional acetate tracing techniques.

Kassebaum et al. (1989) conducted a study to determine the appropriate spatial resolution for digitizing and transmitting dental radiographs. Subjective analysis evaluated the detectability of periapical pathosis on periapical images, proximal surface caries on bitewing images, and various bony abnormalities on panoramic images at different levels of spatial resolution. They concluded that the diagnostic accuracy of the original radiograph was superior to all other modalities. However, a statistically significant difference in diagnostic accuracy was observed between the 0.4 mm pixel size and all other modalities (0.3 mm, 0.2 mm, and original radiograph) suggesting that a 0.3 mm or less pixel size may be required for adequate digital diagnostic assessment. Further analysis indicated a general improvement in diagnostic accuracy of the digital modalities as the pixel size was decreased for both the periapical pathosis and proximal caries detection but not for abnormalities detection with the panoramic digital image. The size of the panoramic radiograph and limitations of the digitizing system prevented the digitization of panoramic images at a pixel size of 0.2 mm. Despite these limitations, the authors speculated the previous finding might be based on the obvious noise of the superimposition of anatomic

structures on a panoramic radiograph, similar to noise found on a lateral cephalogram. Authors concluded that digital dental radiographs provide adequate diagnostic accuracy for evaluating each of the fore-mentioned criteria, however, when viewing panoramic radiographs, a resolution higher than 0.3 mm may be necessary for adequate image interpretation due to excessive noise created by superimpositions. This recommendation may be applicable to the imaging of lateral cephalograms based on the similarity in structural superimposition observed on panoramic radiographs.

Monitor Display

Digital image resolution is also dependent on the display resolution it is viewed upon. With improving technology, the limitations of pixel size and the number of gray levels can be overcome and the limiting factor in the quality of digital images will be the spatial resolution of the display monitor (Forsyth et al. 1996b). Monitors have distinctive resolution capabilities usually measured in dpi, dot size, and/or raster lines. The more dpi and raster lines, or smaller dot size, the higher the resolution. Typical computer monitors range in dot size from 0.25 mm to 0.27 mm. Forsyth et al. (1996b) states that monitors displaying up to 625 raster lines are routinely used for viewing of digital images. Further, if image quality is of particular importance, a 2,048-line monitor should be used to give comparable resolution to a radiographic film.

Additionally, monitors have a choice of display options that characterize the frame size of a given display. By changing the display size (or print size when printing hardcopies), the size of each pixel is either stretched or shrunk and the resolution changes. For example, enlarging an image on the computer display will

enlarge the pixel size, consequently decreasing image resolution. Conversely, if the display dimensions are reduced in the same image, the pixel size decreases resulting in a finer resolution. Standard "factory" settings of monitors depend on screen size. A 17" VGA monitor display is typically set at 800 pixels by 600 pixels; however, custom display options are usually available.

Printing to Hardcopy

Hardcopies of digitized images can be produced by a variety of available printers and media. Printer resolution can play a role in digitized cephalogram image quality and subsequent accuracy of potential analyses and/or superimposition. Printer resolution is usually measured in dpi or pixels/mm (i.e., 5760 X 1440 dpi or 10 pixels/mm). Hardcopy image quality can also be affected by the type of media the image is printed on. Plain paper combined with an inkjet printer typically provides the most economical means for hardcopy production, however resolution may be limited. Radiographs can also be printed on higher-end materials such as grayscale paper or film allowing for better resolution and image quality. Dolphin Imaging recommends radiographs and superimpositions printed on plain paper.

Lyttkens et al. (1994) evaluated the image quality of ink-jet printed-paper of digital chest radiographs compared to film for lesion detection. Images were printed on an ink-jet quality, matt-coated paper with a spatial resolution of 10 pixels/mm and 10 bit gray scale. Their analysis showed no significant difference between the performance of film and that of the ink-jet paper prints. Because the cost for a paper copy was only a tenth of that of film, the authors concluded that remarkable cost

reductions could be achieved by using the ink-jet technique, while retaining the same diagnostic capability of a film-based hardcopy approach.

Ibbott et al. (1998) evaluated the use of a high-resolution laser printer for printing plain-paper images as substitutes for both original and duplicate radiographic film images. A selection of medically related radiographs were used to evaluate the image reproduction capabilities of the printer in terms of linearity, detail, and contrast. The authors concluded that in many cases, printed images had a quality comparable to that of the original images. No numerical data or statistical significance tests were given, however, authors reported printed images produced approximately 12 lp/mm, represented all 129 original shades of gray, and maintained an image linearity of better than 0.1% (edges intended to be perpendicular or parallel were within 0.5° and 0.1°, respectively). Additionally, printed images were subjectively compared to original images on the basis of acceptability for demonstration purposes and diagnostic ability. Of the eighty-four images that were rated, 92.5% of the printed images were rated acceptable for documentation, whereas 48% were rated acceptable for diagnostic purposes.

Compression and Storage

Upon image acquisition, most scanners create files in a tagged image file format (TIFF), a widely accepted non-compressed format for gray-scale images. TIFF is well supported as an image transfer format not tied to specific scanners, printers, or computer display hardware. Unfortunately, TIFF can require a large amount of memory, potentially creating problems in both storage and transmission (Gurdal 2001). Data compression, a technology that reduces the size of image files

by special image coding, can be performed to conserve storage space, reduce transmission time, and make files more stable and manageable (Held et al. 2001; Slone et al. 2000).

Image compression software programs are referred to as lossy or lossless. In lossy form of compression, an irreversible loss of data is accompanied by some loss in image detail in an effort to eliminate unnecessary information; however, higher compressions levels can be attained. Lossless compression techniques conserve all of the information, but result in compression factors on the order of 2:1 to 3:1 for radiographic images, which are insufficient for adequate reductions in data storage or transmission times (Slone et al. 2000). Slone et al. indicated a 10:1 compression factor or higher was required to achieve the goals of storage conservation, transmission time reduction, and data stability and manageability. Therefore, lossy compression must be used. Slone et al. further pointed out some loss of data can be tolerated without affecting the visual interpretation of an image, classifying this compression as "visually lossless."

Currently, the most widely accepted lossy compression method is JPEG (Joint Photographic Experts Group) compression. JPEG compression allows the user to choose the level of compression by selecting the quality or "Q" factor, which directly corresponds to the amount of image detail that will remain after compression and inversely corresponds to the amount of compression (Held et al. 2001). Slone et al. (2000) reported on a study that evaluated radiographic chest film image quality after variable compression factors, that images compressed with JPEG algorithms were indistinguishable from original films for most observers at compression ratios

between 8:1 and 16:1. They concluded that the "visually lossless" threshold was seen between 8:1 and 16:1, and 10:1 compression was acceptable for primary image interpretation and clinical diagnosis. In contrast, Gurdal et al. (2001), in a study determining if variations in radiodensity on digitized dental radiographs were introduced by JPEG compression, showed lossy JPEG compression introduced variations to image gray-scale data. Gurdal et al. further concluded that, depending on the required sensitivity of the detection (caries detection being regarded as highly sensitive), JPEG compression might not be the most reliable choice to detect subtle radiodensity changes.

In an earlier project assessing the effect of data compression on diagnostic accuracy in digital chest radiography, MacMahon et al. (1991) compared data compression based on adaptive block cosine transform coding (an irreversible compression technique allowing considerable compression of digital radiographs with minimal degradation of image quality) at 25:1, 50:1, and no compression. An analysis showed that, with this compression scheme, compression ratios as high as 25:1 could be acceptable for primary diagnosis in chest radiography. Held et al. (2001) suggested the loss of detail that occurs when an image was compressed into a JPEG format did not significantly affect the diagnostic quality of the image when standard compression was used. A Q factor of 3, or medium setting, was utilized for all image compression from TIFF to JPEG formats in this research project.

Inaccuracy

Inherent in the analog to digital transmission is as extremely intricate process with a number of areas for potential error. The very nature of converting an analog

radiographic image into a digital representation requires multiple steps involving a mixture of hardware, software, and computer functions and settings. Further, the conversion of digital images into functional, printable, and storable formats often requires data compression, alteration, and/or transfer to peripheral hardware increasing the likelihood for possible image distortion (Forsyth et al. 1996a).

Marci and Wenzel (1993) looked at proportionality changes after video-recorded digitized images were displayed on a monitor compared to original film measurements. Digital images were found to be slightly enlarged in the vertical plane an average of two percent (3mm over a total distance of 150 mm). The horizontal plane, however, showed no dimensional distortion. In an evaluation of computer-generated cephalometric analyses using Quick Ceph 5.1, Nimkarn and Miles (1995) found horizontal magnification in measurements made on digitized images of lateral cephalograms obtained through video-camera recording compared to the conventional hand-measured technique. All parameters relating to the horizontal plane from the digital image were 0.7-1.0 mm greater than the original analog film. When evaluating the reproducibility of the computer-generated measurement technique, statistically significant differences were found between the original and repeated measures in the vertical plane for three parameters (ANS, B-point, and lower lip length). B-point had the highest mean difference (2.47 mm) between the original and repeated measurements in a vertical dimension. However, authors attributed this finding to landmark identification error. Further, an evaluation of errors arising from video imaging, digitization of the image, and software in an effort to eliminate errors from tracing and landmark identification, demonstrated two parameters, mandibular

incisor position and menton, exhibiting statistically significant differences (0.24 mm and 0.29 mm, respectively) in the vertical plane between the original and repeated measurements. However, authors discounted these differences, citing them too minute to be clinically significant.

Another interesting finding in the study by Nimkarn and Miles (1995) revealed a distortional effect when comparing known distances of linear measurements to distances generated from the computer analysis software. Analysis showed an increasing difference between the computed and known measures as digitization progressed to the right of the video screen. On the left side of the screen, the average difference between known measures and the computed measures was 0.49 mm, in the center, 0.14 mm, and on the right, 0.78 mm. This demonstrated the occurrence of image reduction on the left side of the screen and image magnification on the right side. Since most cephalometric landmarks appear on the right side of a lateral cephalogram, the relative magnification observed in this study would be of concern if accurate computerized cephalometric analysis is desired. Minimal distortion was found in the vertical plane (measured from the center point). However, measurements were not reported for vertical discrepancies along the horizontal plane on either side of the center point. The authors speculated on possible explanations involving the distortion of the image to videocamera or capturing process error, inaccuracies in the software's measurement process, and/or nonparallel placement of the video lens, recording surface, and/or object being imaged.

Similar findings were reported by Sarver et al. (1988) when testing three possible sources of distortion in image capture and projection. These included

distortion introduced by the lens of the camera, the possibility of software distortion between the process of gathering the image and display on the monitor, and distortion in the computer screen. The most common source of distortion was the computer screen. When video-recorded images were manually measured on the computer screen, the highest accuracy was found in the center of the monitor, with magnification increasing towards the periphery of the screen. The distortion ranged from 16% on the left side of the screen to 11% on the right side. Authors contended that the probable sources of distortion were primarily in the monitor and videocamera because the image was projected through the curved surface of the video recorder lens and onto the curved screen of the monitor. Sarver et al. speculated that the use of a flat-screen monitor and flat-field camera lens might decrease distortion. However, they believed that calibration of the software maintained the accuracy of the computerized measurements.

Chen and Hollender (1995) conducted a study testing the physical performance of a flatbed scanner with regard to the digitization of radiographs including the dynamic range in optical density and reproducibility under variable settings. Stepped exposure film was scanned at various locations on the flatbed scanning field and at three different time settings. Their analysis showed that the digitized images scanned with decreased scanning times had pixel values distributed in a narrower range than the optical density values of the film. The dynamic range of the digital image could be amplified by increasing scanning time. Further, variations in location of cephalogram positioning on the scanner yielded different pixel value distributions. The authors concluded that reliable results could be attained digitizing

dental radiographs using a flatbed scanner when the images were repeatedly scanned in the same area of the scanning field. Nevertheless, flatbed scanners showed a narrower dynamic range in optical density compared to the original film, which may affect the diagnostic capability of the digitized image. A slower scanning time setting can improve the optical density range.

Digital Image Manipulation

A potential advantage of digital imaging is the ability to manipulate an image through enhancement controls such as contrast, brightness, smoothing, histogram equalization and edge enhancement, potentially improving diagnostic quality. Using algorithms that mathematically manipulate the individual pixel gray level values, image enhancement may aid the operator in identifying uncertain or indistinguishable hard tissue landmarks or soft tissue profile on lateral cephalograms. Image enhancement refers to the suppression of information that the operator deems unnecessary to images that are of insufficient quality due to factors such as incorrect exposure or blurring, rather than the addition of supplementary information (Forsyth et al. 1996b).

Jäger et al. (1989) suggested digital imaging provides a high quality display and reduces the need for replacement of lost or insufficiently exposed films by improving the quality of radiographs in overall representation, as well as in regional or localized image areas, thereby reducing subsequent radiation exposure to patients. Jäger et al. also claimed an additional benefit of image enhancement techniques through adaptation to general digital communication systems (i.e., DICOM standards). Because, it is possible to use faster film/screen combinations, radiation

exposure can be reduced enhancing the image without compromising diagnostic quality (Wenzel 1988).

Landmark identification errors are considered the major source of error in cephalometry (Baumrind & Frantz 1971a). Many factors have been reported to affect the reproducibility of landmark recording, including the quality of the radiograph, which has considerable importance (McWilliams & Welander 1978). Through digital imaging, image enhancement processing can alter image quality, potentially affecting the diagnostic quality and facilitating landmark identification on the radiograph.

In an effort to assess the affect of digital image processing on cephalometric landmark identification and subsequent superimpositioning of sequential radiographs, Jäger et al. (1989) conducted a study that applied digital image processing of conventionally produced cephalometric radiographs and measured the representation of gray level values over a given area and pixel number. Radiographs were digitized by a microscope-photometer with a spatial resolution of 0.1 mm and 12 bit gray level. Various image enhancement techniques were then applied to the digitized radiographs including histogram equalization and edge enhancement. A comparison of gray level and number of pixels in a defined area, such as cranial base and midface, showed the majority of gray values stacked up unilaterally, demonstrating an over-representation of dark values. After digital enhancement utilizing histogram equalization, a flatter distribution curve was observed employing the whole spectrum of gray levels. Unfortunately, no statistical analysis was given, leaving an uncertainty as to the significance of these data. However, the authors concluded that an improvement of the original image could be observed, and contours of the cranial base, orbit, and

maxilla could be identified more conveniently due to the wider sampling of gray values. Using the contours of the anterior cranial base after image enhancement, the authors speculated it should be possible to superimpose successive digitized radiograph films with the aid of image matching techniques.

Jackson et al. (1985) conducted a pilot study looking at the affects of image enhancement techniques on cephalometry. Several available enhancement techniques were subjectively selected to aid in landmark identification. They showed the random error of angular measurements with the digitally enhanced images were slightly, although not invariably, higher than those obtained through manual tracings. The authors concluded that angular measurements made by common point identification with digital images versus conventional techniques were comparable when enhancement control of the image was used. However, a finer spatial resolution and increased gray level sampling were suggested to improve image quality. Eppley and Sadove (1991) showed similar results when digitally enhanced and standard cephalometric radiographs were compared by osseous and soft tissue landmark analysis. Testing showed both radiographic methods maintained comparable accuracy at identifying hard tissue landmarks, while digital enhancement was in fact more reliable at delineating soft tissue relationships. In soft tissue identification, portions of the profile were often incompletely distinguished on the conventional radiograph. Conversely, all digitally enhanced films had clearly visible soft tissue delineation, and were found to be significantly more accurate in soft tissue identification compared to conventional radiographs.

In contrast, Davis and Mackay (1991) showed no significant differences in six angular measurements made from hand traced original radiographs when compared to digitally enhanced images using contrast enhancement via a high frequency filter. However, a statistical difference was noted in the variability of measurement for different angles when comparing an un-enhanced digital image to the original and digitally enhanced versions of the corresponding radiographs. This suggested that digital enhancement might actually decrease the accuracy of landmark identification and subsequent cephalometric analysis. Similarly, Forsyth et al. (1996b) compared the diagnostic quality of conventional cephalometric radiographs to those of digital-image cephalometric radiographs. The random error associated with angular and linear measurements recorded on the digital images was greater than on conventional radiographs. The errors that occurred with some measurements were of clinical significance, particularly in situations in which a high degree of accuracy was required. Authors suggested a resolution higher than 512 X 512 and 64 gray levels for digital imaging of cephalometric radiographs to maintain the diagnostic quality of conventional radiographs.

The initial quality of the radiographic image is a significant limitation in regards to the affects of digital enhancement on digital imaging. Marci and Wenzel (1993) evaluated reliability in landmark identification in digitally processed high quality and low quality images compared to the original hardcopy cephalograms. Digital images underwent contrast enhancement and filtering to enhance edges. A comparison of landmark identification between the original radiograph and the pre-processed digital image showed measurements from the original cephalogram were

significantly more reliable than the digital images ($p < 0.02$). The authors attributed this discrepancy to the insufficient spatial resolution (512 x 512 x 8 bits) of the image capturing process, which affected both image quality and measuring accuracy. Further testing with digitally enhanced images showed that, although no difference was noted in landmark identification for the high quality digital versus high quality original image, a statistical difference was noted in the low quality digital and low quality original cephalogram. The study concluded that through digital processing, it was possible to attain a reproducibility in landmark location in the digital images comparable to that obtained with the original radiographs for higher quality radiographs, however, digital processing did not improve the overall reliability of landmark identification in poorer quality radiographs.

Wenzel (1988) evaluated the affects of image enhancement on the detectability of bone lesions in digitized intraoral radiographs with impaired density. In vitro lesions were created and radiographs were exposed at three time settings to produce films of optimal, light, and dark density. After digitization with a 512 x 512 x 8 matrix resolution, light and dark images were digitally enhanced utilizing contrast stretching and smoothing filters. The light original radiographs produced decreased accuracy in bone lesion identification compared to optimal density, while no significant differences were found between the dark and optimal density original films. Further, no significant differences were found between the original and digitized radiographs of optimal density and digitally enhanced images of light and dark radiographs. Thus, the digital contrast enhancement and filtering of the low-

exposure (light) radiographs improved image quality and revealed information that escaped detection during examination of the original films.

The ability of digital enhancement techniques to offer improved diagnostic accuracy and/or landmark identification remains unsupported in individual research endeavors thus far. Many confounding factors including quality of the original radiograph, resolution and gray scale settings, and digitization method lead to variations in assessment between differing studies. Given the previous results, digital processing can be described at best comparable to the original film or un-enhanced digital images. However, to suggest digital enhancement provides superior results would be unsubstantiated with exception to soft tissue delineation.

Time

One claimed advantage of computer-aided cephalometric analysis is the decreased amount of time required to measure and analyze a lateral cephalogram. Data acquisition and analysis is supposedly faster than in conventional methods. Davis and Mackay (1991) investigated the time needed to perform cephalometric analysis by the traditional manual method and an interactive computer digitization process. Although a faster mean time was found for the interactive computer technique, it was statistically significant. The time needed to capture the digital image was not taken into account. Baskin and Cisneros (1997) found data acquisition and analysis substantially faster with computerized digital cephalometric analysis programs compared to manual tracing. Similarly, Sandler (1988) found that analysis with the use of hand measurements was by far the most tedious and time-consuming method compared to computer-assisted analysis programs. Direct digitization was

reported to be the fastest and least cumbersome method requiring half the time needed for hand tracing and measurement. These varying results may be due to different digitization methods and/or more recent technological advances in cephalometric programs, indicating a positive benefit for the digital modality. Regardless, timesaving may be an influential factor when clinically evaluating the need to change to digital cephalometric analysis in the orthodontic practice.

Cephalometry

The analysis of lateral cephalograms plays an important role in orthodontic diagnosis, treatment planning, growth monitoring and treatment assessment. Traditional techniques incorporating identified craniofacial radiographic landmarks with manually hand-traced linear and angular measurements have been the preferred method for cephalometry since the utilization of cephalometrics began. Baumrind and Frantz (1971a) showed that inconsistency in landmark identification was an important cause of errors in conventional cephalometry. Evaluating sixteen standard headfilm landmarks in replicated tracings of the same headfilm, the authors described three important observations. First, the errors in landmark identification were too great to be ignored, even when one person was replicating assessments of the same headfilm. Second, the extent of error from landmark to landmark varied greatly. Third, most individual landmarks had a distinctive "noncircular envelope" of error that was not random but systematic in distribution. The factors influencing accurate identification were quoted as distinctness of structural detail, noise from adjacent structures due to superimposition of conflicting anatomical details and conceptual judgment (a factor which is largely based on the past experience and radiological

knowledge of the observer). In a follow-up study, Baumrind & Frantz (1971b) assessed the affects of error in landmark location transmitted to the values of linear and angular measurements of some commonly used head film analyses. Twenty-three measurements in total were used, of which seventeen related to angular measurements, five related to linear measurements, and one corresponded to a ratio between two distances. Similar findings to their previous study demonstrated the fact that angular and linear measurements from head films contain considerable errors, which cannot be disregarded. Further, as the case in the earlier study, the magnitude of error differed from measurement to measurement, discounting any notion of reliability between angular and linear measurements. Overall, based on absolute value of error and variability among estimated replicates, angular measurements tended to display a greater error than linear measures. Baumrind and Frantz suggested the observed error for a given measurement was a function of the degree of error for the specific landmarks utilized in the given measurement, the distance between the given landmarks, and the interrelation of the line segments and the given landmark's envelopes of error. Therefore, inherent in the nature of radiography and cephalometry is an intrinsic, human error observed in the identification of known structures, as well as the in measurement of various formed angles and lines used for cephalometric analysis. To this end, film-based, direct digital, and indirect digital radiography all possess intrinsic error, which must be taken into account when making comparisons between these different modalities.

Cephalometric landmark identification has been a heavily examined subject when comparing digital imaging to traditional tracing methods in cephalometric

analysis. A variety of studies have been published contrasting landmark identification using digitized radiographs to hand traced cephalograms. Richardson (1981) compared computerized digitization of the cephalogram using a cartographic digitizer and conventional hand tracing in determining the location of fourteen landmarks on fifty lateral cephalometric radiographs. By using coordinate points on the x-y axes, it was shown that the digitizer discrepancies were smaller than those from the hand tracing method in twelve of fourteen points for the horizontal coordinates. However, when comparing the standard deviations, the digitizer was superior in only nine of fourteen points. Mean discrepancies for the vertical coordinates showed the digitizer measurements were smaller in twelve of fourteen points. However the standard deviation was smaller in only eight of fourteen points. No statistical significance tests were included. Richardson concluded that traditional methods were inferior to the digitized technique, but not alarmingly so. Overall, digitization appeared to have an advantage in measurement accuracy of cephalometric radiographs.

Sandler (1988) examined three methods of measurement of cephalometric radiographs; conventional hand tracings, digitization of tracings and direct digitization of the radiograph. Twenty-five radiographs were traced and/or digitized twice, and linear and angular measurements were analyzed. An analysis of the results indicated an appreciable amount of error in taking cephalometric measurements from radiographs with any chosen technique. Sandler pointed out that angular measurements involving incisor teeth had consistently higher errors and, therefore, must be treated with caution. In general, direct digitization was slightly more

reproducible for most angular measurements, although overall there was no statistically significant difference. Direct digitization was notably unreliable with linear measurements involving bilateral structures such as gonion and articulare, and the use of hand tracing was recommended. He concluded by stating hand measurement compared reasonably well with methods involving the digitizer.

In another study, Oliver (1991) compared five cephalometric measurement methods; manual technique, direct digitization of the radiograph with a digitzer pad and crosshair cursor, direct digitization of the tracing with the radiograph (traced without pre-identification of the landmarks prior to the digitization process), digitization of the enhanced video image of a radiograph and digitization of the enhanced digital image of a tracing with a radiograph. Using a sample of five cephalometric radiographs, Oliver measured six common cephalometric angles. He concluded that the digitization of a radiograph was less precise than both the manual method and the digitization of a tracing with the radiograph. This was true for both digitization methods (direct and indirect). The enhancement of the digital radiographic image did not produce any statistically significant improvement in the precision of identification of the cephalometric variables under study. In contrast, Davis and Mackay (1991) compared six angular measurements from cephalometric images generated from three different methods; manual tracing, digitization with a graphics mouse and digitization with a graphics mouse after image enhancement through a high frequency filter image that tended to increase the contrast. No differences were found in the manual and enhanced methods. However, direct

digitization without contrast enhancement showed significantly less variability and, therefore, higher accuracy than the two other tested methods.

A more recent study conducted by Chen et al. (2000) compared landmark identification on digital images to those obtained from original radiographs. In order to assess the concordance between landmarks identified, an x-y coordinate grid system was used to analyze horizontal and vertical differences between the two modalities. Analysis of the results showed statistically significant differences between the two methods in the horizontal component on the x-axis relating to landmarks Me, Gn, ANS, PNS, LIA, and in the vertical component on the y-axis corresponding to landmarks Po, Or, and Gn. The differences, however, were generally less than 1 mm with the exception of Or, Me, PNS, and LIA. Furthermore, the reliability for each landmark, as measured by the inter-observer error, was shown to be significantly lower in four of the digitally identified landmarks (Po, Ar, PNS, and UM) compared to that in the original radiographs. The authors concluded that these four landmarks should be carefully considered during applications of digital cephalometry.

In a similar study conducted by Marci and Wenzel (1993), the reliability in landmark location in digitally imported cephalograms of varying quality was compared to the reliability of the original films. Mean x and y values were plotted for all measured landmarks to obtain the best estimate of each landmark position. Variance comparisons were performed between the digital images and original cephalogram, as well as between subgroups of differing film quality. In general, results showed measurements from the original cephalograms were more reliable than

those from digital images. The conventional technique displayed a higher reliability for measurements along the x-axis, however, no significant differences among modalities in the y-axis were noted. Turner and Weerakone (2001) compared the reproducibility of landmark identification between three modalities; scanned radiographic images and the cephalometric analysis program ScreenCeph (without the use of digital enhancement), manual tracing followed by digitization, and direct digitization of identified points. Using a similar x-y coordinate system as in previously mentioned studies, along with eight angular and four linear cephalometric measurements, the authors found the scanned image and cephalometric program produced comparably favorable results in landmark identification to the other tested methods. Direct digitization of the cephalometric landmarks showed the most accuracy in measurement. However the authors concluded that scanned cephalometric images utilizing the ScreenCeph analysis program were acceptable for cephalometric analysis in routine clinical practice. Similarly, Baskin and Cisneros (1997) showed two popular cephalometric analysis programs, Quick Ceph® and Dentofacial Planner, had comparable reliability and reproducibility to manual tracing based on angular and linear measurements. Furthermore, data acquisition and analysis were substantially faster with either computer program compared to manual tracing.

Although selected studies indicate minor errors involved in landmark identification with the use of digital cephalometric programs, most authors agree that landmark identification through the digital environment can be used adequately in everyday clinical applications in orthodontics with certain caution. Turner and

Weerakone (2001) concluded their study by stating that the tested computerized cephalometric analysis program, ScreenCeph, combined with scanned digital imaging, is acceptable in routine clinical practice for cephalometric analysis. Chen et al. (2000) reported comparable reliability of landmark identification with digital images and original radiographs except for four points (Po, Ar, PNS, UM) and suggested these landmarks be carefully scrutinized when implementing digital radiography. Finally, both Richardson (1981) and Davis and Mackay (1991) found digitization techniques to be superior in accuracy for cephalometric analysis than traditional manual methods.

Superimposition

Superimposition of cephalometric film and tracings is a vital instrument used by orthodontists for longitudinal evaluation of treatment effect and growth of craniofacial and dental structures. Modern cephalometric analysis programs possess the ability to superimpose digitized tracings over one another to visually represent craniofacial skeletal and dental changes. Programs such as Dolphin Imaging cephalometric tracing and analysis allow for a variety of reference structures to be selected for superimposition. Recent updates to the Dolphin Imaging software allow for both overall and regional superimpositions to be made (Dolphin's Cephalometric Tracing and Analysis 8.0 2002). However, the accuracy and reliability of such programs has not been researched to date, leaving potential users uncertain of their diagnostic and evaluative capability.

Although a variety of methods exist in terms of structures utilized for stable reference points, certain key landmarks and/or regions have been accepted as the

standard for superimposition techniques. The cranial base morphology tends to lend itself as a stable structural area for overall superimpositions. Elmajian (1959) showed the internal structures of the sphenoid and ethmoid bases, as observed on a cephalogram, are excellent reference points for overall superimposition due their stability and cessation of growth after age seven. However, cephalometric analysis programs such as Dolphin's allow only certain configurations of adjoining landmarks (i.e., sella-nasion, Frankfort horizontal, etc.) to be selected as reference planes for overall superimposition, proving to be a limitation to computer assisted superimposition. Björk (1963) cites three areas of stability in mandibular growth that have been considered the essential reference landmarks for mandibular superimposition. The inferior aspect of the third molar crypt, the inner cortical structures of the inferior border of the symphysis, and the detail structures of the mandibular canal are all indicators for accurate orientation of the mandible in growth analysis. Doppel et al. (1994) demonstrated, through a metallic implant study, that the posterior and anterior portions of the zygomatic process of the maxilla to be the most reliable anatomic landmarks for cephalometric superimposition in an anterior-posterior direction. In the vertical plane, the floor of the orbit raised more than the palatal plane lowered by an average ratio of 1.5 to 1 mm. Thus, this ratio was suggested for landmark orientation in the vertical plane for maxillary superimpositions. Again, computerized cephalometric programs such as Dolphin Imaging limit the capability of regional superimposition by allowing only preset reference points to be utilized. Dolphin Imaging uses ANS and PNS for maxillary superimposition reference points and mandibular plane and outer border of

mandibular symphysis for mandibular superimposition reference structures. Doppel et al. (1994) indicated that maxillary structures ANS and PNS were not reliable landmarks for maxillary superimposition. Björk (1963) stated that the lower border of the mandible was "unsuitable" as a reference line for mandibular orientation in growth analysis due to variable apposition and resorption, especially in the angulus region. Thus, limitations in computerized cephalometric superimposition analysis must be considered when assessing the diagnostic accuracy and treatment evaluation capability of these programs.

STATEMENT OF THESIS

This study is designed to determine whether a cephalometric radiograph can be scanned with a flatbed scanner equipped with a transparency adapter, and produce an accurate representation of the original radiograph, thereby replacing the traditional radiographic hardcopy film? In other words, how accurate is the process of scanning a lateral cephalogram into a digital image, and can this digital format be effective in reliably accomplishing the everyday needs of a cephalogram including cephalometric analysis, superimpositioning, and hardcopy printouts? This project has three objectives: 1) To measure the potential distortion and/or enlargement of image transfer from the original cephalogram to the on-screen digital image via a digital scanning process, as well as assessing potential distortion through transfer of digital image to a printed hardcopy version of the original cephalogram; 2) To evaluate the accuracy of a digital cephalometric program (Dolphin's Cephalometric Tracing and Analysis) and a hand-traced printed digital hardcopy of the original cephalogram using linear and angular measurements from four common cephalometric analyses (Downs, Steiner, Tweed, and Riedel) compared to results using the original radiograph and traditional manual hand-traced techniques; and, 3) To compare the accuracy of computerized superimposition techniques using the scanned digital cephalogram with Dolphin's superimposition program to traditional, manual superimposition techniques.

The goal of this research is to provide orthodontists with an evidence-based analysis of a digital method of acquiring, utilizing, and archiving lateral cephalograms. If scanning of radiographs into a digital format can be proven accurate in all considerations, orthodontists may choose it as an inexpensive and efficient means to update their practice.

Hypothesis

Cephalometric radiographs can be accurately scanned into a digital format with little or no significant distortion that would impact clinical applications.

MATERIALS AND METHODS

Sample

Thirty subjects were chosen based on the following criteria: 1) Signed informed consent by patient or parent allowing use of records for research purposes; and 2) An initial and final cephalogram of adequate diagnostic quality with identifiable craniofacial structures and landmarks. All radiographs were obtained from charts of active patients at Case Western Reserve University, Department of Orthodontics. Radiographs were taken using the Bolton cephalometer located in Orthodontic Department at Case Western Reserve University. The thirty initial and corresponding thirty final radiographs were placed into three experimental groups: original radiograph, digital image, and hardcopy.

Original Radiograph

The original radiograph group consisted of the thirty initial and thirty final original radiographs. All radiographs were indexed with four corner fiducials and four internal fiducials (Figure 1) using a template according to the method described by Baumrind (1980). The sixty radiographs were manually traced using acetate tracing paper placed over the original radiograph on a standard light-box in a darkened room. A 0.5 mm lead pencil was used to trace all required hard and soft tissue landmarks. Bilateral structures were averaged to make a single structure and/or landmark. Mechanical porion was used to identify porion.



Figure 1. Lateral cephalogram with stamped fiducial points labeled for identification. The four external points are labeled A, B, C, and D. The four internal points are labeled a, b, c, and d.

Manual superimpositions were completed for all thirty subjects utilizing initial and final original cephalograms. Superimpositions were completed using acetate tracing paper placed on a standard light-box in a darkened room. A 0.5 mm black lead pencil was used to trace all required initial structures, while a 0.5 mm blue lead pencil was utilized for final structures. S-N at sella was used as the reference plane for the overall superimpositions, ANS-PNS plane registered at ANS was utilized for maxillary superimpositions, and GO-ME plane registered at ME was used for

mandibular superimpositions. All procedures were performed by a single operator (LQB).

Digital Image

After fiducial indexing on the original radiograph, the thirty initial and thirty final cephalograms were scanned into a digital format by use of an Epson® Expression® 1600 scanner fitted with a EU-35 transparency unit adapter. All radiographs were placed in the upper right hand corner of the scanner base adjacent to a calibration ruler provided by Dolphin Imaging Systems and scanned using Adobe® Photoshop® 6.0 software at the following settings:

1. Document Source: TPU for positive film
2. Image Type: 24 bit color descreening
3. Resolution: 150 dpi

Images were originally created as TIFF images since TIFF offers a lossless image, resulting in no information loss upon digital transfer. Dolphin's imaging software, however, does not accept TIFF files. Therefore, images were subsequently saved as JPEG files to facilitate image acquisition by Dolphin's software. Individual files were compressed using Adobe® Photoshop® 6.0 compression software and saved. All images were compressed at a Q-factor of 10 or "maximum" quality setting according to Adobe® Photoshop® 6.0 software settings. Final image properties included average dimensions of 1200 pixels X 1600 pixels, approximate size of 220 KB, and resolution of 150 dpi.

Images were imported into Dolphin's Cephalometric Tracing and Analysis software, and charts were created for each individual patient and labeled one through

thirty, respectively. Landmark digitization was then completed for each initial and final cephalometric image. Images were displayed on a NEC MultiSync LCD 1550V 15-inch flat screen monitor with display resolution of 1024 pixels x 768 pixels. Utilizing Dolphin's digitization software, forty-two hard and soft tissue landmarks were identified using a mouse linked to a crosshair locator. The landmark definitions used are listed in Appendix A.

Four specific internal fiducial points were also digitized using Dolphin's custom cephalometric landmark function (Figure 1). Images were calibrated during landmark digitization by identifying two crosshairs 100 mm apart located on a ruler provided by Dolphin Imaging Systems. The ruler was taped to the transparency adapter and scanned during image acquisition. Various image enhancement adjustments including brightness, contrast, and magnification were utilized as needed to identify individual landmarks as precisely as possible.

Utilizing the superimposition application provided in Dolphin's software, superimpositions for the thirty subjects were created using the digitized initial and final images. Reference planes used in the manual superimpositions were maintained in the digital superimposition (S-Na at S for overall superimpositions, ANS-PNS plane registered at ANS for maxillary superimpositions, and GO-ME plane registered at ME for mandibular superimpositions). In order to facilitate measurement data collection, superimpositions were printed out using a 1:1 scale representation from Dolphin's program onto plain, 8.5 x 11 inch standard white paper using a HP LaserJet 4100N printer at 1,200 dpi. All procedures were performed by a single operator (LQB).

Hardcopy

Hardcopies of the thirty initial digital images were created to analyze potential distortion upon image transfer to hardcopy. Digital images were printed from stored JPEG files in Adobe® Photoshop® 6.0. Images were printed onto plain, standard white paper using a HP LaserJet 4100N printer at 1,200 dpi.

Manual tracings were completed for the thirty hardcopy radiographs directly on the hardcopy printout for optimal landmark visualization in a lighted room. A 0.5 mm lead pencil was used to trace all required hard and soft tissue landmarks. All bilateral structures were averaged to make a single structure and/or landmark. Mechanical porion was used to identify porion. All procedures were performed by a single operator (LQB).

Measurements

Distortion/Enlargement

The first objective of the current investigation was to measure potential distortion of the image transfer from the original cephalogram to the on-screen digital image through a digital scanning process, as well as to assess possible distortion during the transfer from the digital image to a printed hardcopy version of the original cephalogram. In order to test for distortion of the digitized image and corresponding hardcopy version, four corner fiducial points (Figure 1) were measured from both modalities and compared to the measurements recorded from the corresponding original radiographs. Five linear measurements, two horizontal (line segments BC and DA), two vertical (line segments AB and CD), and one transverse (line segment AC), were recorded for each of the thirty cephalograms using a standard millimeter ruler.

Measurements were made in millimeters to the nearest tenth of a millimeter and recorded and stored in a Microsoft® Excel® spreadsheet.

Adobe® Photoshop® 6.0 was used to measure the linear distances between the four corner fiducials for the digital representation of the cephalometric image. Using the ruler function in the Adobe® Photoshop® software, the same five linear measurements were recorded for each of the thirty cephalograms. Measurements were made in millimeters to the nearest tenth of a millimeter and recorded and stored in a Microsoft® Excel® spreadsheet.

To test for potential distortion of the printed digital image hardcopy, fiducial points on the thirty printed images of the digital radiograph were measured manually. In an identical fashion to the fiducial measurements from the original images, five linear measurements were recorded from the hardcopy printout. All measurements were recorded in millimeters to the nearest tenth of a millimeter using a millimeter ruler attached to a cephalometric protractor and stored in a Microsoft Excel® database. Digital and hardcopy measurements were compared to corresponding measurements from the original radiographs.

Angular and Linear Cephalometric Measurements

The second objective in the present study aimed at evaluating the accuracy of a digital cephalometric program (Dolphin Imaging Systems) and a hand-traced printed digital hardcopy of the original cephalogram compared to results using the original radiograph and traditional manual hand-traced techniques. In order to test this objective, twenty-three linear and angular measurements (Table 1) from four common cephalometric analyses (Downs, Steiner, Tweed, and Riedel) were obtained from a

TABLE 1.--The Four Cephalometric Analyses and Associated Twenty-Three Measurements Utilized for Comparison of Experimental Groups. Means and Standard Deviations are Given for Individual Measurements.

Downs Analysis	**Mean**	**SD**
Facial Angle	87.8	6.5
Angle of Convexity	7.1	3
A-B plane to Na-Pogonion	-4.9	3
Y-axis to Frankfort Horizontal	60.6	3.4
Occlusal plane angle	8.7	5
Interincisal angle	127	9
Lower incisor to Occlusal plane	18	5
Lower incisor to Mandibular plane	5	7
Upper Incisor to A-Pogonion	6	2.2
Riedel Analysis		
SNA	82	3.5
SNB	80.9	3.4
ANB	1.6	1.5
Upper Incisor to Frankfort Horizontal	116	5.5
Frankfort Horizontal to Nasion/A-point	90	3
Tweed		
Mandibular Plane Angle (FMA)	22	5
Lower Incisor to Mandibular Plane Angle (IMPA)	95	7
Frankfort Horizontal to Mandibular Incisor Angle (FMIA)	64	8.5
Steiner		
Upper incisor to Nasion/A-point (mm)	4.3	2.7
Upper incisor to Nasion/A-point (degree)	22.8	5.7
Lower incisor to Nasion/B-point (mm)	4	1.8
Lower incisor to Nasion/B-point (degree)	25.3	6
Pogonion to Nasion/B-point	1.9	1.7
Pogonion to Nasion/B-point to Lower Incisor	2.6	1.7

digitized representation of a scanned cephalometric film and a printed digital hardcopy.

The twenty-three measurements for each of the thirty previously digitized cephalograms were first acquired using Dolphin's Cephalometric Tracing and Analysis program. The measurements were obtained by selecting the appropriate

analysis from a list of possible analyses. Measurements were recorded and stored into a Microsoft® Excel® spreadsheet. Values were recorded to the nearest tenth of a millimeter and degree.

The same twenty-three measurements were then made for both the printed digital initial hardcopy tracing and the original initial cephalogram tracing via conventional hand-traced techniques. Angular and linear values were measured with a 3M™ orthodontic protractor and ruler, recorded to the nearest tenth of a millimeter and degree and saved into a Microsoft® Excel® spreadsheet for statistical analysis. All measurements were obtained by a single operator (LQB).

Superimpositions

The final objective of the current investigation was to compare the accuracy of a computerized superimposition technique using a scanned digital cephalogram via Dolphin's superimposition program to traditional manual superimposition techniques. Linear changes in the position of four fiducial points were measured on thirty superimposed initial and final radiographs printed from Dolphin's program. The four fiducial points were digitized with Dolphin's custom cephalometric analysis feature and were labeled a, b, c, and d as shown in Figure 1. Respective timepoint-1 and timepoint-2 tracings were superimposed using sella-nasion registered at sella as the reference plane. These measurements were then compared to the same measurements made from manual superimpositions of the original cephalograms using the same reference plane (sella-nasion at sella) to align the separate tracings. All measurements were recorded in millimeters to the nearest tenth of a millimeter using a millimeter ruler in a Microsoft® Excel® spreadsheet.

Further analysis was conducted to assess the accuracy of a computerized superimposition program in correctly displaying the positional skeletal and dental changes occurring during treatment and growth compared to conventional manual superimposition techniques. Sixteen linear and two angular measurements were used to evaluate the horizontal and vertical changes in maxillary, mandibular, maxillary molar, maxillary incisor, mandibular molar, mandibular incisor and soft tissue positions using the same thirty cases as previously described (Table 2). Additionally, mandibular growth was assessed by comparing differences in articulare at initial and final timepoints between the two modalities. Figures 2, 3, and 4 demonstrate how each of the eighteen superimposition and four fiducial measurements were obtained. Angular and linear values were measured with a 3M™ orthodontic protractor and ruler, recorded to the nearest tenth of a millimeter and degree, and saved into a Microsoft® Excel® spreadsheet for statistical analysis.

Method of Error

Intra-operator error was examined by randomly selecting ten cephalograms from the original sample of thirty. The ten initial and ten final radiographs were then scanned, saved, and imported into Dolphin's software using the same settings and setup as previously described in the original data collection section. The ten initial radiographs were printed on the same printer at identical settings as in the original image acquisition. The ten initial and final radiographs were re-digitized utilizing Dolphin System software using the same forty-two hard and soft tissue landmarks.

As with the original data collection, five fiducial distances and cephalometric angular and linear measurements based on four commonly used cephalometric

TABLE 2.--Sixteen Linear and Two Angular Measurements Constructed to Compare Superimposition Accuracy Between Digital and Manually Produced Images

Overall Superimposition Measurements	
SN⊥A-Pt (Max. A-P) mm	Anterior-Posterior positional change of the maxilla measured at A-point from a perpendicular reference line to Sella-Nasion plane
SN⊥A-Pt (Max.Vertical) mm	Vertical positional change of the maxilla measured at A-point from a perpendicular reference line to Sella-Nasion plane
Pog-Pog⊥SN (Mand. A-P) mm	Anterior-Posterior positional change of the mandible measured at Pogonion from a perpendicular reference line to Sella-Nasion plane
Me-Me⊥SN (Mand. Vertical) mm	Vertical positional change of the mandible measured at Menton from a perpendicular reference line to Sella-Nasion plane
Maxillary Regional Superimposition Measurements	
M6-M6⊥Ans/Pns (A-P Molar Position) mm	Anterior-Posterior change of the maxillary first molar position measured at the most mesial aspect of the molar crown from a perpendicular reference line to Ans-Pns plane
O6-O6⊥Ans/Pns (Vertical Molar Position) mm	Vertical change of the maxillary first molar position measured at the mesiobuccal cusp tip from a perpendicular reference line to Ans-Pns plane
T1-T1⊥Ans/Pns (A-P Incisor Position) mm	Anterior-Posterior change of the maxillary incisor position measured at the incisal tip from a perpendicular reference line to Ans-Pns plane
T1-T1⊥Ans/Pns(Vertical Incisor Tip Position) mm	Vertical change of maxillary incisor position measured at the incisal tip from a perpendicular reference line to Ans-Pns plane
A1-A1 (Incisor Angulation) °	Change in maxillary incisor angulation measured as the angle formed between the maxillary incisor at initial and final timepoints
Mandibular Regional Superimposition Measurements	
M6-M6⊥Go/Me (A-P Molar Position) mm	Anterior-Posterior change of the mandibular first molar position measured at the most mesial aspect of the crown from a perpendicular reference line to Gonion-Menton plane

TABLE 2.--Sixteen Linear and Two Angular Measurements Constructed to Compare Superimposition Accuracy Between Digital and Manually Produced Images (Continued)

O6-O6⊥Go/Me (Vertical Molar Position) mm	Vertical change of the mandibular first molar position measured at the mesiobuccal cusp tip from a perpendicular reference line to Gonion-Menton plane
T1-T1⊥Go/Me (A-P Incisor Tip Position) mm	Anterior-Posterior change of the mandibular incisor position measured at the incisal tip from a perpendicular reference line to Gonion-Menton plane
T1-T1⊥Go/Me (Vertical Incisor Tip Position) mm	Vertical change of mandibular incisor position measured at the incisal tip from a perpendicular reference line to Gonion-Menton plane
A1-A1 (Incisor Angulation) °	Change in mandibular incisor angulation measured as the angle formed between the mandibular incisor at initial and final timepoints
Ar-Ar (Mandibular Growth) mm	Evaluation of mandibular growth measured as the difference between Articulare at initial and final timepoints
Soft Tissue Superimposition Measurements	
Me-Me mm	Evaluation of change in position of soft tissue Menton measured as the difference between soft tissue Menton at initial and final timepoints
Soft Tissue A-Pt-Soft Tissue A-Pt mm	Evaluation of change in position of soft tissue A-Point measured as the difference between soft tissue A-Point at initial and final timepoints
Tip of Nose-Tip of Nose mm	Evaluation of change in position of tip of nose measured as the difference between tip of nose at initial and final timepoints
Fiducial Superimposition Measurements	
a-a^{l} mm	Evaluation of change in position of fiducial point *a* measured as the difference between fiducial point *a* at initial and final timepoints
b-b^{l} mm	Evaluation of change in position of fiducial point *b* measured as the difference between fiducial point *b* at initial and final timepoints
c-c^{l} mm	Evaluation of change in position of fiducial point *c* measured as the difference between fiducial point *c* at initial and final timepoints
d-d^{l} mm	Evaluation of change in position of fiducial point *d* measured as the difference between fiducial point *d* at initial and final timepoints

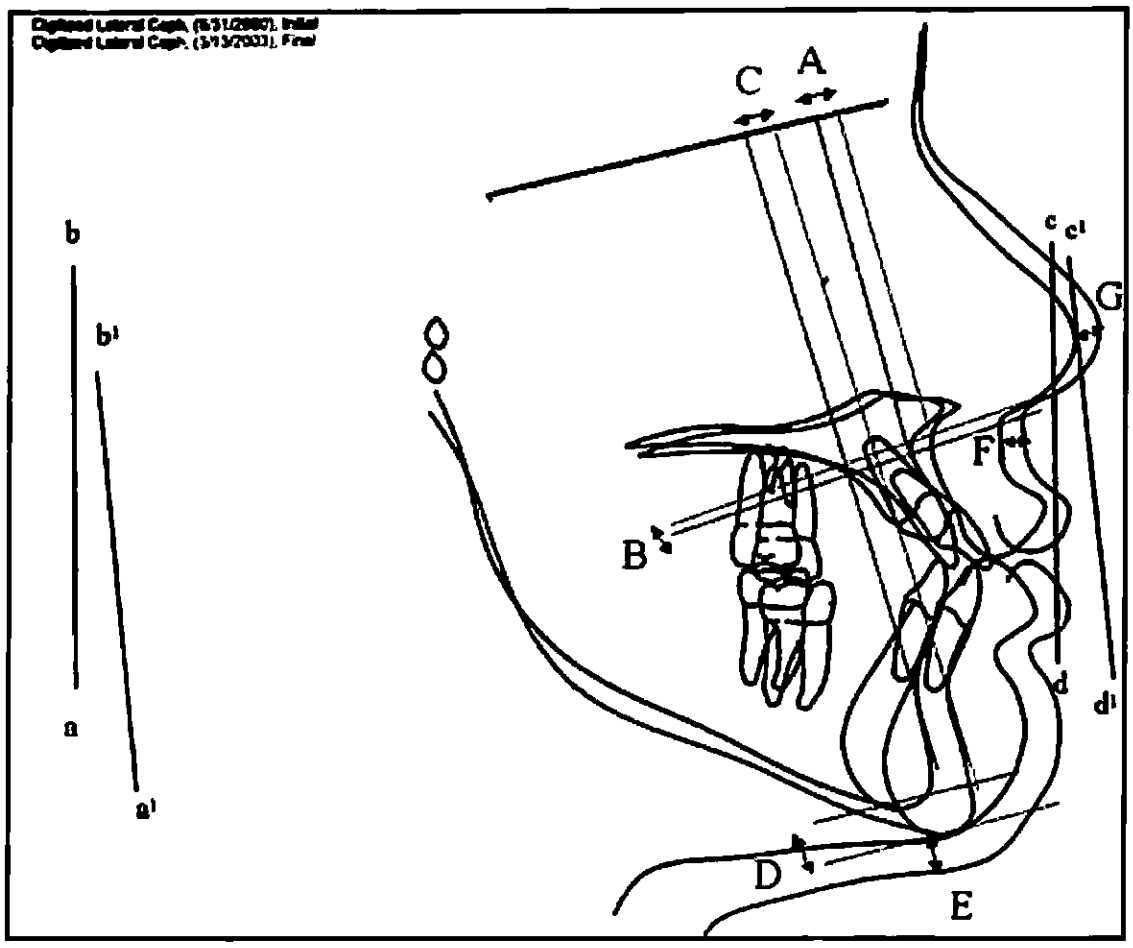


Figure 2. Overall superimposition superimposed on SN at S with constructed measurements used to assess maxillary, mandibular, soft tissue, and fiducial point positional changes. Black lines indicate the initial tracing and green lines represent the final tracing landmarks. A and B represent the A-P and vertical change in the maxilla, respectively. C and D represent the A-P and vertical change in the mandible, respectively. E, F, and G represent soft tissue changes at soft tissue Menton, A-point, and tip of nose, respectively. Initial fiducial points are labeled a, b, c, and d. Final fiducial points are labeled a^1, b^1, c^1, and d^1.

analyses were recorded for manually traced cephalograms, hardcopy printouts, and digitized images. In addition, ten superimpositions, using both Dolphin's software and manual tracings, were completed again to evaluate intra-operator error during superimposition data collection. Values were recorded to the nearest tenth of a

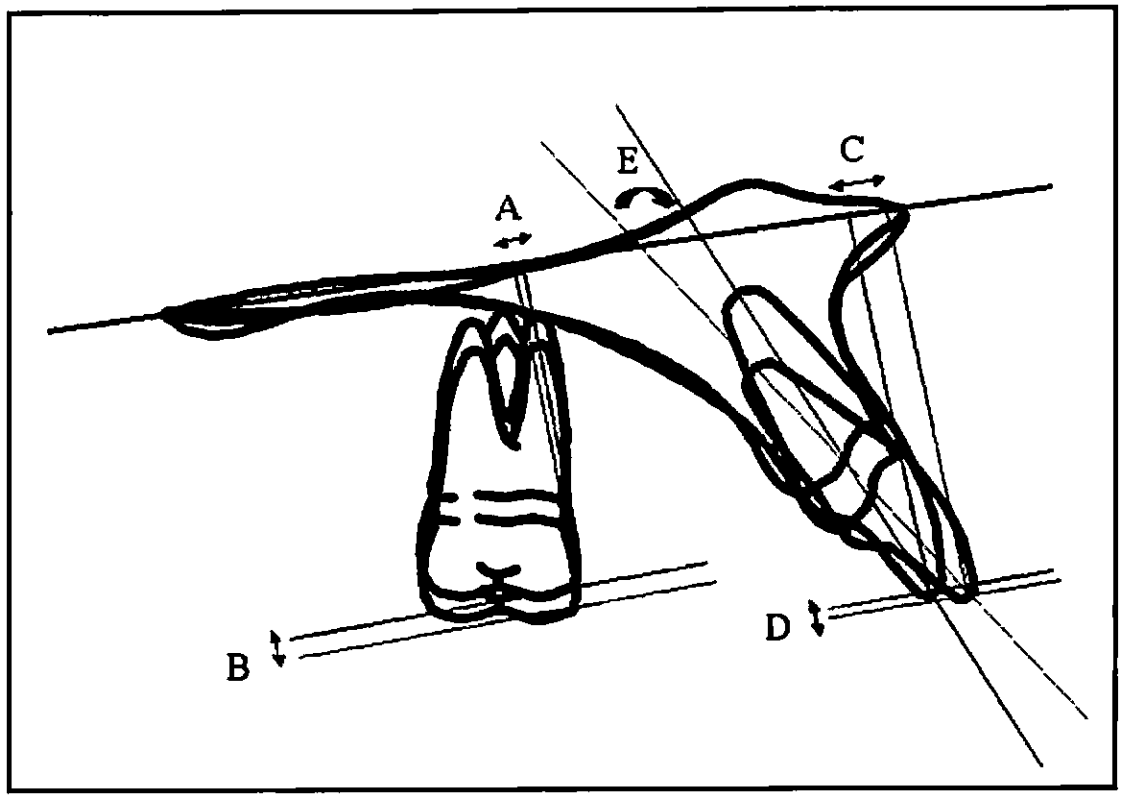


Figure 3. Maxillary superimposition superimposed on ANS-PNS at ANS with constructed measurements used to assess maxillary molar and incisor positional changes and incisor angulation change. Black lines indicate the initial tracing and green lines represent the final tracing landmarks. A and B represent the A-P and vertical change in molar position, respectively. C and D represent the A-P and vertical change in incisor position, respectively. E represents the angular change in incisor position.

millimeter and degree. All data were imported into a Microsoft® Excel® database for statistical analysis, and all data collection was performed by a single operator (LQB), four weeks after the original data collection had commenced.

Statistics

Means, standard deviations, and ranges were calculated for all data utilizing Microsoft® Excel® software. Paired Student t-tests were used to evaluate statistical

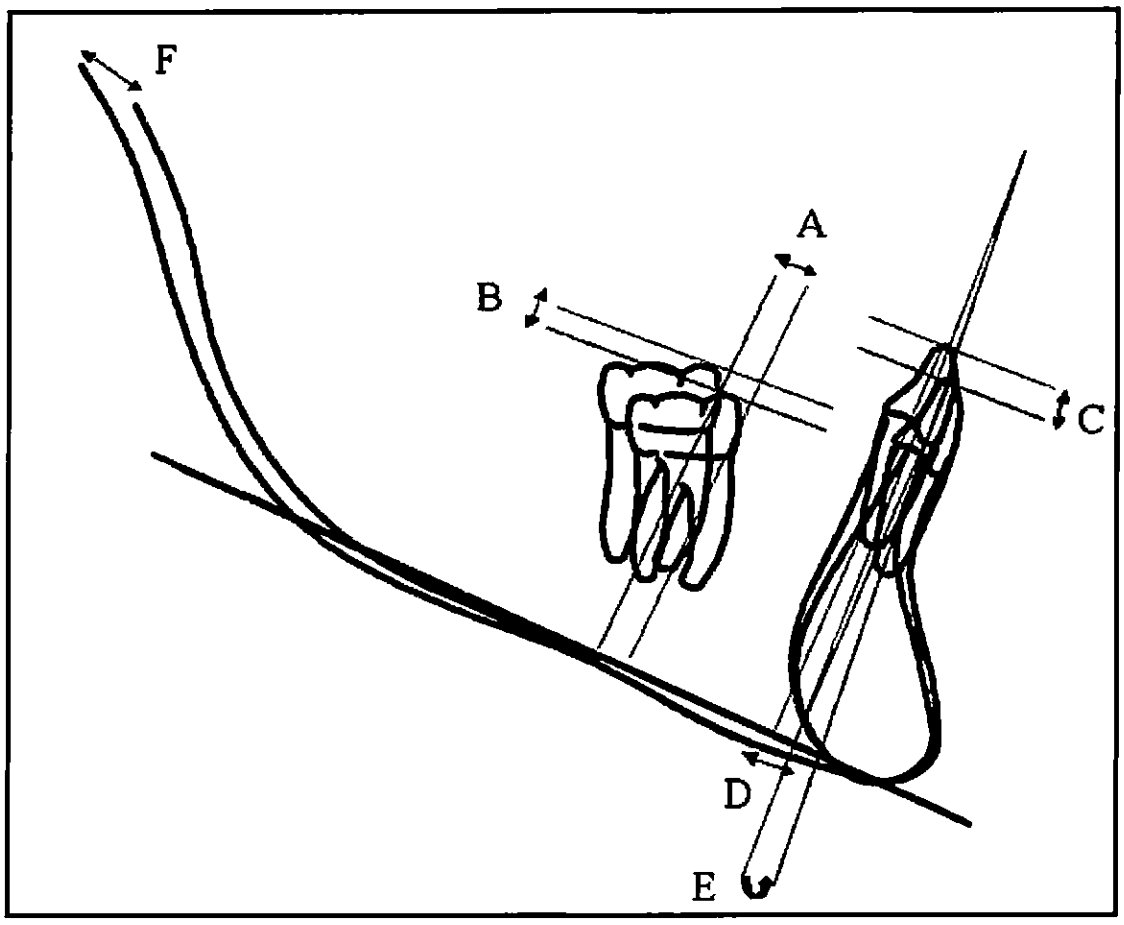


Figure 4. Mandibular superimposition superimposed on Go-Me at Me with constructed measurements used to assess mandibular molar and incisor positional changes, incisor angulation change, and mandibular growth. Black lines indicate the initial tracing and green lines represent the final tracing landmarks. A and B represent the A-P and vertical change in molar position, respectively. C and D represent the A-P and vertical change in incisor position, respectively. E represents the angular change in incisor position. F shows mandibular growth measured at Articulare.

significance for comparing mean values between corresponding data sets. Statistical significance was initially set at $p < 0.05$. However, the Bonferroni correction (α/total number of measurements) was applied to correct for the numerous measurements utilized. Intra-operator error was analyzed using SPSS software. Intra-class correlation was calculated for all intra-operator measurements to determine the

corresponding correlation coefficient (r-value). A r-value < 0.75 was considered to demonstrate weak correlation.

RESULTS

Fiducial Measurements

Thirty lateral cephalograms were marked with four corner fiducial points using a template as described by Baumrind and Miller (1980). Five linear measurements (two vertical, two horizontal, and one transverse) were made using a millimetric ruler as shown in Figure 1. The thirty original cephalograms were subsequently scanned into a digital format using a commercial scanner, equipped with a transparency adapter, and a desktop computer as previously described. Individual files were then created and opened in Adobe® Photoshop® 6.0. Utilizing the ruler tool in Adobe® Photoshop® 6.0, fiducial points were measured using the same five linear measurements. Finally, individual images were printed to a hardcopy format using a laser printer and standard 8 ½" x 11" white office paper. Using the same technique as with the original film, five linear measurements were recorded for each of the thirty cephalograms.

Results for the three modalities of fiducial measurements are shown in Table 3. Means, standard deviations and ranges are presented. Mean values increased for all measurements expect BC and DA as the original image was transferred into a digital format. All mean values in the hardcopy group were larger than the original cephalogram values. Standard deviations and ranges for the original cephalogram values were quite low, as would be expected. However, for both digital and hardcopy

TABLE 3.--Mean, Standard Deviation, and Range of Fiducial Measurements Between the Original Film, Digital Image, and Printed Hardcopy

Fiducial Distance *	Original			Digital			Hardcopy		
	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
AB	159.3	0.1	159.1/159.5	160.1	0.5	158.4/160.5	160.4	0.5	159/161.2
BC	177.2	0.1	177/177.5	176.8	0.2	176.5/177.2	177.5	0.2	177.2/177.9
CD	152.3	0.1	152.2/152.5	153.1	0.2	152.4/153.4	153.4	0.3	153/154
DA	177.6	0.1	177.4/177.8	177.1	0.1	177/177.3	178.1	0.1	177.9/179
AC	233.8	0.1	233.5/234	234.3	0.2	233.7/234.5	234.7	0.2	234.4/235
Total	900.2	0.2	899.8/900.7	901.5	0.9	898.4/902.5	904.0	1.1	901.8/905.8
Average	180.0	0.0	180/180.1	180.3	0.2	179.7/180.5	180.8	0.2	180.4/181.2

*All distances in mm

values, an increase in variability for both standard deviation and range are noted.

Lines AB and CD represent vertical measurements, while lines BC and DA characterize the horizontal component. Line AC incorporates both a vertical and horizontal vector, however, due to the rectangular nature of the lateral cephalogram that the four corner fiducials represent, the horizontal component appears to be more heavily emphasized in this measurement. As observed in Table 4, the total mean difference between the original cephalogram and digital version for the two *vertical* fiducial components is 0.8 mm for each. This represents a (+) 0.8 mm magnification in the vertical dimension. Conversely, the total mean difference for the two horizontal measurements, BC and DA, was 0.4 mm, however, a decrease in the mean values from the original to digital format indicates a shrinkage in the horizontal dimension. The mean difference of line AC (0.5 mm) confirms the horizontal influence in the transverse dimension.

When examining the mean differences between the digital image and printed hardcopy fiducial measurements, a different trend was noticed. As previously

TABLE 4.--Mean Differences of Fiducial Measurements Between the Original Film, Digital Image, and Printed Hardcopy

Fiducial Distance *	Original/Digital	Digital/Hardcopy	Original/Hardcopy
	Mean Difference	Mean Difference	Mean Difference
AB	0.83	0.28	1.11
BC	0.42	0.66	0.23
CD	0.84	0.27	1.11
DA	0.44	0.91	0.47
AC	0.49	0.39	0.88
Total	3.02	2.51	3.80
Average	0.60	0.50	0.76

*All distances in mm

Observed, magnification occurred in the vertical dimension. Both measurements AB and CD shared a 0.3 mm increase in size. However, horizontal mean differences BC and DA, (0.7 mm and 0.9 mm, respectively) indicated magnification in the horizontal dimension as the digital image was printed to hardcopy form. Again, the transverse measurement AC (0.4 mm) showed an influence of both dimensions.

The results for the comparison between the original cephalogram and hardcopy showed the total dimensional discrepancy that occurred beginning with the transformation from the original version of the cephalogram to the final printed hardcopy. This incorporates the dimensional changes that occurred from the scanning and digitization process.

All measurements used in the comparisons were subjected to a Student t-test to evaluate statistical significance. Statistical significance was set at $p < 0.01$ after applying the Bonferroni correction. As shown in Table 5, all fiducial measurements used in the data comparisons showed highly significant values ($p < 0.0000$).

TABLE 5--Student t-test p-values for Fiducial Measurements

Fiducial Distance *	Original/Digital p-value (α = 0.01)	Digital/Hardcopy p-value (α = 0.01)	Original/Hardcopy p-value (α = 0.01)
AB	0.0000 **	0.0000 **	0.0000 **
BC	0.0000 **	0.0000 **	0.0000 **
CD	0.0000 **	0.0000 **	0.0000 **
DA	0.0000 **	0.0000 **	0.0000 **
AC	0.0000 **	0.0000 **	0.0000 **
Total	0.0000 **	0.0000 **	0.0000 **
Average	0.0000 **	0.0000 **	0.0000 **

*All distances in mm

** Significant at $p < 0.01$ after Bonferroni Correction ($\alpha = 0.01$)

Cephalometric Measurements

Tracings were completed on the thirty original lateral cephalograms, as previously described. All required hard and soft tissue landmarks necessary to perform the outlined cephalometric analyses were identified. Bilateral structures were averaged to make a single structure and/or landmark. Mechanical porion was used to identify porion. Similarly, the thirty hardcopy printouts of each lateral cephalogram were traced and measured in an identical manner as the original radiograph. The scanned digital representations were then imported into Dolphin Imaging for computerized cephalometric analysis. Utilizing Dolphin Imaging's digitization software, forty-two hard and soft tissue landmarks were identified as well as two crosshair landmarks to facilitate calibration of each imported cephalogram (Appendix A). Various image enhancement adjustments including brightness, contrast, and magnification were employed as necessary to identify individual landmarks as precisely as possible. The appropriate cephalometric analysis was selected to generate a list of identical measurements as those used in the manual

tracing data collection. Means, standard deviations, ranges, and inter-group mean differences were computed for all three modalities. The Student t-test was used to evaluate statistical significance. Statistical significance was determined at $p < 0.002$ after applying Bonferroni's correction.

Table 6.--Mean, Standard Deviation, and Range of Cephalometric Measurements from the Manually-traced Film, Digital Image Provided from Dolphin Imaging, and Manually-traced Printed Hardcopy

	Manual			Digital			Hardcopy		
Downs	**Mean**	**SD**	**Range**	**Mean**	**SD**	**Range**	**Mean**	**SD**	**Range**
FP °	88.82	3.16	80/95	87.15	3.38	79.2/94.6	89.47	3.38	82/96.5
CON °	5.00	5.70	-7/16	4.88	5.88	-7.4/16.1	5.54	5.64	-5/19.5
AB °	-4.04	4.41	-9/12	-5.57	2.78	-11.4/.6	-5.64	2.65	-11.5/0
Y °	57.87	3.60	51/64	59.76	3.84	51.8/67.7	57.46	3.57	50/65
OP °	6.04	4.57	-1/17.5	7.83	4.58	-1.6/17.5	6.07	4.07	-1/13.5
INT °	129.10	11.15	100.3/152	129.26	10.10	101.8/148.6	127.92	11.97	96.5/154
L1OP °	20.69	7.91	2.5/39.5	20.03	7.40	3/37.9	20.48	8.42	2/41
L1MP °	2.79	8.67	-14/23.5	2.41	8.03	-13.9/21.7	2.95	8.71	-13/21.5
U1AP mm	6.77	2.62	2.5/17	6.83	2.65	2.3/16.6	6.73	2.73	1/17
Riedel	**Mean**	**SD**	**Range**	**Mean**	**SD**	**Range**	**Mean**	**SD**	**Range**
SNA °	81.45	2.94	76.5/88	81.02	3.70	75.1/89.1	81.74	3.56	74/91
SNB °	78.21	3.20	72/84.5	77.77	3.95	71.8/85.3	78.80	4.63	71/91
ANB °	3.24	2.35	-1.5/7.8	3.25	2.28	-1.5/7.8	2.94	1.99	-1/7.5
U1FH °	114.96	6.20	103.5/126.5	113.26	6.31	98.9/124	115.78	6.33	104.5/130
FH/NA °	91.08	3.81	78/99	89.69	4.22	79.4/97.1	92.12	4.41	82.5/103
Tweed	**Mean**	**SD**	**Range**	**Mean**	**SD**	**Range**	**Mean**	**SD**	**Range**
FMA °	24.09	5.94	11.5/35.5	25.62	6.07	12.2/36.7	23.61	5.75	13/34
IMPA °	92.79	8.67	76/114	92.41	8.03	76.1/112	92.95	8.71	77/111.5
FMIA °	63.12	7.77	47/80	61.97	7.62	44.9/78.9	63.44	8.51	46.2/82
Steiner	**Mean**	**SD**	**Range**	**Mean**	**SD**	**Range**	**Mean**	**SD**	**Range**
U1NA mm	5.70	2.48	1.1/11.5	5.25	2.74	0.5/11.4	5.68	2.33	1/10
U1NA °	23.74	6.66	12/39	22.97	6.76	8.4/37.4	22.85	6.74	12.5/36.5
L1NB mm	5.64	3.01	0/16.5	5.56	4.23	0.4/22.6	6.04	2.98	1.3/17.5
L1NB °	24.35	7.02	7.5/44	24.22	6.72	11.1/44.3	24.97	6.63	11.5/41
PONB °	2.13	1.85	0/8	1.97	1.98	-1.4/7.9	2.05	1.78	-.5/7.5
POL1NB °	3.51	4.03	-4/16.5	3.59	5.31	-4.6/22.4	3.99	4.05	-4/18

Table 7.--Mean Differences and Student t-test p-values from Four Common Cephalometric Analyses Between Manual and Digital, Manual and Hardcopy, and Digital and Hardcopy Experimental Groups

	Manual/Digital		Manual/Hardcopy		Digital/Hardcopy	
Downs	**Mean Difference**	**p-value**	**Mean Difference**	**p-value**	**Mean Difference**	**p-value**
FP °	1.67	0.0000 **	0.65	0.0384	2.32	0.0000 **
CON °	0.12	0.6153	0.54	0.1005	0.66	0.0976
AB °	1.53	0.1882	1.60	0.0904	0.07	0.8429
Y °	1.89	0.0000 **	0.41	0.1596	2.30	0.0000 **
OP °	1.79	0.0002 **	0.03	0.9558	1.76	0.0914
INT °	0.16	0.1077	1.18	0.8307	1.34	0.0935
L1OP °	0.66	0.1796	0.21	0.7711	0.45	0.4363
L1MP °	0.38	0.3725	0.16	0.7347	0.54	0.2425
U1AP mm	0.06	0.7147	0.03	0.8395	0.09	0.5944
Riedel	**Mean Difference**	**p-value**	**Mean Difference**	**p-value**	**Mean Difference**	**p-value**
SNA °	0.43	0.0458	0.29	0.4060	0.72	0.0503
SNB °	0.44	0.0523	0.59	0.1854	1.03	0.0251
ANB °	0.01	0.9321	0.31	0.2999	0.31	0.3135
U1FH °	1.70	0.0002 **	0.83	0.5208	2.53	0.0020
FH/NA °	1.38	0.0000 **	1.04	0.0045	2.43	0.0000 **
Tweed	**Mean Difference**	**p-value**	**Mean Difference**	**p-value**	**Mean Difference**	**p-value**
FMA °	1.53	0.0000 **	0.48	0.1990	2.01	0.0000 **
IMPA °	0.38	0.3725	0.16	0.7347	0.54	0.2425
FMIA °	1.15	0.0356	0.31	0.5665	1.47	0.0091
Steiner	**Mean Difference**	**p-value**	**Mean Difference**	**p-value**	**Mean Difference**	**p-value**
U1NA mm	0.45	0.0074	0.02	0.2128	0.43	0.1165
U1NA °	0.77	0.1022	0.89	0.0751	0.12	0.7892
L1NB mm	0.08	0.8552	0.39	0.0586	0.48	0.2913
L1NB °	0.13	0.8190	0.61	0.3220	0.74	0.0979
PONB °	0.16	0.1197	0.08	0.5228	0.08	0.4146
POL1NB °	0.08	0.8562	0.47	0.0456	0.39	0.3765

** Significant at $p < 0.002$ after Bonferroni Correction ($\alpha = 0.002$)

A summary of means, standard deviations, and ranges of individual cephalometric measurements are presented in Table 6. Table 7 shows the calculated mean differences and statistical significance between the three experimental groups. Statistically significant values were found for six of the twenty-three total

measurements when comparing the manually traced cephalogram and the computerized cephalometric analysis completed by Dolphin's software (Table 7). The six statistically significant measurements included the facial plane, y-axis, occlusal plane, upper incisor to Frankfort-Horizontal, Frankfort-Horizontal to nasion-A-point, and Frankfort-Mandibular angle. Similar results were found when comparing the computerized analysis and the hardcopy tracing. Four of the twenty-three measured values resulted in a statistically significant difference between the two modalities. These measurements included the facial plane, y-axis, Frankfort-Horizontal to Nasion-A-point, and Frankfort-Mandibular angle. Of note, upper incisor to Frankfort-Horizontal ($p = 0.002$) is extremely close to demonstrating statistical significance as well. Conversely, no statistical significance was noted when comparing the manually traced radiograph and the printed hardcopy. Standard deviations for individual measurements were relatively consistent between each modality.

Superimpositions

In order to test the accuracy of the superimposition function of a computerized cephalometric program using scanned lateral cephalograms, superimpositions were completed by this program and compared to a traditional, hand-traced superimpositions technique. Thirty final cephalograms, corresponding to the thirty initial cephalograms previously mentioned in this study, were manually traced with the same technique as described earlier. Additionally, four fiducial marks were identified and labeled a, b, c, and d (Figure 1). An overall superimposition, maxillary regional, and mandibular regional superimposition were then completed. The thirty

final cephalograms were then scanned into a digital format and imported into Dolphin Imaging using the same protocol as used for the initial cephalogram scanning procedure. The cephalograms were digitized using the identical forty-two hard and soft tissue landmarks and two crosshair calibration points as previously described (Appendix A). Four fiducial marks were digitized as well, using the customized cephalometric analysis feature offered in Dolphin's software (Figure 1). The superimposition tool was selected for initial and final cephalograms and hardcopies were printed for data gathering.

To evaluate the accuracy of the superimposition function of the cephalometric analysis program using scanned radiographs, linear changes in positions of the four fiducial points were measured and compared to the same measurements from manual superimpositions ($a\text{-}a^1$, $b\text{-}b^1$, $c\text{-}c^1$, $d\text{-}d^1$). Further analysis was conducted in order to assess the accuracy of a computerized superimposition program in correctly displaying the positional skeletal and dental changes occurring during treatment and growth compared to conventional manual superimposition techniques. Sixteen linear and two angular measurements were used to evaluate the horizontal and vertical changes in maxillary, mandibular, maxillary molar, maxillary incisor, mandibular molar, mandibular incisor and soft tissue positions (Table 2, Figures 2, 3, and 4). Additionally, mandibular growth was assessed by comparing differences in Articulare at initial and final timepoints between the two modalities. Means, standard deviations, ranges, and inter-group mean differences were computed for the two techniques. The Student t-test was used to evaluate for statistical significance.

Statistical significance was determined at $p < 0.002$ after applying Bonferroni's correction.

Means, standard deviations, ranges, mean differences, and statistical p-values for fiducial superimposition measurements of both modalities are presented in Table 8. No statistically significant differences were found in fiducial changes.

TABLE 8.--Mean, Standard Deviation, Range, Mean Difference, and Student t-test p-value of Fiducial Measurements from Manually-Traced Superimpositions and a Digital Cephalometric Superimposition Program. Both Superimpositions Registered on Se-Na at Se.

Fiducial Distances *	MANUAL			DIGITAL			Manual vs. Digital	
	Mean	SD	Range	Mean	SD	Range	Mean Diff.	p-value (α = 0.002) †
a-a'	21.25	9.39	9.8/43.8	21.12	9.41	8.4/41.3	0.14	0.7095
b-b'	20.82	9.90	5/44.7	20.55	10.23	3.5/44.9	0.28	0.3599
c-c'	19.11	11.83	3.4/41.2	19.05	12.01	3.1/41.2	0.06	0.7862
d-d'	19.77	11.18	3/41	19.81	11.04	2.5/40.8	0.04	0.3990

†Statistical Significance determined at $p < 0.002$ after Bonferroni Correction ($\alpha = 0.002$)
*All distances in mm

Accordingly, means and standard deviations were fairly similar between techniques for all four measurements.

A dissimilar presentation, however, was noted for the measurements used to assess skeletal, dental, and soft tissue changes. Table 9 shows the means, standard deviations, ranges, mean differences, and statistical p-values for the eighteen angular and linear measurements utilized to compare superimposition accuracy between digital and manually produced images. Although no statistically significant differences were found for any of the eighteen measurements, a number of

TABLE 9.-- Mean, Standard Deviation, Range, Mean Difference, and Student t-test p-value from Eighteen Angular and Linear Measurements from Manually-Traced Superimpositions and a Digital Cephalometric Superimposition Program.

	MANUAL			DIGITAL			Manual vs. Digital	
Overall Superimposition Measurements	**Mean**	**SD**	**Range**	**Mean**	**SD**	**Range**	**Mean Diff.**	**p (α=0.002)†**
SN⊥A-Pt (Max. A-P) mm	0.35	3.38	-5/15.5	1.02	3.18	-3/14.5	0.67	0.0285
SN⊥A-Pt (Max.Vertical) mm	1.99	3.08	-2.8/10.2	2.16	2.90	-2.8/10.1	0.18	0.5891
Pog-Pog (Mand. A-P) mm	1.21	5.79	-6/28	1.73	5.41	-4.1/27	0.52	0.1326
Me-Me (Mand. Vertical) mm	5.21	5.00	-1.8/17.5	5.45	5.16	-1.5/19.3	0.23	0.2512
Maxillary Regional Superimposition Measurements								
M6-M6⊥Ans/Pns (A-P Molar Ptn) mm	1.28	3.17	-6.5/11.4	1.08	2.74	-3.6/8.9	0.20	0.4733
O6-O6⊥Ans/Pns (Vertical Molar Ptn) mm	1.69	2.30	-2.1/7.3	1.98	1.87	-1/6.5	0.29	0.1759
T1-T1⊥Ans/Pns (A-P Incisor Ptn) mm	-0.92	3.35	-9.5/7.2	-0.98	3.65	-9.9/8	0.06	0.8523
T1-T1⊥Ans/Pns(Vertical Incisor Tip Ptn) mm	0.53	2.12	-6.5/4.3	0.82	1.88	-3/5.1	0.29	0.2047
A1-A1 (Incisor Angulation) °	6.22	5.18	0.1/19	6.67	6.05	0/29	0.45	0.5094
Mandibular Regional Superimposition Measurements								
M6-M6⊥Go/Me (A-P Molar Ptn) mm	0.42	2.48	-5.2/5.5	0.24	2.61	-6/4.5	0.18	0.4621
O6-O6⊥Go/Me (Vertical Molar Ptn) mm	2.01	1.95	-0.8/7.8	2.49	2.10	-0.5/9.2	0.48	0.0036
T1-T1⊥Go/Me (A-P Incisor Ptn) mm	-0.70	3.81	-13.5/5	-1.11	3.97	-13/5.1	0.41	0.0334
T1-T1⊥Go/Me (Vertical Incisor Tip Ptn) mm	0.97	2.33	-2.5/10.4	1.53	2.51	-1.3/11.1	0.56	0.0067
A1-A1 (Incisor Angulation) °	7.13	6.55	0/26	7.38	5.76	1/25.6	0.25	0.5998
Ar-Ar (Mandibular Growth) mm	5.29	4.09	0.6/20.8	5.74	4.37	0.3/20.9	0.44	0.0650
Soft Tissue Superimposition Measurements								
Me-Me mm	7.36	6.54	0/33.4	7.01	6.22	0/31	0.35	0.1814
Soft Tissue A-Pt-Soft Tissue A-Pt mm	4.43	4.13	0.2/21	4.50	3.75	0.5/18.4	0.07	0.8290
Tip of Nose-Tip of Nose mm	4.32	4.63	0/21.4	4.25	4.44	0/20.5	0.07	0.8061

†Statistical Significance determined at $p < 0.002$ after Bonferroni Correction ($\alpha = 0.002$)

measurements came close to being significant values. Similarly, means and standard deviations for the eighteen structural measurements were more variable and disparate compared to those from the fiducial superimposition data.

Intra-Operator Error

Intra-operator error was evaluated by randomly selecting ten sets of cephalograms from the original sample of thirty. All steps were completed in an identical manner to the initial data preparation and collection for fiducial, cephalometric analysis, and superimposition measurements. Using SPSS software, intraclass correlation analysis was performed to evaluate intra-operator accuracy. An approximate value of $r < 0.75$ tends to signify a weak correlation.

Table 10 exhibits an intra-operator measurement summary for fiducial measurements including correlation coefficient values. R-values are inconsistent, with no definitive trends noted. A number of correlation coefficient values are quite low, however, since standard deviations are so small, concordantly, one might expect variable intraclass correlation.

Correlation coefficient values for cephalometric measurements are presented in Table 11, 12, and 13 for the manually-traced original film, computerized cephalometric analysis program, and manually-traced digital hardcopy printout, respectively. Only one of the statistically significant measurements assessed previously by the Student t-test had a correlation below 0.75. The occlusal plane measurement maintained an r-value of 0.72, which is very close to the 0.75 threshold. Further, all r-values for both the manual tracing and digital cephalometric analysis show strong correlation between time point-1 measurements and time point–2

measurements. The hardcopy measurements, however, did contain numerous intra-operator cephalometric measurements within the weak correlation range. Nevertheless, no statistically significant mean values were associated with the weaker correlation values contained in the hardcopy measurement data.

TABLE 10.--Intra-operator Mean, Standard Deviation, Range, Mean Difference and Intraclass Correlation Coefficient Values for Fiducial Measurements Between the Original Film, Digital Image, and Printed Hardcopy

FIDUCIALS *	Manual 1			Manual 2				
	Mean	SD	Range	Mean	SD	Range	Mean Diff.	r
AB	159.3	0.1	159.1/159.5	159.3	0.1	159.2/159.5	0.0	0.8560
BC	177.2	0.1	177.1/177.4	177.3	0.1	177.2/177.5	0.1	0.5255
CD	152.3	0.1	152.2/152.4	152.3	0.0	152.2/152.4	0.0	0.3333
DA	177.6	0.1	177.4/177.8	177.6	0.1	177.4/177.7	0.0	0.8400
AC	233.8	0.1	233.6/234	233.8	0.1	233.6/233.9	0.0	0.8498
Total	900.2	0.3	899.8/900.6	900.2	0.3	899.9/900.8	0.0	0.8884
Average	180.0	0.1	180/180.1	180.0	0.1	180/180.2	0.0	0.8884
FIDUCIALS *	Digital 1			Digital 2				
	Mean	SD	Range	Mean	SD	Range	Mean Diff.	r
AB	160.1	0.6	158.4/160.5	159.6	0.4	158.5/160	0.5	0.9919
BC	176.8	0.1	176.6/177	176.6	0.7	175.3/177.6	0.2	0.6689
CD	153.1	0.3	152.4/153.4	152.6	0.1	152.2/152.6	0.5	0.9468
DA	177.1	0.1	177/177.2	177.3	0.3	177/178	0.2	0.1747
AC	234.3	0.2	233.8/234.5	233.8	0.4	233.3/234.3	0.5	0.7665
Total	901.3	1.2	898.4/902.5	899.8	1.1	897.3/900.9	1.6	0.9507
Average	180.3	0.2	179.7/180.5	180.0	0.2	179.5/180.2	0.3	0.9507
FIDUCIALS *	Hardcopy 1			Hardcopy 2				
	Mean	SD	Range	Mean	SD	Range	Mean Diff.	r
AB	160.3	0.6	158.9/160.9	160.3	0.6	159/160.8	0.1	0.9262
BC	177.4	0.2	177.2/177.8	177.5	0.2	177.3/177.8	0.1	0.2454
CD	153.3	0.2	152.9/153.6	153.1	0.2	152.8/153.3	0.2	0.4578
DA	178.0	0.1	177.9/178.2	178.2	0.2	178/178.5	0.2	0.3432
AC	234.7	0.3	234.1/235	234.6	0.3	233.8/235	0.1	0.5838
Total	903.8	1.1	901.2/905.1	903.7	1.1	901.2/904.8	0.1	0.8512
Average	180.8	0.2	180.2/181	180.7	0.2	180.2/181	0.0	0.8512

r = Intraclass Correlation Coefficient

*All distances in mm

TABLE 11.--Intra-operator Mean, Standard Deviation, Range, Mean Difference and Intraclass Correlation Coefficient Values for Manually-traced Cephalometric Measurements

	Manual 1			Manual 2				
Downs	Mean	SD	Range	Mean	SD	Range	Mean Difference	r
FP °	90.4	4.0	84/95	90.4	4.2	83.5/96	0.09	0.9875
CON°	5.5	4.9	-1.5/13	5.0	5.1	-1.7/12	0.46	0.9717
AB °	-5.2	2.4	-9/-1	-5.5	2.3	-9.5/-1.9	0.28	0.9628
Y °	56.1	4.5	51/64	56.0	4.9	49.9/63.3	0.09	0.9783
OP °	3.7	4.6	-1/12	4.4	5.2	-2.5/13.5	0.67	0.9626
INT °	130.1	9.4	113.9/144.5	129.5	10.5	112/144.9	0.61	0.9727
L1OP °	20.7	5.2	13/28	22.5	6.2	13/29.8	1.77	0.7815
L1MP °	2.2	6.2	-7/11	2.2	7.1	-8.8/11.5	0.00	0.9506
U1AP mm	6.3	1.4	4.5/8.5	6.5	1.7	3.8/9	0.18	0.9194
Riedel								
SNA °	81.8	2.9	77.7/85	81.9	2.9	78/85.5	0.08	0.9878
SNB °	78.4	3.1	74.8/82.5	78.6	3.1	75/83	0.22	0.9943
ANB °	3.5	2.1	0.5/6.5	3.3	2.0	0.3/6.5	0.14	0.9871
U1FH °	115.4	7.8	103.5/125.5	116.0	8.7	104/127.5	0.63	0.9810
FH/NA°	92.8	2.7	89/98	92.5	3.8	88.2/99	0.27	0.8652
Tweed								
FMA °	22.6	7.5	11.5/35.5	22.5	7.7	11/34.6	0.09	0.9909
IMPA°	92.2	6.2	83/101	92.2	7.1	81.2/101.5	0.00	0.9506
FMIA °	65.2	6.3	57.5/76	65.3	7.2	57/78.2	0.09	0.9413
Steiner								
U1NA mm	5.4	1.5	3.2/8	5.8	1.7	3.2/8	0.41	0.8634
U1NA °	22.4	6.9	12/33	22.8	7.2	13/33.8	0.38	0.9878
L1NB mm	5.4	1.9	2.5/8	5.7	1.7	3.4/8	0.36	0.9424
L1NB °	23.0	4.7	16.5/30.5	24.4	5.0	16.3/33	1.42	0.7395
PONB °	1.9	1.8	0/5	2.0	1.8	0/5.5	0.17	0.9469
POL1NB °	3.5	3.3	-1.5/8	3.7	3.2	-2.1/26.8	0.19	0.9837

r = Intraclass Correlation Coefficient

Intra-class correlation coefficients for the superimposition fiducial measurements are shown in Table 14. All r-values were highly suggestive of strong correlation between the two sets of data. Conversely, correlation coefficient values for the eighteen structural superimposition measurements (Table 15 & 16)

TABLE 12.--Intra-operator Mean, Standard Deviation, Range, Mean Difference and Intraclass Correlation Coefficient Values for Cephalometric Measurements Obtained from a Computerized Cephalometric Analysis Program

	Digital 1			Digital 2				
Downs	**Mean**	**SD**	**Range**	**Mean**	**SD**	**Range**	**Mean Difference**	**r**
FP °	89.0	3.8	82.9/94.6	89.6	3.8	83.2/94.7	0.57	0.9569
CON °	5.5	4.6	-2.4/12.1	5.2	4.9	-1.9/12.3	0.28	0.9485
AB °	-5.3	2.4	-9/-1.8	-5.8	2.4	-8.9/-2.1	0.49	0.8606
Y °	58.2	4.7	52.4/66	57.3	4.5	52.1/64.7	0.89	0.9280
OP °	5.9	5.2	-1.6/13.8	5.2	5.4	-1.7/14.3	0.71	0.9721
INT °	130.5	9.2	120.9/147	132.1	9.1	119.4/148.2	1.55	0.9540
L1OP °	19.3	5.9	11/27.2	18.8	6.0	9.3/26.4	0.54	0.9774
L1MP °	1.3	7.1	-10.3/9.6	0.4	6.3	-7.5/9.7	0.90	0.9339
U1AP mm	6.7	1.5	4.6/9	6.6	1.4	4.8/8.8	0.13	0.9108
Riedel								
SNA °	81.3	3.1	76.8/84.8	81.7	3.0	77.4/84.8	0.42	0.8451
SNB °	77.9	3.7	72.7/83.4	78.2	3.1	74.4/83.4	0.32	0.9704
ANB °	3.4	1.9	0.3/6.2	3.5	2.0	0.6/6.4	0.10	0.9842
U1FH °	114.2	8.1	98.9/124	114.0	7.7	101/124.9	0.22	0.9885
FH/NA °	91.7	3.1	87.8/96.7	92.1	3.0	88.6/97.3	0.39	0.9590
Tweed								
FMA °	24.1	7.5	12.2/36.7	23.6	7.0	14/34.9	0.54	0.9889
IMPA °	91.3	7.1	79.7/99.6	90.4	6.3	82.5/99.7	0.90	0.9339
FMIA °	64.6	7.1	55.8/78.9	66.0	7.3	57.1/80.5	1.44	0.9575
Steiner								
U1NA mm	4.7	1.8	1.6/7.3	4.5	1.9	1.8/6.7	0.23	0.9180
U1NA °	22.1	6.4	10/31.6	21.9	6.3	10.6/31.7	0.18	0.9894
L1NB mm	4.6	2.0	1.6/6.7	5.2	1.7	2.5/7.6	0.58	0.7751
L1NB °	23.2	5.5	13.7/31.7	22.5	5.5	12.4/30.8	0.61	0.9815
PONB °	1.8	2.0	-1/5.2	1.9	1.8	-0.5/5.1	0.13	0.9497
POL1NB °	2.9	3.4	-2.4/7.3	3.3	3.1	-2.1/7.1	0.45	0.9247

r = Intraclass Correlation Coefficient

demonstrated varying degrees of correlation. However, none of the eighteen structural measurements were deemed statistically significant, therefore discounting possible systematic error derived from data collection.

TABLE 13.--Intra-operator Mean, Standard Deviation, Range, Mean Difference and Intraclass Correlation Coefficient Values for Cephalometric Measurements Obtained from the Manually-traced Digital Printed Hardcopy

	Hardcopy 1			Hardcopy 2				
Downs	**Mean**	**SD**	**Range**	**Mean**	**SD**	**Range**	**Mean Difference**	**r**
FP °	90.8	3.2	87/96.5	91.4	3.7	86/98	0.55	0.9465
CON °	6.2	4.6	-1/11.5	6.8	5.3	0/16	0.55	0.9436
AB °	-6.2	2.3	-10/-1.5	-6.6	2.6	-11/-2.2	0.36	0.7863
Y °	55.9	4.0	51.2/61.8	55.4	4.1	49/61	0.50	0.9680
OP °	4.8	4.3	-1/10	3.8	4.6	-1.5/11.5	0.95	0.7202
INT °	130.2	11.1	113/148	133.2	13.7	120/159	3.00	0.5771
L1OP °	18.9	6.9	9/30	20.4	4.5	13.5/27	1.53	0.7091
L1MP °	1.4	7.2	-9/12	3.0	4.6	-4.5/9	1.62	0.4401
U1AP mm	6.5	1.4	4.5/9	6.0	1.3	4.5/8.5	0.49	0.9521
Riedel								
SNA °	82.1	3.1	77.5/87	82.6	3.4	77/87.5	0.48	0.9319
SNB °	78.7	3.9	74/85.5	78.7	3.4	74/83.5	0.01	0.8680
ANB °	3.4	2.0	0.2/6.5	3.8	2.0	1/7	0.47	0.6954
U1FH °	117.3	6.5	108/128	117.1	7.3	106/127.5	0.17	0.8269
FH/NA °	93.9	3.4	88.8/99	94.5	3.7	90/101.4	0.59	0.9241
Tweed								
FMA °	22.6	6.6	13/32	22.5	7.2	12/32	0.15	0.9625
IMPA °	91.4	7.2	81/102	93.0	4.6	85.5/99	1.57	0.4401
FMIA °	66.1	7.2	60/70	64.6	7.3	50.5/74.5	1.52	0.6310
Steiner								
U1NA mm	5.1	1.5	3/7	5.0	1.8	1.7/7	0.09	0.8419
U1NA °	22.1	6.9	13/33.5	22.2	6.8	10/33	0.10	0.9307
L1NB mm	5.4	1.8	2.5/8	5.6	1.8	2.8/7.5	0.21	0.6295
L1NB °	23.8	5.4	12.8/30	22.1	6.6	5/28	1.68	0.0780
PONB °	1.9	1.7	0/3.2	2.0	1.7	0/5	0.12	0.9596
POL1NB °	3.4	2.7	-0.5/7.5	3.6	3.1	-0.2	0.19	0.8763

r = Intraclass Correlation Coefficient

TABLE 14.--Intra-operator Mean, Standard Deviation, Range, Mean Difference and Intraclass Correlation Coefficient Values for Superimposition Fiducial Measurements Between the Manually-traced Original Cephalogram and Computerized Superimposition Program

Fiducial Distances *	Manual 1			Manual 2				
	Mean	SD	Range	Mean	SD	Range	Mean Difference	r
a-a'	23.08	8.64	9.8/40	22.84	8.93	8.6/39.5	0.24	0.9974
b-b'	22.52	9.33	7.1/39.3	22.16	9.64	6.3/39.1	0.36	0.9977
c-c'	15.02	9.44	6/32.2	14.85	9.15	7.4/31.3	0.17	0.9983
d-d'	15.62	9.57	3/34	15.15	9.35	2/32.2	0.47	0.9968
	Digital 1			Digital 2				
	Mean	SD	Range	Mean	SD	Range	Mean Difference	r
a-a'	23.38	9.56	8.4/41	23.15	9.76	8/42.9	0.23	0.9657
b-b'	21.94	9.85	7/41	21.69	9.93	7/42.2	0.25	0.975
c-c'	14.75	9.83	3.1/33	14.34	9.53	2.9/31.8	0.41	0.9981
d-d'	15.33	9.78	2.5/33.8	14.88	9.60	2/33.2	0.45	0.9972

r = Intraclass Correlation Coefficient

*All distances in mm

TABLE 15.--Intra-operator Mean, Standard Deviation, Range, Mean Difference and Intraclass Correlation Coefficient Values for Eighteen Angular and Linear Measurements from Manually-traced Original Cephalogram Superimpositions

	Manual 1			Manual 2				
Overall Superimposition Measurements	**Mean**	**SD**	**Range**	**Mean**	**SD**	**Range**	**Mean Diff.**	**r**
SN⊥A-Pt (Max. A-P) mm	0.34	2.44	-5/3	0.37	2.14	-4.5/3	0.03	0.9509
SN⊥A-Pt (Max.Vertical) mm	3.14	2.84	-0.4/10	2.54	1.87	0/6.2	0.60	0.7768
Pog-Pog (Mand. A-P) mm	1.86	2.13	-3/5.1	0.93	2.49	-1.9-5.5	0.93	0.7854
Me-Me (Mand. Vertical) mm	5.63	4.75	0/14.7	5.86	4.73	-0.2/14.4	0.23	0.9922
Maxillary Regional Superimposition Measurements								
M6-M6⊥Ans/Pns (A-P Molar Ptn) mm	1.21	1.50	-0.4/4.4	1.29	1.53	-1/4.7	0.08	0.3349
O6-O6⊥Ans/Pns (Vertical Molar Ptn) mm	1.52	1.56	-0.8/4.5	1.64	1.92	-0.5/5.5	0.12	0.8253
T1-T1⊥Ans/Pns (A-P Incisor Ptn) mm	-0.83	2.65	-7.1/1.9	-0.8	2.46	-5.9/2	0.03	0.8242
T1-T1⊥Ans/Pns(Vertical Incisor Tip Ptn) mm	-0.39	2.72	-6.5/2	-0.23	2.27	-5.3/2	0.16	0.9647
A1-A1 (Incisor Angulation) degrees	3.77	3.17	1/11.1	4.23	3.56	0.5/12.2	0.46	0.9234
Mandibular Regional Superimposition Measurements								
M6-M6⊥Go/Me (A-P Molar Ptn) mm	0.28	1.48	-2.6/2.3	0.28	1.68	-2.6/2.5	0.00	0.8189
O6-O6⊥Go/Me (Vertical Molar Ptn) mm	2.18	2.18	-0.6/5.1	1.84	2.22	-0.1/5.5	0.34	0.9562
T1-T1⊥Go/Me (A-P Incisor Ptn) mm	-0.43	1.80	-4.2/2.3	-0.35	2.20	-4.8/2.8	0.08	0.8654
T1-T1⊥Go/Me (Vertical Incisor Tip Ptn) mm	0.85	1.70	-2.5/3.2	0.55	1.73	-2.3/3.2	0.30	0.8882
A1-A1 (Incisor Angulation) degrees	5.29	3.67	1.2/11	4.92	3.79	1/12	0.37	0.9382
Ar-Ar (Mandibular Growth) mm	5.54	3.04	1.3/11	5.19	3.10	0.4/10.6	0.35	0.9767
Soft Tissue Superimposition Measurements								
Me-Me mm	6.87	5.17	0/16	7.13	5.44	0/16.8	0.26	0.9650
Soft Tissue A-Pt-Soft Tissue A-Pt mm	4.47	3.03	0.9/10.5	4.81	2.39	1.2/9	0.34	0.8942
Tip of Nose-Tip of Nose mm	4.66	3.34	1.4/13	4.69	3.53	0/12.6	0.03	0.9447

r = Intraclass Correlation Coefficient

TABLE 16.--Intra-operator Mean, Standard Deviation, Range, Mean Difference and Intraclass Correlation Coefficient Values for Eighteen Angular and Linear Measurements from a Computerized Superimposition Program

	Digital 1			Digital 2				
Overall Superimposition Measurements	**Mean**	**SD**	**Range**	**Mean**	**SD**	**Range**	**Mean Diff.**	**r**
SN⊥A-Pt (Max. A-P) mm	1.52	1.91	-2/3.9	0.52	2.20	-2/3.9	1.00	0.1323
SN⊥A-Pt (Max.Vertical) mm	3.06	1.80	0.2/6.9	2.94	1.59	0.3/6.6	0.12	0.7650
Pog-Pog (Mand. A-P) mm	2.12	1.23	0/3.6	1.62	2.17	-0.9/5.7	0.50	0.3116
Me-Me (Mand. Vertical) mm	5.41	5.04	-1.5/14	5.39	5.10	-1.2/14.5	0.02	0.9137
Maxillary Regional Superimposition Measurements								
M6-M6⊥Ans/Pns (A-P Molar Ptn) mm	1.15	1.84	-1/5	0.44	2.58	-2.2/5	0.71	0.5800
O6-O6⊥Ans/Pns (Vertical Molar Ptn) mm	1.86	1.63	-1/4.2	1.47	1.93	-1.6/4.5	0.39	0.9018
T1-T1⊥Ans/Pns (A-P Incisor Ptn) mm	-0.74	2.73	-6.2/3.8	-0.82	2.75	-5.8/3.2	0.08	0.6281
T1-T1⊥Ans/Pns(Vertical Incisor Tip Ptn) mm	0.09	1.96	-2.5/3	-0.05	2.00	-2.9/3.6	0.14	0.9560
A1-A1 (Incisor Angulation) degrees	3.78	2.11	0/7.2	4.64	3.28	0.2/12.4	0.86	0.8054
Mandibular Regional Superimposition Measurements								
M6-M6⊥Go/Me (A-P Molar Ptn) mm	-0.65	1.44	-3.1/1.2	-0.5	1.46	-4/0.9	0.15	0.4567
O6-O6⊥Go/Me (Vertical Molar Ptn) mm	2.49	2.24	-0.5/6.5	2.36	2.04	-0.6/4.9	0.13	0.8759
T1-T1⊥Go/Me (A-P Incisor Ptn) mm	-0.47	1.99	-3/2.6	-0.31	2.10	-3.1/2.5	0.16	0.7516
T1-T1⊥Go/Me (Vertical Incisor Tip Ptn) mm	1.28	1.73	-1.2/4.7	0.99	1.79	-1.4/4	0.29	0.9656
A1-A1 (Incisor Angulation) degrees	5.36	4.10	1.2/13.6	5.42	3.41	1.8/9.8	0.06	0.7213
Ar-Ar (Mandibular Growth) mm	6.3	3.29	1.5/12	6.32	3.38	1.9/13.1	0.02	0.9719
Soft Tissue Superimposition Measurements								
Me-Me mm	6.75	5.66	0/18	6.83	5.36	-0.4/17	0.08	0.9628
Soft Tissue A-Pt-Soft Tissue A-Pt mm	4.36	3.15	0.5/12	4.25	3.09	-0.9/10.2	0.11	0.9027
Tip of Nose-Tip of Nose mm	4.15	3.87	0/13	3.83	3.91	-1/12	0.32	0.9924

r = Intraclass Correlation Coefficient

DISCUSSION

The purpose of this investigation was to evaluate digital images captured by scanning analog lateral cephalograms into a digital format and assessing the accuracy of the digital radiograph for their reliability including cephalometry, superimposition, and hardcopy printout duplication. In essence, could a lateral cephalogram from a standard radiograph unit be scanned into a computerized digital format with complete confidence in the accuracy of using this digital representation for all clinical applications in orthodontics, thereby, rendering the original radiograph as dispensable?

The current investigation was arranged in three sections using a sample size of thirty subjects. The first section considered the relationship of four stamped fiducial points to determine if any distortion was noted upon both digital acquisition and hardcopy printing. Secondly, four common cephalometric analyses containing twenty-three angular and linear measurements were recorded from the original radiograph, digitized film (using Dolphin Imaging Systems software), and a printed digital hardcopy to assess the accuracy of diagnostic cephalometric measurements among the three modalities. The final section included a comparison of the degree of accuracy associated with superimpositions of initial and final cephalograms made by traditional manual tracing and a computerized method using scanned lateral cephalograms.

Fiducial Measurements

The measurement of the fiducial points theoretically removes any subjective judgment in landmark identification. Fiducial points were marked with a single template, thus providing consistent locations of landmarks on all thirty cephalograms. As the results demonstrate (Tables 3 & 4), some distortion occurred as the analog film was converted to and displayed in a digital format. Data showed a vertical enlargement of 0.5% and a horizontal reduction of 0.3%, both with a high degree of statistical significance (Table 5).

A similar finding in the vertical dimension was reported by Marci and Wenzel (1993). The authors looked at proportionality changes after video-recorded images were displayed on a monitor and compared to original film measurements. Digital images were found to be slightly enlarged in the vertical plane an average of 2% while the horizontal plane showed no dimensional distortion. Nimkarn and Miles (1995) found 1% vertical magnification and 3% percent horizontal magnification of measurements from a 150 mm^2 grid obtained through video-camera recordings compared to the conventional hand-measured values. Unfortunately, these two studies were completed using a video-camera as a means of radiograph digitization instead of a scanner. A comparison between the two types of image acquisition is limited due to differing techniques and properties associated with the corresponding methods. No studies were found involving the distortional effects involved in the process of scanning radiographs.

Further results from the current research indicate additional distortion when the digitized cephalogram was printed to hardcopy. An average enlargement of 0.3 mm was observed in the vertical dimension and 0.8 mm in the horizontal dimension, which was statistically significant. Thus, an enlargement of 1.1 mm, vertically, and 0.4 mm horizontally, occurred in transfer from original cephalogram to hardcopy.

The very nature of converting an analog radiographic image into a digital representation, and ultimately to a printed hardcopy, requires multiple steps involving a mixture of hardware, software, and computer functions and settings. In addition, the conversion of digital images into viewable, printable, and storable formats often requires data compression, alteration, and/or transfer to peripheral hardware, increasing the likelihood for possible image distortion (Forsyth et al. 1996a). Therefore, with the multitude of variables possibly contributing to distortion, determining which variable or variables was the cause would be very difficult.

Of importance, however, is how the observed distortion might affect the clinical aspect of orthodontic diagnosis and treatment planning. Although all fiducial measurement comparisons were statistically significant, the clinical significance must be assessed separately. Linear distortion was no greater than 1.1 mm and the greatest standard deviation for any one single measurement was 0.5 mm. Moreover, since standard deviations were so low, statistical significance was, in fact, found, even though only minimal differences in mean values were recorded. Considering the width of the fiducial mark itself is approximately 0.5 mm, one may contend that the total disparity between modalities is truly clinically insignificant. O'Callaghan (1993) found that identification of fiducial marks on a digitized image using a mouse

and cross-hair was only accurate to within a 0.5 mm envelope of error. He further reported that identification of the fiducial marks on the original radiograph displayed better inter-operator accuracy, but similar patterns of vertical and horizontal displacement were documented when comparing on-screen digital fiducial measurements.

Orthodontics is sometimes labeled a profession of millimeters. A difference of a millimeter may lead to an alteration in treatment plan selection. Therefore, results may be interpreted differently according to one's own personal degree of acceptable error. Nonetheless, a certain degree of distortion should be expected when scanning a lateral cephalogram into a computerized digital format.

Cephalometric Measurements

One of the most important features of the lateral cephalogram in orthodontics is its use in analyzing craniofacial skeletal and dental positions. This is routinely accomplished though cephalometric analysis using a wide variety of standardized measurements. The cephalometric measurement section of this investigation was conducted to evaluate the accuracy of the scanned digital image with software measurements and hardcopy printout in attaining commonly used cephalometric measurements compared to the "gold standard" of the traditional, hand-measured technique.

The results in Tables 6 and 7 indicate that six of the twenty-three cephalometric measurements are significantly different when compared to the digital image measurements, derived from Dolphin Imaging, to the hand-measured technique. Four of these six significant measurements also showed statistically

significant differences when comparing the digital to hardcopy measurements. No significant differences were found in the manual to hardcopy measurements. Moreover, intra-operator error for all measurements involving statistically significant differences indicated strong correlation between two separate time-points. Interestingly, all measurements demonstrating statistical significance were associated with the Frankfort-horizontal plane. Additionally, *each* measurement containing a reference plane coupled to the Frankfort-horizontal plane exhibited statistical significance in the manual/digital comparison. Similarly, all but one measurement in the digital/hardcopy comparison containing Frankfort-horizontal plane showed statically significant differences.

Baumrind and Frantz (1971a) concluded that inconsistency in landmark identification is an inherent cause of errors in conventional cephalometry. O'Callaghan (1993) found the error pattern associated with the landmark identification on original radiographs similar to that reported by Baumrind and Frantz (1971a). In a follow-up study, Baumrind & Frantz (1971b) assessed the effects of error in landmark location transmitted to the values of linear and angular measurements of some commonly used head film analyses. Similar findings to their previous study demonstrated angular and linear measurements from head films contain considerable errors. Results in the present research indicate Frankfort-horizontal plane is unreliable in identification using digital media. Previous studies concur.

O'Callaghan (1993) found the size of the error in locating landmarks from a digital image to be approximately the same as those are located on the original

radiograph. However, O'Callaghan also noted that certain landmarks were visualized more easily, and therefore, identified more accurately depending on which media they were viewed. For example, landmarks sella, PNS, Or, and A-point had less error when identified on the computer monitor. Other points were more accurately located on the original radiographs, eg., Me, nasion, Pog, and upper incisor apex. Thus, a discrepancy in landmark identification may be created within certain media based on the visualization acuity of that specific media.

Chen et al. (2000) compared landmark identification on digital images to those obtained from original radiographs. Results showed statistically significant differences between the two methods in the vertical component corresponding to landmarks Po, Or, and Gn. Differences were generally under one millimeter with the exception of Or. In addition, the reliability for each landmark, as measured by the inter-observer error, was significantly lower for landmarks (Po, Ar, PNS, and UM). Larger errors were noted for the digital images in 16 of the 19 landmarks identified. The authors concluded that these four landmarks (Po, Ar, PNS, and UM) should be carefully considered during applications of digital cephalometry. Thus, Po and Or (the two landmarks contributing to Frankfort-horizontal plane) appear to demonstrate a significant level of unreliability in landmark identification which may have affected the present studies results. In addition, Gn, a landmark contributing to a statistically significant measurement (y-axis) in the current investigation, appears to have a certain degree of inconsistency in the vertical dimension as well.

In an effort to increase the accuracy of identifying porion in this study, mechanical porion was selected for porion. However, identifying porion proved

difficult due to the cephalometer used in the radiograph acquisition. The ear-rod holder bar was highly radio-dense and obscured the position of porion (the ear-rod) on the cephalogram, making identification arduous, even with digital image enhancement.

One would expect an inconsistency in the identification of Po and Or when examining intra-operator error, yet, results indicate good intra-operator consistency in each measurement deemed statistically significant. Therefore, a consistency in landmark identification was noted within each modality. However, an inconsistency in Po and Or identification was found between the digital/manual and digital/hardcopy measurements. Frankfort-horizontal plane was identified consistently using manual identification and digital digitization, but was placed in a different location within each modality. Reasons for this occurrence are unclear. One possible cause may be that using the digital enhancement features offered upon landmark digitization allowed for a less obscured view of porion and/or orbitale resulting in a different location of the Frankfort-horizontal plane. Identification without this enhancement feature on both the original cephalogram and printed hardcopy, clearly showed a dissimilar location of Frankfort-horizontal plane compared to the digital identification, which used digital enhancement, resulting in statically significant differences in measurements. Moreover, no statistically significant differences were found between manually-traced and hardcopy techniques, both of which contained no enhancement features.

A second possible reason for the discrepancy with Frankfort-horizontal plane could be attributed to distortional effects caused by image acquisition and

digitization. Results shown in Table 4 indicate a vertical enlargement when comparing fiducial point measurements on the original radiograph to the digital representation. However, the enlargement appears unilaterally consistent as demonstrated with fiducial line segment AB and CD. Both measurements demonstrate 0.8 mm of vertical enlargement. Therefore, since Frankfort-horizontal spans a considerable portion of the cephalogram horizontally, the distortional inconsistency would affect both landmarks equally.

Upon closer examination of the measurements involved with the Frankfort-horizontal plane, a trend was spotted in the actual position of the plane. In the digital measurements, the Frankfort-horizontal plane was consistently canted upwards (Po lower and/or Or higher) compared to the manual placement. Again, a cause for this discrepancy is unclear, except for the possible influence of digital enhancement.

Previous studies show mixed results when comparing the accuracy in landmark identification using digital enhancement features compared to identification on the original radiograph. Jackson et al. (1985) and Eppley and Sadove (1991) both concluded that landmark identification was comparable, if not better in some instances, such as soft tissue delineation, *with* digital enhancement over the original film. Wenzel (1988) and Jäger et al. (1989) both suggest digital enhancement can increase image quality improving landmark identification. In contrast, Davis and Mackay (1991) showed no significant differences in six angular measurements made from hand traced original radiographs compared to digitally enhanced images using contrast enhancement via a high frequency filter. They suggested that digital enhancement may actually decrease the accuracy of landmark identification and

subsequent cephalometric analysis. Similarly, Forsyth et al. (1996b) showed random error associated with angular and linear measurements recorded on the digital images was greater than on conventional radiographs. Therefore, discrepancies between media from the current study may very well be associated with the digital image enhancement features utilized. Whether or not the results were affected in a positive or negative manner remains unknown. If we accept the manual tracing and measurement as our "gold standard" technique in determining cephalometric measurements, then the effect caused by the image enhancement controls would be deemed a negative consequence and thus inhibitory to accurate cephalometric analysis. In any manner, definite disparities exist between the three modalities.

An additional potential contributing factor to the present significant results in cephalometric analysis may include the initial quality of the radiograph and/or quality after scanning. Marci and Wenzel (1993) evaluated landmark identification in digitally processed high quality and low quality images compared to the original cephalogram. They found no difference in landmark identification for the high quality digital versus high quality original image. However, a statistical difference was noted in the low quality digital and low quality original cephalogram. Low quality films were generally characterized by some blurring and sub-optimal contrast. They concluded that digital processing did not improve the overall reliability of landmark identification in poorer quality radiographs. In an earlier study, Wenzel (1988) demonstrated that digitized underexposed radiographs decreased accuracy in bone lesion diagnosis compared to radiographs with optimal density. However, digital

contrast enhancement and filtering of the low-exposure radiographs improved image quality.

Every effort was made to select cephalograms of adequate diagnostic quality with identifiable craniofacial structures and landmarks. However, during data acquisition, it was noticed that certain films were of poorer quality than originally suspected. For example, such cases exhibited large bilateral structure discrepancies, less than ideal contrast, and/or soft tissue burnout. An even more closely scrutinized case selection may have contributed to improved accuracy in landmark identification and digitization.

Further, radiographs were scanned at 150 dpi according to the recommendation from Dolphin Imaging Systems (2003). During landmark digitization, magnification was often utilized in an effort to more accurately identify certain structures. In several instances the magnification would cause significant pixelation and blurriness of the image, increasing the difficulty of accurate identification. Selecting a higher scanning dpi would possibly assist in circumventing this problem in future studies. A recently published study by Ongkosuwito et al. (2002) suggested scanning cephalometric radiographs at a resolution of 300 dpi. The study compared the reproducibility of longitudinal cephalometric measurements of analog and digital scans using 300 dpi and 600 dpi. They showed that the 300 dpi scan was comparable to the analog method and a 600 dpi scanned image. Therefore, the authors concluded that a scanning resolution of 300 dpi was sufficient for clinical purposes and comparable to analog cephalometric measurements. A scanning resolution below 300 dpi was not evaluated.

O'Callaghan (1993) examined the spatial resolution requirements necessary to use digital representations of lateral cephalograms. Twenty-five cephalograms viewed at three different spatial resolutions (256 pixels X 384 pixels, 512 pixels X 768 pixels, and 1024 pixels X 1536 pixels) at *8-bit* grayscale were viewed by twenty-eight judges for subjective analysis. Subjective analysis demonstrated that clinicians preferred digital cephalometric images with a spatial resolution of 512 pixels X 768 pixels (medium resolution). In a second part to the study, O'Callaghan compared accuracy in landmark and fiducial identification between the original radiograph and a digital representation using the preferred spatial resolution from the first part of the study. Landmark identification was found to be essentially the same between modalities, however, the location of the fiducial landmarks was significantly less accurate with the digital images. This result raises some question at to what the optimum resolution may actually be for not only viewing digital images of lateral cephalometric radiographs, but also for accurate use of these images for landmark identification in cephalometric analysis. Therefore, O'Callaghan, concluded by recommending high resolution for digital image acquisition based on the discrepancy in fiducial identification using medium resolution and the uncertainty of the effect gray scale resolution could play in resolution requirements.

Even if image quality or dpi affected landmark identification accuracy, one would expect a variety of measurements to be affected, other than those identified as being statically significant. In the current investigation, this was not the case. All significant measurements involved Po and Or, indicating a diminishing confidence in

the reliability of accurately identifying structures Po and Or and therefore Frankfort-horizontal plane.

Superimposition Measurements

Lateral cephalogram superimpositions play an integral role in the field of orthodontics for longitudinal evaluation of treatment effect and growth in craniofacial skeletal and dental structures. Traditional methods of superimpositions involve manual tracings of multiple time-point films to create both overall and regional (maxillary and mandibular) superimpositions. A variety of landmarks, structures, and methodologies exist for reference plane alignment, however, the most common and arguably most accurate make use of biologically stable reference structures in the anterior cranial base, mandible, and maxilla. These structures and techniques (Björk; Elmajian; Doppel et al.) are often considered the "gold standards" in cephalometric superimposition. The final section of this investigation was completed in an attempt to evaluate and compare a digital version of superimpositions using scanned radiographs to a manually traced technique.

Dolphin Cephalometric Tracing and Analysis 8.0 software was employed to construct superimpositions using the initial and final cephalograms from the sample of thirty used in the earlier sections. Dolphin's software allows for both overall and regional superimpositions and has nine reference planes to select from for the overall superimposition reference plane. Regional superimpositions are aligned on default settings. Maxillary superimpositions are completed using the palatal plane (Ans-Pns) at Ans as the reference plane, while mandibular superimpositions use mandibular plane (Me-Go) at Me. Ideally, a superimposition technique, as described by Björk

(1963), Doppel et al. (1994), and Elmajian (1959), involving biologically stable reference structures, should have been employed to provide the highest degree of accuracy during superimposition. However, to ensure an accurate comparison between modalities, the manual superimpositions were completed with identical reference planes as used by the digital system. This method allowed for a direct comparison of the accuracy between the digital and manual techniques. The investigation looked at superimposition changes in eighteen structural angular and linear measurements and four fiducial measurements. The eighteen structural measurements were subdivided into four separate groups to evaluate overall skeletal, maxillary, mandibular, and soft tissue changes. Additionally, the four fiducial measurements were analyzed in an effort to eliminate subjective landmark identification errors.

Tables 8 and 9 show the results of the superimposition measurements. No statistically significant differences were noted for any of the eighteen structural or four fiducial measurements. Although no statistical significance was shown, p-values for the eighteen structural comparisons tended to fall closer to significant levels than those from the fiducial measurements. Similarly, mean and standard deviation values were more variable in the structural measurements than those corresponding with the fiducial measurements. A cause for this difference most likely involves landmark identification errors and a more complex analysis associated with the eighteen structural measurements. A certain degree of standardization in the identification of measured points was incorporated into the current studies experimental design, by identifying these points utilizing perpendicular lines to common reference planes (S-

N, Ans-Pns, Me-Go). By using this method in both modalities, an attempt was made to maintain high reliability when selecting the specific points for measurement comparison. The reference plane also functioned as a repeatable reference base to make multiple measurements from different media. Nonetheless, a clear-cut deviation in p-values, means, and standard deviations is perceived between the structural and fiducial measurements pointing to a possible source of error involving initial landmark identification and a higher degree of complexity for the structural analysis measurements.

Future Studies

The current investigation was completed in total by a single operator (LQB). Therefore, a potential systematic bias was inherent throughout all phases of the study, which could be especially pronounced during landmark identification. Although a single operator eliminates inter-operator error, ideally, multiple operators may reduce and balance out the errors associated with landmark identification, improving the accuracy of the comparisons. In addition, a finer quality of cephalograms may have enhanced the accuracy in landmark identification for all three modalities. The cephalograms used in the current study contained a large rectangular radiopacity in the posterior cranial base area due to the cephalometer used when the cephalograms were taken. This radiopacity made the identification of porion difficult for all three media type, possibly affecting the proper position of Frankfort-horizontal plane and all related measurements. Likewise, a soft tissue filter was not used on some of the cephalograms, decreasing the accuracy in identifying soft tissue profile landmarks.

As mentioned previously, cephalograms were scanned at 150 dpi, as instructed by Dolphin Imaging Systems. Although research provided by Chen and Hollender (1995) and a recommendation by Rogers (2002) both suggest a scanning dpi of 75 dpi, a higher scanning dpi in the current investigation may have improved image quality for digital enhancement and magnification during landmark digitization.

CONCLUSION

Cephalometry has long been an important tool to the practicing orthodontist. Cephalometric analysis and superimposition provide an invaluable insight into dental and skeletal growth, development, and treatment response. Each contributes an essential adjunct in diagnosis, treatment planning and evaluation in modern orthodontics. Manual tracing and analysis has remained the longstanding "gold standard" technique. However, with the advent of digital imaging and computerized cephalometric programs, a new approach to cephalometric analysis is emerging, bringing orthodontics into the digital era. Standard analog radiographs can easily be converted into a digital format using relatively inexpensive, consumer grade scanners along with any current computer system. An important question then arises: "Can a scanned digital representation of the original radiograph accurately represent the original radiograph and replace traditional radiographic hardcopy films in all aspects of cephalometrics?" The aim of the current study was to answer this question.

Although the present investigation clearly demonstrated statistically significant distortion as the original image was transferred to a digital format and printed as hardcopy, the distortion was quite small and, therefore, the clinical significance may be considered inconsequential. In assessing the accuracy of cephalometric analysis among modalities, an analysis of the results showed six of twenty-three measurements from four common cephalometric analyses to be

significantly different between the manually-traced original film and the computerized analysis using a scanned digital image. In addition, four of twenty-three measurements were found significantly different between the digital format and the printed hardcopy tracing. All significant measurements, however, contained the landmarks porion and orbitale. Based on similar studies that determined these landmarks inconsistent and unreliable, the significant results in the current section were considered likely due to discrepancies in landmark identification between the digital image and original film. Furthermore, a comparison of superimposition accuracy between modalities showed no significant differences between the manually-traced technique and computer-generated format using both fiducial and linear and angular measurements. Therefore, superimpositions using the computerized program with a scanned digital images seem to be as accurate as the manually-traced technique. However, certain limitations were discovered when choosing the reference landmarks in the computerized superimposition program.

In summary, results from the current investigation indicate some distortion and discrepancies between the original cephalogram and digital representation, however, clinical significance may be questioned and landmark identification errors possibly contributed to these discrepancies. Thus, the scanning of analog cephalograms into a digital format may be considered as accurate as the original radiograph in the everyday usage by an orthodontist including cephalometric analysis, superimpositions, and hardcopy duplication. However, caution must be taken when determining Po and Or and when evaluating measurements associated with these landmarks.

Gonion	Most convex point along the inferior border of the ramus
Ramus Point	Most posterior point up the border of the ramus
Articulare	Posterior border of the neck of the condyle
A Point	Deepest point of the curve of the maxilla, between anterior nasal spine (ANS) and the dental alveolus
ANS	The tip of the anterior nasal spine
PNS	The tip of the posterior nasal spine
U6 Occlusal	Mesial buccal cusp tip of the maxillary molar
L6 Occlusal	Mesial buccal cusp tip of the mandibular molar
Distal U6	Distal surface of the upper first molar, perpendicular to the occlusal plane
Mesial U6	Mesial surface of the upper first molar, perpendicular to the occlusal plane
Distal L6	Distal surface of the lower first molar, perpendicular to the occlusal plane
Mesial L6	Mesial surface of the lower first molar, perpendicular to the occlusal plane
L1 Labial Gingival Border	Labial cemento-enamel junction (CEJ) of the lower central incisor
L1 Tip	Tip of the lower central incisor
L1 Root	Root apex of the lower central incisor
L1 Lingual Gingival Border	Lingual cemento-enamel junctin (CEJ) of the lower central incisor
U1 Labial Gingival Border	Labial cemento-enamel junction (CEJ) of the upper central incisor
U1 Tip	Tip of the upper central incisor
U1 Root	Root apex of the upper central incisor
U1 Lingual Gingival Border	Lingual cemento-enamel junction (CEJ) of the upper central incisor

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