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Cephalometric regional superimpositions -- digital vs. analog accuracy and precision: 2. the mandible

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CEPHALOMETRIC REGIONAL SUPERIMPOSITIONS – DIGITAL VS. ANALOG

ACCURACY AND PRECISION: 2. THE MANDIBLE.

KEVIN P. MCCAFFREY, D.M.D.

A Thesis Presented to the Faculty of the College of Dental Medicine,

Nova Southeastern University in Partial Fulfillment of the Requirements for the Degree

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I certify that I am the sole author of this thesis, and that any assistance I received in its preparation has been fully acknowledged and disclosed in the thesis. I have cited any sources from which I used ideas, data, or words, and labeled as quotations any directly quoted phrases or passages, as well as providing proper documentation and citations. This thesis was prepared by me, specifically for the M.S. degree and for this assignment.

STUDENT SIGNATURE:____

Kevin P. McCaffrey, D.M.D. Date

DEDICATION

I dedicate this thesis to my wife and anchor, Stacey, and to our two girls, Roxy and Reilly.

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I would like to acknowledge Richard Singer, Abraham Lifshitz, and Patrick Hardigan, for their incessant support over the last 30 months.

ABSTRACT

CEPHALOMETRIC REGIONAL SUPERIMPOSITIONS – DIGITAL VS. ANALOG ACCURACY AND PRECISION: 2. THE MANDIBLE.

DEGREE DATE: DECEMBER 12, 2014

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Introduction: Lateral cephalometric superimpositions (LCS) are used to measure dental and skeletal changes that occur in the craniofacial complex over time. Orthodontists use LCSs to assess treatment outcomes. The purpose of this study was to conduct an assessment of the measured displacement of defined dental landmarks across digital and analog methods of mandibular regional serial superimposition as compared to an implant-registered superimposition reference. The data used in this study was derived from the Mathew's Acquisition Group implant sample; the first United States longitudinal study of growing children with maxillary and mandibular Björk type metallic implants. **Methods:** Sixty-six lateral cephalometric radiographs were selected from twenty-two children. Three cephalometric tracings were completed for each subject that were then superimposed pairwise (T1 vs. T2, T2 vs. T3) across four separate methods of superimposition, two analog: Implant, Structural; and two digital: Dolphin, Quick Ceph. Each superimposition was then imported into Adobe Photoshop where the images were scaled and the displacement of defined dental structures was measured. Defined dental structures included: (1) first molar mesial contact point, (2) first molar apical root bisection, (3) central incisor root apex, and (4) central incisor crown incisal edge. A random-effects, generalized linear model was used to contrast dental landmark displacement measurements. **Results:** There was no difference between the mean displacement of defined dental structures between different methods (p=0.145). There was no difference between the different methods by defined dental structure (p=0.150). **Conclusions:** Our study demonstrated that there are no statistically significant differences among three methods of mandibular regional superimposition in comparison to an implant-registered (reference) method (analog: Structural, Implant; digital: Dolphin, and Quick Ceph). The historical data set utilized in our study, limited by the small sample size, resulted in a relatively low power (0.15). A low power increases the likelihood of incorrectly failing to reject a null hypothesis that is actually false. which must be considered in our study.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1: Introduction

1.1. Background

1.1.1. Anthropometry, craniometry, and cephalometry

Anthropometry, derived from the Greek word 'anthropic' (man) and 'metron' (to measure), refers to measurement of the human body. One of the earliest branches of anthropometry was craniometry, or measurement of the human head. Although it had been possible to make soft tissue measurements of the human head for centuries, internal hard tissue measurements of the skulls of living subjects were not possible until approximately 1930.[1] A prominent craniometrist, John Hunter (1771) compared human skulls from different age groups in order to study craniofacial development from infancy until adulthood.[2] Hunter is credited as being the first to use superimpositions of drawings to compare stages of craniofacial growth and development (Figure 1).[3] Hunter's superimpositions appeared as a series of mandibular drawings, drawn side by side and to scale, such that changes in size and shape between each successive drawing could be observed. Petrus Camper was the first to have studied the skull from a standardized orientation.[3] Camper placed each skull in a device known as a 'dioptra' that allowed skulls to be positioned reproducibly. Camper's serial comparative drawings illustrated each skull oriented to "Camper's horizontal plane" (i.e., a plane formed by connecting the external acoustic meatus to the nasal spine) and registered on the external acoustic meatus. Camper also drew metamorphoses composed of an older face drawn over a younger face, in order to demonstrate relative changes (Figure 2). Camper's facial angle, the first known, standardized measurement of the human head (1768),[4] was the inferior posterior angle formed between a line connecting the external acoustic meatus to the nasal spine and a line from the most prominent point on the frontal bone to the anterior alveolar margin of the upper jaw. Camper's facial angle is recognized as the traditional birth of craniometry[5] and was initially used as part of a broader theory to describe intelligence, differentiate humans from other primates, and to differentiate among the human races.[4] While early craniometrists believed that human intelligence and social abilities could be determined by measuring specific angles within the cranium, those ideas have long since been discredited.[6]

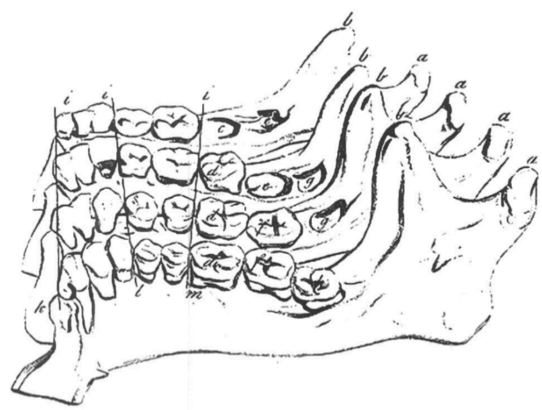

Figure 1. Hunter's mandibular superimposition[2]

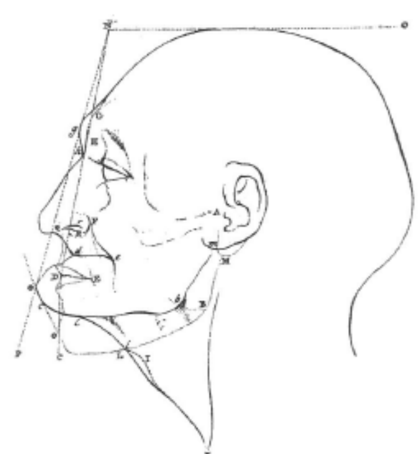

Figure 2. Camper's metamorphosis[3]

Six decades after the introduction of Camper's facial angle, Adolphe Quetelet (1835) introduced the "homme moyen*,"* or central individual.[7] The homme moyen was a composite of the average of all the human anthropometric measurements that Quetelet had collected. Quetelet's work represents the first large-scale attempt of a standardized statistical analysis of the human form. The result of Quetelet's detailed measurements of height and weight was known as the Quetelet Index, later renamed the body mass index (BMI).[8] The body mass index is the ratio of an individual's weight in kilograms divided by the square of their height in meters and informs body weight relative to height.[8]

Hermann Welcker (1863) specifically studied the human skull and published the first craniometric study based solely on the superimpositions of drawings of sagittal cuts of skulls.[9] Similar to Camper's metamorphoses, Welcker's superimpositions were nested compositions of drawings of an infant's skull, surrounded by a larger adolescent skull, in turn surrounded by a larger adult skull (Figure 3). Welcker's superimpositions were registered on sella and oriented so that the nasion-basion line of each drawing was parallel to the nasion-basion line of successive drawings, readily permitting observation of changes in size and shape.[9] Welcker demonstrated that there was reduction in prognathism throughout growth and the nasion-sella-basion angle became known as the Welcker angle.[9]

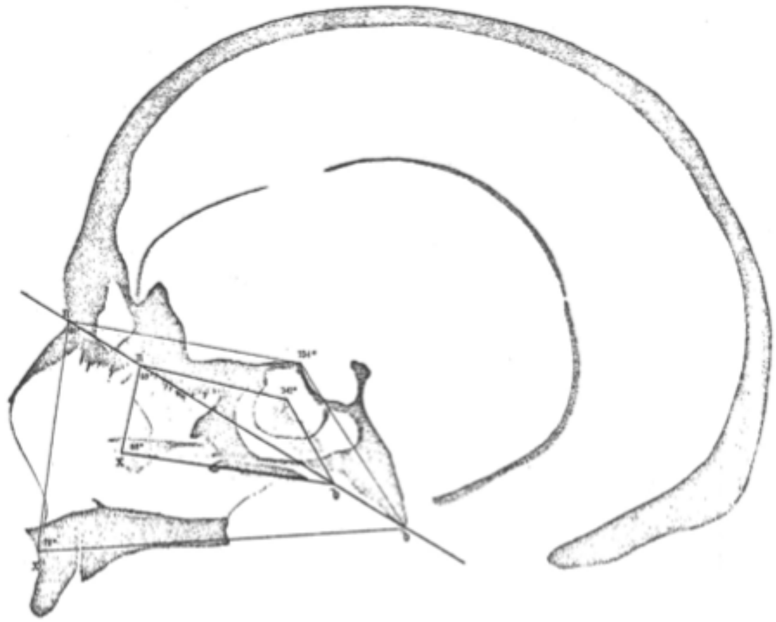

Figure 3. Welcker's skull superimposition[9]

Despite the increase in craniometric research conducted following these seminal studies, research findings were not readily comparable due to lack of methodological standardization. Von Ihering's horizontal plane, defined by right and left infraorbital margin and superior tangent of the left external auditory meatus, was accepted as the universal horizontal plane at the World Conference on Anthropology (Frankfort, Germany, 1882), and known as the "Frankfort horizontal plane."[10,11] Frankfort horizontal is one of many planes that were defined so that anthropometrists could standardize orientation of skulls in order to facilitate comparative studies of craniofacial morphology.

Keith and Campion (1922) published a study containing both soft tissue measurements (from living human heads) and hard tissue measurements (from preserved skulls).[12] Keith and Campion's study was unique in that it presented superimpositions of complete skulls from infancy through adulthood and illustrated the researchers' concepts of development of the boney facial skeleton by comparing superimpositions of specific facial bones throughout growth. Keith and Campion's study popularized two important concepts: the first was *structural superimposition*, that is, aligning drawings upon anatomic structures in order to study changes during development; the second was that each individual bone in the face has its own pattern of growth, and moreover, that the summation of each of the individual components contributes to the total growth of the facial skeleton. Keith and Campion's proposed mechanism of bone growth, while visionary, was based only upon speculation.

Much information was gained from studying the skull in vitro, however, it was unclear how these findings extended to living individuals. Research has demonstrated that the boney dimensions of a skull are altered upon desiccation due to differential shrinkage;[13] consequently, such measurements would constitute an inaccurate representation of a living individual's skull.[13] T. Wingate Todd advocated the necessity to measure the skull in vivo.[13,14] At that time, facial form was thought to be primarily under hereditary control,[14] however, Todd provided among the first empirical evidence that the environment also impacted facial form. Todd demonstrated that there were gross differences between the skulls of children who died due to disease and healthy children who died due to acute injury.[14] Todd argued that hard tissue measurements that would be applicable to living humans needed to be obtained from living humans because the skulls of deceased children were largely a record of defective growth.[14]

The discovery of the x-ray, by Wilhelm Roentgen, led to a solution for those hoping to study craniofacial morphology in the living.[15] The era leading to successful application of radiography was the result of much trial and error. Determining the exact distance between the radiation source, the patient, and the film in order to produce the least amount of magnification was one challenge.[16] A second challenge was determining of the correct amount of radiation necessary to produce a detailed image.[15] Total radiation is dependent upon the filament current (mA), the duration of exposure, and the voltage (kVp).[16] Each of these variables required precise calibration in order to produce detailed and diagnostic radiographs.[16]

Pacini, 1922, was one of the first anthropometrists to experiment with the variables that control radiographic exposure (mA, kVp, and exposure time) in his attempts at radiographic analysis of the craniofacial skeleton.[17] Pacini had access to a large collection of dried skulls, however, the curators of the collection prohibited sectioning of the skulls for the purpose of measurement.[17] Pacini's solution was to radiograph each entire skull from a fixed distance, with each skull positioned in a device known as a "craniostat".[18] The purpose of the craniostat was to standardize the skull's orientation such that lateral, posteroranterior, and oblique cephalometric radiographs could each be compared to other radiographs similarly obtained.[18] Craniostats were constructed with two horizontal ear rods to be inserted into the external acoustic meatus and a chin cup to support the mandibular symphysis.[18] The purpose of the horizontal ear rods was to align and hold the subject skull's midsagittal plane parallel to the radiographic film and perpendicular to the radiation source. The chin cup was adjusted so that the subject skull's Frankfort horizontal plane was maintained parallel to the horizon during the radiographic exposure.[18] Pacini determined optimum distances from the radiation source to the skull and also from the skull to the film, so that minimal magnification was achieved.[17] Pacini was also the first to use a standardized radiopaque reference object to calculate the magnification of the x-ray.[17] Pacini advanced the acquisition of detailed radiographs of dried skulls, however, an effective method of obtaining similar radiographs of living humans was not yet perfected.

B. Holly Broadbent, 1931, presented "A New X-Ray Technique and Its Application To Orthodontia,"[1] wherein Broadbent described methods to produce cephalometric radiographs of living individuals.[1] The lateral cephalometric radiograph is a lateral radiographic image of the craniofacial skeleton. Working independently at the same time, Herbert Hofrath presented a similar technique,[13] referred to as teleroentgenography. Hofrath's technique differed from Broadbent's technique in that teleroentgenography was only designed for lateral cephalometric radiographs, while Broadbent's technique allowed for simultaneous imaging of a both lateral and posteroanterior cephalometric radiographs.

Broadbent understood that standardization was important in lateral cephalometric radiographic technique. Broadbent developed the Broadbent-Bolton reontgenographic cephalometer (BBRC), which incorporated a cephalometer, to hold the head in a standardized, reproducible position (just as the craniostat held skulls in a standardized, reproducible position).[19,20] The cephalometer was designed such that two ear rods and a nose rest could reproducibly secure the patient's head oriented to the Frankfort horizontal plane. The BBRC was a prototype for modern cephalometric imaging devices, leading to the standardized techniques used today (i.e. the radiation source is 60 inches from the patient's mid-sagittal plane, the film is placed perpendicular to the radiation source, and the cephalometer is used to orient the patient's head such that Frankfort horizontal parallel to the horizon). Broadbent's technique[1] and the BBRC combined to enable reliable measurement and comparison of living human skulls.

1.1.2. Cephalometry - purposes

Cephalometry permits the study of facial form and patterns of growth and development. Cephalometry is an aid in recognition of dysplasia and pathology and, it is utilized in orthodontic and orthognathic surgical diagnosis and treatment planning, as well as in the assessment of treatment outcomes.

Broadbent's Bolton Study was a longitudinal study of facial growth and development that included lateral and posteroanterior cephalometric radiographs and orthodontic study models on over 4,300 individuals.[21] In total, Broadbent obtained approximately 45,000 plaster models as well as 40,000 cephalograms.[22] Broadbent's data was used to develop longitudinal age and gender specific normative values for lateral cephalometric measurements, thereby "defining" the pattern of "normal" craniofacial growth and development. Today, physicians, endocrinologists, pediatricians, dentists, and orthodontists use Broadbent's study as a reference when assessing individual growth status.

1.1.3. Cephalometry in Orthodontics

Following Broadbent's description of the lateral cephalometric radiograph technique in 1931, the knowledge of cephalometrics has become an integral part in the training of orthodontists throughout the world.[1,23] Longitudinal cephalometric radiographic studies of individuals from infancy to adulthood, like the Bolton study,[21] have allowed orthodontists the opportunity to study the normal patterns of craniofacial growth and development.[20,24-26] Orthodontists have identified and utilized common skeletal and dental measurements derived from such studies to develop radiographic measurements of the skull defining the normal pattern craniofacial development.[27-33] A lateral cephalometric radiograph can provide information regarding the growth pattern and developmental status of the patient,[29,30,33] where the mandible and maxilla are positioned with respect to the cranial base,[29,34] and where the teeth are positioned within each jaw.[29,30,33] A lateral cephalometric radiograph, in conjunction with a clinical exam, is routinely used for orthodontic treatment planning. In order to better understand how each individual case may differ from ideal, orthodontists created sets of cephalometric measurement values that are considered ideal and result in a well-balanced face.[35]

1.1.4. Cephalometric Analyses

The adoption and widespread utilization of the lateral cephalometric radiograph lead to the identification new radiographic landmarks and measurements.[3] Atkinson, [20] Bolton,[30] and Broadbent,[19] all identified anatomic landmarks or constructed points on lateral cephalometric radiographs that could be useful in analyzing craniofacial and dental relationships. Each new point allowed for the construction of planes as well as angular and linear measurements that could be compared to measurements from other lateral cephalometric radiographs. Orthodontists developed "analyses" that included multiple measurements, deemed the most important for meaningful and accurate orthodontic diagnoses and orthodontic treatment planning.

Orthodontists would routinely manually "trace" lateral cephalometric radiographs, in order to obtain these measurements.[1] To trace a lateral cephalometric radiograph, one would begin by placing a sheet of acetate over the radiograph, which would be placed over a bright light source, so that the radiograph could be seen through the acetate film. He would then mark landmarks with a pencil, outline the soft tissue profile (Figure 4), construct planes between landmarks, and finally, obtain linear/angular measurements (between points/planes, respectively) with a ruler or protractor.[36,37]

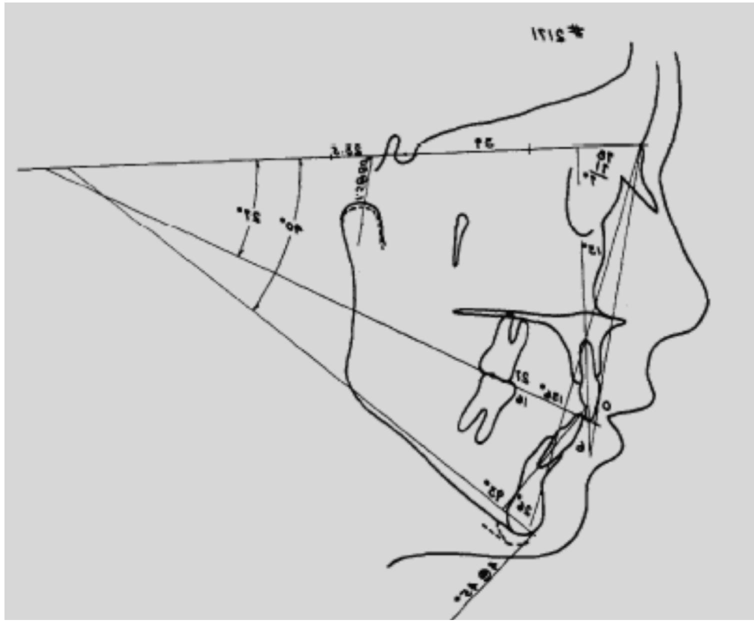

Figure 4. Lateral Cephalometric Tracing[29]

Cephalometric analyses focus on dental, skeletal, and soft tissue relationships, or a combination of the three.[29-33] Among analyses, the most well known are the Tweed,[33] Sassouni,[32] McNamara,[31] Downs,[30] Ricketts,[38] and Steiner analyses.[29] Each analysis is focused on the aspects *its author* deemed most important (i.e. the Sassouni analysis was concerned with the relationship of skeletal and facial features and their relative proportions, while Down's analysis placed more emphasis on the dentition and the way it relates to skeletal landmarks[30]). Each analysis includes subjective, author defined "normative values."[32,33,35,39,40]

The comparison of an individual's measurements to the normative values allows the identification and assessment of the magnitude of deviations from normal. The origin of such deviations could thus be determined as skeletal, dental, or a combination of the two. Application of such analyses and careful consideration of discrepancies informs diagnosis and the subsequent treatment plan for individual patients.

Despite the utility of many popular analyses, each is subject to the opinions of the author in determining "ideal" reference values.[30,32] Additionally, the utility of each analysis rests on the "reference" sample's age, race, and gender. Current studies are aimed at analyzing previously undocumented populations.[39-41]
For example, in 2011, Sharma conducted a study to obtain Steiner's cephalometric norms for the Nepalese population.[40]

1.1.5. Digital Radiography

Weighart and McNulty produced the first digital radiograph in 1963 while working on naval aircraft research.[42] Intraoral dental digital radiography was first introduced by Mouyen in 1984[43] and by 2007, 36.5% of all dentists reported using digital radiography.[44] Digital radiography offers many advantages compared to analog radiography, including: elimination of hazardous film processing chemicals, the ability to digitally alter images, immediate image production, reduced storage space requirements, facilitation of communication among healthcare providers, and reduced patient exposure to radiation.[16,45-52]

Digital images are acquired by three broad methods: direct imaging, semi-direct imaging[48,49] and indirect acquisition.[53,54] Direct imaging involves acquiring images using a charged coupled receptor, semi-direct imaging uses a photostimulable phosphor plate, and indirect imaging involves digitization of analog films.[47,55,56] All result in a digital image that is composed of a matrix of pixels (picture elements[57]), which are individual rectangles, each of which is represented by a shade of grey.[16,47,58] Each pixel's shade is determined by the amount of radiation that arrived at the sensing medium corresponding to that portion of the image. Portions of the sensor or film that receive more radiation correspond to darker pixels on the resultant digital radiograph and portions of the digital sensor or film detecting less radiation correspond to lighter pixels on the resultant digital radiograph. Dense tissues such as bone absorb more radiation, less radiation is transmitted at that location, and therefore, the appearance of bone on a digital radiograph is a light shade of grey. Alternatively, the nasal sinuses absorb less radiation, allowing more radiation to be transmitted, and the appearance of the nasal sinuses on a radiograph is a dark shade of grey.[16] Photon energy contributes to the contrast of the digital radiographic image. High-energy photons enhance contrast between tissues of unequal density, but may mask visualization of differences in density within like tissues.[59]

"Contrast resolution" describes a digital imaging system's ability to produce a limited number of pixels and greyscale values, and is defined as the ability to distinguish true differences in density on a radiograph.[16] Contrast resolution is dependent upon the interaction of the attenuation characteristics of the tissues being imaged, the ability of the digital sensor to distinguish the number of photons coming from different areas of the subject, the ability of the computer monitor to display grey values, and the individual observer's visual discrimination between greyscale values.[16] Analog radiographs have an infinite number of grey values[60] and their resolution is limited only by silver halide grain size of the developing medium;[16] however, digital radiography is subject to constraints in both number of grey values and number of pixels.[58] The computer imaging system calculates a discrete value for the intensity of radiation absorbed at each location on the radiographic sensor or scanned image and assigns a shade of grey to the corresponding pixel on the digital radiograph.[16] The value of grey observed in a single pixel on a digital radiograph is limited by the sensitivity of the sensor, the total number of grey values coded in the software, and the computer monitor's capability to produce each shade of grey communicated by the software.

In addition to the finite number of greyscale values, the sensor and computer monitor limit the number of discrete pixels that can be seen. Properties of pixels affect the contrast resolution in three distinct ways; the total number of pixels, the pixel density, and the number of bits per pixel. The greater the total number of pixels displayed in an image, the clearer that image will appear. An image that is 600 x 600 pixels will contain a total of 360,000 pixels while an image that is 1000 x 1000 pixels will contain 1,000,000 pixels. This is important considering that the image will be displayed on a monitor with a fixed number of pixels. If a monitor can display 1000 pixels wide and 700 pixels vertically, the maximum number of pixels it can display is 700,000. If the two images discussed above were shown on such a monitor and displayed to fill the entire height and width of the monitor, the 1,000,000-pixel image would fill the entire screen while the 360,000-pixel image would not. In the latter case, if the smaller image projected to fill the entire screen, the image may appear pixelated [61] (Shown in figure 5).

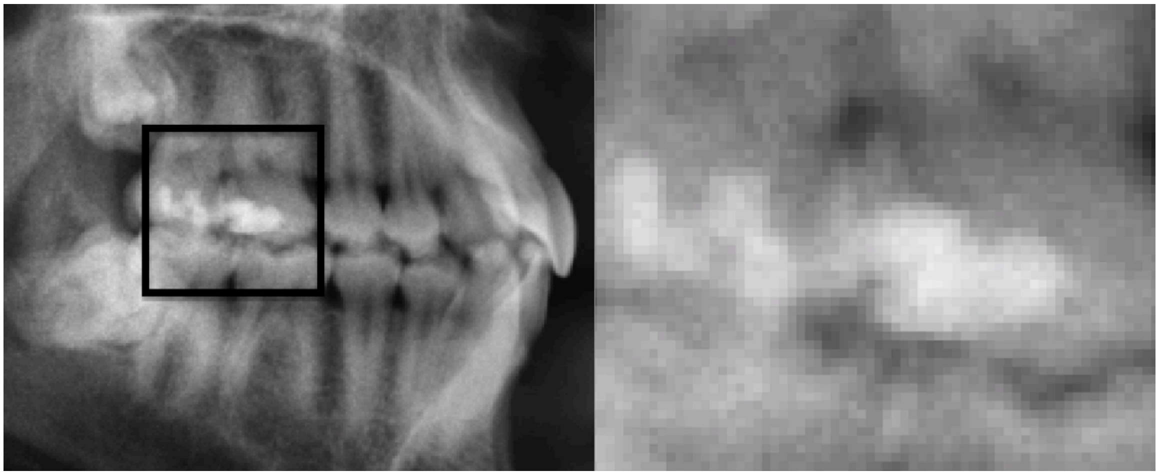

Figure 5. Pixelation is not seen in the left image because there are sufficient pixels to fill the display area of the monitor, however the image quality is such that if a portion of the image were made to fill a larger area of the monitor, pixelation would occur (right).

Pixel density describes image resolution and is designated by pixels per inch (ppi). Dots per inch (dpi) are also used to describe image resolution and while some use this notation interchangeably with ppi,[61] dpi is a term that specifically refers to the image quality of printed images.[16,60] The greater the pixel density, the smaller the dimensions of each individual pixel, and the more detailed an image appears. Humans visual acuity is limited to 300 ppi,[62] and therefore pixel densities greater than 300 ppi do not contribute to human perception of image resolution. If an image on a monitor is enlarged, the ppi will decrease. For example, an image that is 1500 pixels by 1200 pixels is shown on a 15-inch x12 inch monitor, it would have 100 ppi displayed. If that image is enlarged such that one-fourth of the image fills the entire screen, the resulting image size is then 750 x 600 pixels and would appear to be 50 ppi. Pixel density may also change when an image is made to completely fill different size monitors. The greater the dimensions of the monitor an individual image is displayed upon, the lower the resulting ppi displayed.

"Bits per pixel" describes the number of different grey values each pixel can hold.[47] An 8 bit/pixel digitizing system can produce 28 values of grey while a 12 bit/pixel digitizing system can produce 212 shades of grey. The greater the bits/pixel ratio, the greater number of grey shades can be produced and the more information is stored in the image. Additionally, the greater the bit/pixel ratio, the more accurate the image will display differences in tissue density.[47]

1.1.6. Digital Cephalometric Analysis

Digital radiographic technology has allowed orthodontists to capture lateral cephalometric radiographs digitally and also permitted tracing and analysis of those radiographs using computer software. Baumrind and Miller, two pioneers in computerized lateral cephalometric radiograph analysis, published a method of computer aided lateral cephalometric radiograph analysis in 1980, after 10 years of development.[63] Several other methods[46,53,64-74] of computer aided lateral cephalometric radiograph analysis were developed in the following years and by 2005, 40% of orthodontic offices in the U.S. reported using computers for cephalometric analysis.[75]

The perceived benefits of computerized tracing include: immediate cephalometric calculations,[76] simultaneous computation of multiple analyses, ease of generating treatment predictions, user friendly tracing software,[53] reduced tracing time,[77] reduced need for storage space,[78,79] image superimposition capabilities,[80] ability to digitally enhance images,[81] and obviation of image deterioration.[46,82] Computerized tracing may offer some benefits, but the accuracy of digital tracing is subject to many of the same limitations of analog tracing (magnification errors, projection errors, tracing errors, landmark identification errors[77,83-85]) as well as limitations specific to digital cephalometry (image storage, image transmission, image quality, calibration issues between software[58]). Moreover, digital tracing of a radiographic image is constrained by the discrete nature of a pixel. During the identification of a landmark in an analog tracing, the operator can place a pencil point at the landmark's exact location on the tracing medium, however, for a digital image, only 'whole' pixels can be selected, therefore, resolution of any point is reduced to the size of the pixel containing it. Thus, the limitations inherent in selecting an entire pixel may reduce the precision of digital landmark selection. In addition, some software programs will not allow the placement of a point that coincides with an outline that has already been traced.[36] Miller, Savara, and Singh,[86] found that the variability in cephalometric landmark identification is five times greater than the variability in measurement, further supporting that accuracy and precision of landmark identification are extremely important.

Variability in both inter-operator and intra-operator landmark identification during analog lateral cephalometric radiograph tracing has been demonstrated in research conducted by Baumrind and Frantz,[83] Morrees,[87] Richardson,[88] and Sekiguchi and Savara.[89] Many studies have also compared the accuracy of landmark identification between analog and digital methods of lateral cephalometric radiograph tracing.[46,53,54,64,72,77,82,90-100] Some researchers have reported superior ability identifying landmarks using the analog method of lateral cephalometric radiograph tracing,[49,55,71,93,101] yet other investigators found that both digital and analog methods of landmark identification had similar accuracy.[56,64,102-104] Chen, Chen, Huang, Yao, and Chang found smaller inter-observer errors in landmark identification using direct digital lateral cephalometric radiographs rather than analog radiographs for 18 of 19 points in their study.[95] The results are equivocal evaluating the accuracy of landmark identification between analog and digital lateral cephalometric radiograph tracing methods.

It is important to consider the rapid development of digital technology when reviewing the literature pertaining to digital and analog lateral cephalometric radiograph landmark identification and measurement. The variability of study results is likely not only related to the date from inception of the technology that studies were conducted (due to advances in technology), but also to the specific software program used. Dolphin Imaging (Dolphin Imaging and Management Solutions, Chatsworth, California, USA) and Quick Ceph (Quick Ceph Systems, San Diego, California, USA) are two of the most widely used digital imaging programs for tracing lateral cephalometric radiographs.[105,106] C*urrent* studies comparing landmark identification and measurement differences between analog and digital methods (Dolphin and Quick Ceph) inform the state of our knowledge.

Power, Breckon, Sherriff, and McDonald,[64] analyzed the reliability and reproducibility of Dolphin Imaging v8 and analog tracing of lateral cephalometric radiographs. [107] Power found manual tracing more reliable for identification of four measurements and Dolphin more reliable for two measurements. Power et al. also found clinically significant differences for tracing accuracy of three of those measurements. Further, Power et al. found systematic error in the Dolphin's calculation of lower anterior facial height (due to incorrect software coding), resulting in measurements 4% larger than manual techniques.[64] Power et al. suggested that measurements including gonion may be more reliable in analog tracing as gonion is "constructed" rather than digitally selected. Power et al. also stated that measurements including incisors may be more reliable using Dolphin due to Dolphin's ability to digitally enhance images.

Tan, Ahman, Moles, and Cunningham[108] compared analog lateral cephalometric radiograph tracing to digital tracing using Dolphin Imaging Plus v10 and concluded that both methods showed "clinically acceptable" repeatability, even though statistically significant differences were found in four of the six measurements used. Analog tracing was significantly more repeatable for two of the measurements and Dolphin was significantly more repeatable for two other measurements. Tan et al. reported that the differences between the two methods were within "clinically acceptable" limits using criteria that were liberal. Tan stated that "clinically acceptable" limits were set according the British Standards Institution Coefficient of Repeatability (CR) formula[109] (clinically acceptable limit = measurement's SD x 1.96), which resulted in some measurements being “clinically acceptable” even if they differed by as many as twelve degrees. Using such limits, Tan et al. concluded that on average, both methods agreed and are acceptable for clinical use. The study design used by Tan et al. did not accurately represent traditional analog lateral cephalometric radiograph tracing, rather, radiographs were captured *digitally* and then printed onto film, with no provisions mentioned concerning magnification.[108] Tan et al. provided no information regarding verification that there were no distortions between the original digital radiographs and the printed radiographs, a prerequisite for meaningful comparison between techniques.

AlBarakati, Kula, and Ghoneima[81] compared Dolphin Imaging v11 to analog tracing and found statistically significant differences in 12 of 16 measurements.[81] AlBarakati et al. stated that the differences of the angular measurements had little clinical significance; giving no justification for such a statement. AlBarakati et al. explained that the differences could be due to the fact that onscreen digitization does not allow identification of landmarks located on a previously traced line or points which are constructed at the intersection of two planes; both of which are possible with manual tracing. Further, AlBarakati et al. stated that the cursor might obscure the precise location of landmarks during identification, making precise landmark selection more difficult.[36] While statistically significant, the authors concluded that the differences between methods were not clinically meaningful.[36] AlBarakati et al. provides no rationale for such conclusions and provides no quantitative threshold that constitutes when a significant finding *would be* clinically meaningful.

Roden-Johnson, English, and Gallerano[66] compared the accuracy of landmark identification and measurement of Quick Ceph 2000 to analog lateral cephalometric radiograph tracing. Roden-Johnson et al. stated that most of the measurements between the methods were reproducible within ±1 mm,[73,110] however, three measurements exceeded this limit (maxillary central incisor to sella-nasion, cranial base to nasion-horizontal, and cranial base to A point-horizontal). Additionally, the authors pointed out the following error in the statistical analysis:

> "One shortcoming of this investigation was that the Mann-Whitney U Test was used; it is a nonparametric tool for the analysis of 2 independent samples. This test was chosen because the data did not have parametric distribution, and therefore a 2-sample independent *t* test could not be used. Normalization of the data and usage of an independent *t* test might give different results."[66]

Erkan, Gurel, Nur, and Demirel[67] compared analog, Dolphin Imaging v10.5, and Quick Ceph 2000 methods of lateral cephalometric radiograph tracing. Erkan et al. selected dental, skeletal and soft tissue landmarks that generated five linear and ten angular measurements. The average difference per measurement between Dolphin and analog was 0.43 mm or 0.57°; between Quick Ceph and analog was 0.67 mm or 0.62°. Erkan et al. concluded that computerized cephalometric analysis yields results comparable to analog cephalometric analysis.[67]

1.2. Superimposition

1.2.1. Conceptual purpose

> *"Superimposition of cephalometric images is the universally used method for demonstrating and evaluating growth and/or treatment outcomes in the dentofacial complex in individual patients."* [3]
>
> -Herman S. Duterloo, Author
> Handbook of Cephalometric Superimposition

Similar to the drawings of Hunter[2] and Welcker,[9] tracings of lateral cephalometric radiographs across paired time points can be superimposed to observe the magnitude of dental and skeletal changes that may have occurred and to assess treatment outcomes.[2,9,111] Such superimpositions are known as lateral cephalometric superimpositions (LCSs). B. Holly Broadbent Sr. published a technique to accurately superimpose successive lateral cephalometric radiograph tracings in order to visualize growth in children.[1] Broadbent found that the cranial base appeared stable and therefore, registered paired radiographs on sella and oriented them so that both of their sella-nasion planes were parallel.[1,20] By superimposing two lateral cephalometric radiograph tracings, from a single growing patient, at two time points, registered on sella, it was possible to visualize skeletal changes that occurred.

1.2.2. Cranial Base vs. Regional Superimpositions

Cranial base superimpositions are often registered upon the anterior wall of the sella turcica and anterior cranial base to assess growth *and* treatment changes in the relative positions of the maxilla, mandible and respective dentition.[112] In order to assess the movement of teeth within the maxilla or mandible, independent of the positional changes of the jaws relative to the cranial base, the superimposition must be registered on stable structures within each of the respective jaws. Lateral cephalometric superimpositions registered solely on structures within either jaw, rather than the cranial base, are termed 'regional superimpositions.' Regional LCS is useful because it permits assessment of tooth movement within the jaws, independent of growth, allowing evaluation the orthodontic mechanotherapy employed.[30]

Accurate and carefully detailed superimposition methodology is a prerequisite for meaningful assessment of skeletal and dental positional changes.[113] It is important that the anatomic landmarks used for registering superimpositions are stable (i.e., do not remodel) with respect to the dental structures of interest. If this is not the case, the differences (and their respective magnitudes) attributed to growth or mechanotherapy, are not reliable due to lack of a fixed reference.

The analysis of LCSs based upon pretreatment and post-treatment time points inform orthodontists of the magnitude of the dentofacial changes due to either growth or treatment, and their contribution to the orthodontic correction. Orthodontists can use LCSs to quantify the amount and direction of tooth movement in order to permit assessment of treatment outcomes.[114] However, the validity of the interpretation from LCSs is entirely dependent upon the anatomic structures used to construct the superimposition. Arat, Rubenduz, and Akgul found that there are significant differences in landmark displacement measurements between the Björk,[115] Ricketts,[116] and Steiner[117] methods of superimposition.[118] Arat et al. findings emphasize that orthodontists must use care in selecting a superimposition method that is consistent with current knowledge of craniofacial growth and development.

1.2.3. Implant Method of Superimposition

Björk and Skieller[115,119] studied facial growth using the implant method of cephalometric superimposition by placing small radiopaque "implants" into the jaws of subjects. The maxilla and mandible grow appositionally rather than interstitially[26,120] and therefore, once placed, the Björk implants remained spatially stable within the respective jaws. The spatial stability of implants renders regional LCSs based upon implant superimposition the most accurate and reliable method available.[111,119,121,122] Björk and Skieller utilized regional LCSs, superimposed on the radiopaque implants, to determine the pattern in which each individual jaw remodeled. Studies on mandibular growth have shown that the specific locations in which the metallic implants were placed did not change in relation to each other during growth.[119,123] The locations used were: 1) the anterior mandibular symphysis, below the incisor apices, 2) the right body of the mandible below the first premolar apex, 3) the right body of the mandible below the second premolar or first molar apex, 4) the right ramus, at the level of the occlusal plane.[111] These locations were chosen for their ease of implant placement and because they resulted in retention most often.[111] An important benefit of the implant method is that the implants allow comparison of other superimposition methods by serving as a referent method, utilizing registration on unambiguous implants where superimposition is absolute.

The use of implants in human growth studies led to changes in the understanding of craniofacial growth and development.[120] The growth pattern of mandibular rotation as understood by using the implant method of superimposition stands in sharp contrast to interpretations discerned by studies of mandibular surface remodeling.[120] Björk found that by aligning serial lateral cephalometric radiographs on the cranial base and observing the movement of stable implants, the mandible of a growing child usually rotates anteriorly (relative to the cranial base).[26] The forward rotation is often "masked" by bone resorption at the inferior of the angle of the mandible and deposition of bone at the mandibular symphysis, resulting in an inferior border that appears unchanged; however by studying the rotation of the implants, it is evident that the mandible does indeed rotate. Björk also found that the majority of mandibular growth is through apposition at the condyle and posterior ramus rather than deposition (growth) at the chin.[26]

The use of implants to study facial growth resulted in two impactful findings[3] : 1) that the pattern of individual dentofacial growth is extremely varied, 2) the identification of natural reference structures or structures that did not remodel with respect to the implants. Such natural reference structures serve as the basis for the structural method of superimposition.[26,119]

1.2.4. Structural Method of Superimposition

Björk and Skieller developed the structural method of cephalometric superimposition, which uses hard tissue landmarks as surrogates for implants, for registration and orientation of regional LCSs.[10,26,115,124,125] Björk and Skieller determined which radiographically visible anatomical structures remained stationary relative to one another and to the implants during craniofacial growth.[10,26,124,125] Using the natural reference structures as registration points for superimpositions formed the basis of the structural method.

Mandibular regional superimpositions, for patients without implants, were originally registered upon the inferior border of the mandible.[1,123,125] Once it was proven that the inferior border of the mandible remodeled throughout growth, the realization occurred that such superimpositions were not valid.[26] Downs suggested using a straight line representing the lower border of the mandible as a means to superimpose,[30] however, this method would also be invalid as the inferior border of the mandible remodeled.[13,26,125-127]

Björk and Skieller found that mandibular growth occurs primarily at the condyles, albeit with considerable individual variation. While there is substantial, yet unpredictable, growth at the condyles, the anterior portion of the mandibular symphysis and its boney trabeculae are notably more stable.[120] The angle of the mandible is usually an area of resorption, however deposition can be seen.[120] In individuals with a hyperdivergent growth pattern, excessive resorption is seen at the angle of the mandible resulting in a mandibular border that appears hyperdivergent with respect to the cranial base. However in those individuals with a hypodivergent growth pattern, it is more common to see apposition at the angle of the mandible.[120] For this reason, the lower border of the mandible is not a suitable registration area for an accurate superimposition.[128] Within the body of the mandible, the mandibular canal does not remodel at the same rate as the inferior border and therefore, it rotates with respect to the outer surface of the mandibular body (though it does not actually change position with respect to the mandibular corpus). Björk and Skieller found that the anatomical area surrounding the mandibular canal was extremely stable throughout growth.[120] Another area of stability was the inferior border of a developing third molar germ.[120] Björk and Skieller found that while the general area of the third molar was stable, the germ itself was only suitable for superimposition from the time of initial crown calcification until root formation was visible radiographically. Based on these findings, Björk and Skieller identified the natural reference structures within the mandible.

In summary, the natural reference structures of the mandible are 1) the anterior contour of the chin, 2) the inner contour of the cortical plate at the lower border of the symphysis, 3) the trabecular structures within the symphysis, 4) the contour of the mandibular canal, and 5) the lower contour of a mineralized molar germ before root development begins.[24] Only the aforementioned natural reference structures may be used in the structural method of superimposition to achieve an accurate mandibular regional superimposition.

Implants are no longer placed in humans for the purpose of LCS. While invaluable for research purposes, implant placement is impractical. However, using the information gleaned from Björk's implant studies,[26,125] the structural method has become the best alternative technique for cephalometric superimpositions. Björk's structural method is the only evidence-based method of superimposition; all other superimposition methods that have been proposed were based on circumstantial reasoning.[3] Springate and Jones[129] compared Ricketts[130] and Björk's[26,119] superimposition techniques with a cephalometric data set that included radiographs with tantalum implants. Springate and Jones found that Björk's method of structural superimposition was very similar to superimposition on the implants, while Ricketts' method differed significantly.[129] It is important to note that natural reference structures are not *absolutely* spatially stationary throughout growth,[10] yet they are the best means available for superimposition in the absence of implants.

1.2.5. Digital superimposition

The increase in the use of digital radiography and technology to trace lateral cephalometric radiographs[44,75] has been followed by an increased use of computer software to perform regional and overall LCS.[66,75,131] Most digital superimposition software allow users to identify radiographic structures on a digital radiograph using a mouse. The user can then select a lateral cephalometric radiograph analysis (i.e., Downs,[30] Tweed[33]) and the software will "draw" the necessary planes and compute the linear and angular measurements of the analysis. Digital superimpositions may require less time to produce than analog superimpositions,[58] but more important than time is determining if digital superimposition technique is valid. Currently, 97% of orthodontic programs, 50% of maxillofacial surgery programs, and 25% of pediatric dental programs in North America use Dolphin Imaging[106] and thousands of orthodontists worldwide use

Quick Ceph.[105] Due to the widespread adoption of Dolphin and Quick Ceph in the orthodontic community, it is especially important to understand the accuracy and validity of superimposition when these software are employed.

1.2.6. Digital Regional Superimposition

Digital cephalometric software can complete both cranial base and regional superimpositions.[65,132] There have been only three published studies assessing the accuracy of digital regional LCS.[66,69,97]

Roden-Johnson et al. compared Quick Ceph 2000 to analog regional LCS and found no significant difference.[66] The stated results of Roden-Johnson et al. are questionable because the study showed a statistically significant difference (0.3mm, p= 0.0294) for the change between nasion and cranial base, between methods. Researchers stated, "this leaves the clinical significance questionable because the width of the pencil used to trace the cephalograms was 0.5mm." Additionally, Roden-Johnson et al. never addressed reliability or intra-operator error of landmark identification. Intra-operator error calculations are important to assess how reliable the individual operator completes the task in question. Lastly, Roden-Johnson et al. study used questionable analytic approaches to determine statistical significance in reporting their findings.

Huja, Grubaugh, Rummel, Fields, and Beck[69] compared Dolphin Imaging v10 to analog methods to conduct mandibular regional LCS.[69] Superimpositions were completed on 64 pairs of lateral cephalometric radiograph tracings and Huja et al, found that for both analog and Dolphin superimpositions, the upper 95% confidence limit for the mean of landmark displacement was less than 1mm for all mandibular landmarks. While there were minor differences between the analog method and the Dolphin method, the differences were deemed clinically insignificant.[69] Huja et al. concluded that the study validates the use of Dolphin Imaging v10 for lateral cephalometric superimpositions. One limitation of using Dolphin Imaging v10 according to method used by Huja et al. is that Dolphin does not allow for superimposition of custom structures within the mandible for mandibular regional superimpositions.[69] Huja wrote, "We overcame this limitation by a tedious process for this research, but it is not practical for the orthodontic practitioner."[69] In other words, the method employed in order to enable Huja et al. to use Dolphin for the purpose of this study was not generalizable or practical for use by the typical clinician in a routine way for mandibular regional superimpositions in a practice setting. A second limitation of the study by Huja et al. is that all landmarks were identified on the radiograph prior to any digital tracing. This does reduce error in landmark identification between the two methods, however, this is not the actual procedure that an orthodontist would use when tracing a lateral cephalometric radiograph digitally, and therefore, has little clinical application.

Bruntz, Palomo, Baden, and Hans compared 30 mandibular regional LCSs of pre-treatment and post-treatment radiographs of patients at Case Western Reserve University using both analog and Dolphin Imaging v9 LCS techniques.[97] Bruntz et al. did not find any statistically significant difference between analog superimpositions and those superimpositions completed using Dolphin Imaging. Bruntz et al. reported that any measurements involving the FH plane may have been inaccurate due to a mechanical obstruction making the visualization of porion difficult. It is surprising that no differences were found given Bruntz et al. finding of a 0.5% vertical enlargement and 0.3% horizontal reduction inherent in scanning the radiographs used in the study. Bruntz et al. did note "the conversion of digital images into viewable, printable, and storable formats often requires data compression, alteration, or transfer to peripheral hardware, increasing the likelihood of image distortion."

The three aforementioned studies constitute the entirety of peer-reviewed research comparing mandibular regional LCSs using digital and analog methods. It is noteworthy, that because none of the three studies used the implant method of superimposition (i.e. an absolute reference standard),[115,123,125,128] for comparison, at best, such studies describe only the relative relationship of the digital to analog methods. Additionally, each of the studies had unique limitations that may have affected the conclusions reached by the authors.

1.3. Current Study

1.3.1. Purpose

The proposed study will evaluate measurements of defined dental structure displacements between paired time points, across three methods of mandibular regional LCS, in comparison to the implant reference method. The magnitude of differences in defined dental structure displacement measurements derived from any of the methods observed will be compared to like measurements derived from the implant method. The implant method has been shown to be an extremely reliable registration method for measuring the displacement of defined dental structures.[115,123,125] Implants, such as those used by Björk and Skieller cannot be routinely placed in the mandible of every patient.[115,133] However, by assessing the methods of mandibular regional superimposition utilized in this study, we will examine which method is most accurate and best proxy of the implant method in assessing mandibular tooth movement due to orthodontic treatment. A method of mandibular regional superimposition that is reliably accurate may provide orthodontists a means to confidently assess treatment outcomes, and an evidence-based method for evaluating the effects of treatment mechanics.

This study will provide objective data, comparing measurements of displacement of defined dental structures generated from 2 digital methods of mandibular regional LCS and the structural method (i.e. traditional analog method) of mandibular regional LCS, with comparison of each to the implant method of mandibular regional LCS.

1.3.2. Specific Aim

The specific aim of this study is to compare methods of mandibular regional LCS. The methods being studied are both analog and digital. Our goal is to provide an unbiased comparison of measurement of the displacement of defined dental structures across paired time points, generated by three separate mandibular regional LCS methods, each compared to the implant method. Statistical analysis of such measurements, will allow for evaluation of measures across mandibular regional LCS methods for accuracy and reproducibility. Each displacement measurement will be compared to absolute superimposition upon metallic implants. This will permit quantification of any differences between the methods of superimposition and also allow quantification of differences in comparison to the implant method.

1.3.3. Hypotheses

H_0: There are no differences in the measured displacements of defined dental structures between serial time points among the three techniques of mandibular regional LCS, in comparison to the implant method.

H_1: Differences exist in the measured displacements of defined dental structures between serial time points, among the three techniques of mandibular regional LCS, in comparison to the implant method.

1.3.4. Novelty

The current study will constitute a novel contribution to the literature concerning validity of mandibular regional LCS techniques. The current study will quantitatively and objectively evaluate measurement accuracy of current mandibular regional LCS techniques used in clinical practice. A large body of literature exists concerning cephalometric superimposition technique, differences in technique, and the application of digital radiography for this purpose, yet there is a paucity of published studies regarding analog vs. digital mandibular regional superimposition.[66,69,97,112,115,117,134-148]

Unique to this study is the use of data composed of serial lateral cephalometric radiographs of patients who received Björk-type tantalum implants in the mandible (The

Mathew's Acquisition Group),[3] specifically for the purpose of comparing analog and digital methods of superimposition. A few previous studies have compared the accuracy of digital to analog methods of mandibular regional superimposition,[69,149] however, none have used implants as a reference for comparison.[69,149] Therefore, in contrast to other studies,[56,66,69,81,97,138,141,150] which simply evaluate relative differences in displacement measurements found in various LCS techniques, the proposed study will utilize the implant method for reference, i.e., enabling an objective, near absolute measure of how defined dental structures *actually* moved.[121] Though Gu and McNamara[146] utilized a subsample of the same data set, it was limited in scope to analog superimposition methods alone.

This study is focused specifically on a comparison of analog vs. digital methods of mandibular regional superimposition, whereas most prior investigators studied comparisons of cranial base superimpositions.[69,151,152]

1.4. Location of Data Set

1.4.1. Origin of the data set

J. R. Mathews and W. H. Ware acquired the data used in this study between the years of 1967 and 1979 at the University of California at San Francisco Dental School, Section of Orthodontics.[153] Mathews and Ware's study was the first and only long-term growth study in the United States replicating Björk and Skieller's[154,155] methods of tantalum implant placement in both treated and untreated cases. Mathews headed the study, while Ware was responsible for placing 3-5 implants unilaterally in the mandible and 3-5 transversely in the maxilla of the study participants. The subjects in the study were between 7-18 years of age and were recalled annually for a lateral and posteroanterior cephalometric radiographs, and left and right 45-degree oblique cephalometric radiographs.

1.4.2. Role of CRIL

The Craniofacial Research Instrumentation Laboratory (CRIL) at the University of the Pacific, Arthur A. Dugoni School of Dentistry, Department of Orthodontics is an organization committed to advancing evidence-based treatment through peer-reviewed research. CRIL is home to the American Association of Orthodontics Foundation's (AAOF) Craniofacial Growth Legacy Program, which intends to preserve, digitize, and make available to the public irreplaceable materials from nine major craniofacial research collections started throughout the United States and Canada.

CRIL is responsible for the maintenance of the Mathew's data set[153] as well as many other data sets. As stated previously, Mathews' images are unique in that they are the first and only collection of samples utilizing Björk-type tantalum implants for precise superimposition in the United States. Mathews' family has been very generous in their support of CRIL, allowing these priceless images to be available to the craniofacial and orthodontic research community.[153] CRIL is the laboratory that provides access to, and protection of, these images. The data at CRIL has been responsible for more than 80 original, peer-reviewed papers in the fields of orthodontics, medicine, engineering, and statistics. CRIL has been a leader in constructing massive databases of orthodontic information to be shared across the profession. As of 2008, CRIL had obtained orthodontic records for over 1,400 patients, from over 30 experienced orthodontists. Of those 1,400 patient records, over 300 had been converted into high-resolution digital format for easy distribution, aiding in collaborative research.

The mission of CRIL, as written on their website is:

The Craniofacial Research Instrumentation Laboratory is devoted exclusively to clinical research into the effects of therapeutic interventions designed to correct dentofacial malocclusions and craniofacial malformations by orthodontic and/or surgical means. Its long-range objective is to improve the quality of care for malocclusions and craniofacial anomalies by rigorous quantitative analysis of the effects of treatment or of failure to treat. It has four areas of primary focus:

- *The conduct of clinical studies of treated patients and untreated control subjects using the best available sampling and measurement techniques.*
- *The development of improved systems, both physical and conceptual, for the conduct of clinical studies.*
- *The construction of shareable electronic databases and image bases for the dissemination of information derived from our own studies and from the investigations of others.*
- *The education and training of a cadre of investigators with skills focused on the needs of clinical research in the craniofacial region.*

The goal of these enterprises is to create better future conditions for "evidence-based orthodontic practice."[156]

1.4.3. Sheldon Baumrind: Legacy cephalometric data group

Sheldon Baumrind, the current director of CRIL, founded the organization at UCSF in 1979.[156] Baumrind also serves as curator and Administrative Principal Investigator for the AAOF Craniofacial Growth Legacy Collection. Baumrind has authored over 100 original publications, helping to enrich the literature of the orthodontic, medical, statistical and engineering fields. Baumrind is a Professor of Orthodontics at the University of the Pacific and also at the University of Medicine and Dentistry of New Jersey. In the past 25 years, Baumrind has been the Principal

Investigator of many National Institute of Health supported dental studies focusing the development of three-dimensional craniofacial measurement systems. Baumrind has also been an officer and co-chair of the Joint University of California Berkeley-University of California San Francisco Graduate Program in Bioengineering.

As director at CRIL, Baumrind helps to further Mathews' mission of sharing information across all levels of academia. Sheldon Baumrind's direct support has enabled the current study.

Chapter 2: Materials and methods

2.1. Sample

The sampling frame for this study was comprised of 36 patient records from the Matthews Acquisition Group (1967-1979),[133] accessed with permission, through the Craniofacial Research Instrumentation Laboratory (CRIL).[156] Mathews and Ware originally gathered this data in order to study craniofacial growth.[133] The inclusion criteria for subjects in Mathews' study were: (1) the patient sought orthodontic treatment at the University of California, San Francisco between the years of 1967-1979, (2) the legal guardian of each patient consented to allow placement of tantalum implants in the patients' maxillae and mandibles, (3) the records of each patient were complete.

Mathews and Ware recruited a total of 36 patients (13 male, 23 female, aged 3.6-9.1 years) who met these criteria and subsequently placed three to five tantalum implants in each of the patients' mandibles and three to five more in their maxillae.[153] Patients returned annually (for 5-14 years) for lateral and posterior-anterior cephalometric radiographs and left and right 45-degree oblique cephalometric radiographs.[153]

The inclusion criteria for the twenty-two patients selected from Mathews' original data set[153] for the current study were: (1) patient records included 3 unaltered lateral cephalometric radiographs approximately 2 years apart, during peak growth years (females 10 -14 years of age, males 12-16 years of age), (2) the lateral cephalometric radiographs exhibited at least 2 tantalum implants in both the mandible and maxilla that were retained and visible throughout all three time points, (3) radiographic records were of sufficient quality such that the implants and defined dental structures could be clearly identified.

This study was observational in nature, radiographs were de-identified prior to tracing and data collection complied with IRB and HIPPA regulations to ensure subject confidentiality. The study and sample selection methods were reviewed and exempted by the Institutional Review Board of Nova Southeastern University.

2.2. Mandibular Regional Superimposition - Analog Method

The analog tracings that were used for the structural and implant methods of superimposition were completed by an experienced orthodontist/researcher. The tracings were completed on acetate using a hand sharpened mechanical drafting pencil and were traced side by side (from T_1 to T_2 and T_2 to T_3) to maximize tracing accuracy and methodological uniformity. [114] All necessary landmarks for the implant and structural methods of superimposition were traced. Specifically, each of the metallic implants, as well as “defined dental structures” were traced. The defined dental structures included the incisal edge, root apex, and long axis of the most anterior mandibular tooth and the mesial contact, apical root bisection, and long axis of the mandibular first molar. Templates were created of the most visibly identifiable teeth from one of the three radiographs in the series for each patient and transferred to each of the tracings in the series to allow precise duplication of traced landmarks for measurement.

2.3. Structural and Implant Superimpositions

Structural superimpositions were completed according to the methods reported by Björk and Johnston.[114,120] In the mandible, this consisted of registration of tracings on the bony architecture of the facial half of the mandibular symphysis and tracing alignment on the mandibular canal and inferior border of the third molar tooth germ prior to root formation.[114,120] Fiducial lines were drawn according to Johnston's method[114] to record the structural superimpositions for each pair of time points (T_1 to T_2 and T_2 to T_3) for future reproducibility. Additionally, the fiducial lines permitted execution of precise and expeditious structural superimpositions during the digital conversion portion of this study.

Analog superimpositions (structural and implant methods) for each of the twenty-two patients for each of the paired time points (T_1-T_2 and T_2 -T3) were scanned into a digital (jpeg) format at 300 DPI[53,157] using an Epson Perfection V750 Pro Scanner (Epson USA, Long Beach, California, USA). The structural superimpositions were reproduced by alignment on the fiducial lines and the implant superimpositions were completed by best-fit registration of the mandibular implants upon one another.

2.4. Dolphin and Quick Ceph Superimpositions

All sixty-six patient radiographs (T_1, T_2, and T_3 for each of the twenty two patients) were scanned into jpeg format as described previously[53,157] (300 DPI, Epson Perfection V750 Pro Scanner). The jpeg lateral cephalometric radiographs were imported into both Dolphin Imaging v11.5 (Dolphin Imaging, Chatsworth, California, USA) and Quick Ceph Studio v3.2.8 (Quick Ceph Systems, San Diego, California, USA) digital cephalometric softwares. The anatomic landmarks necessary for mandibular superimposition were digitally traced according the instruction manuals of each respective software manufacturer. In order to standardize the subsequent measurements of defined dental structures (similar to the analog method), outlines of the most visibly identifiable mandibular central incisor and first molar were transferred across all films in the time series for each of the digital softwares.

Digital mandibular regional superimpositions were completed according to the manufacturers' instructions.[158,159] Analogous to the method employed with the analog tracings, superimpositions were completed with the digital software for each patient at each pair of time points (T_1 to T_2 and T_2 to T_3). Dolphin's automated mandibular regional superimpositions were aligned according to manufacturer recommendations namely, "For the mandible, the tracings are aligned to the Menton-Gonion (Me-Go) line, with the Menton points overlapping."[158] Quick Ceph Studio v3.2.8 automated superimposition preferences use a method similar to Dolphin, using "Corpus left-Menton@Menton."[159] Quick Ceph defines "corpus left" as "Left point of a tangent of the inferior border of the Corpus" (Shown in Figure 6).[160] Superimpositions were saved on a secure institutional server at the Nova Southeastern University College of Dental Medicine.

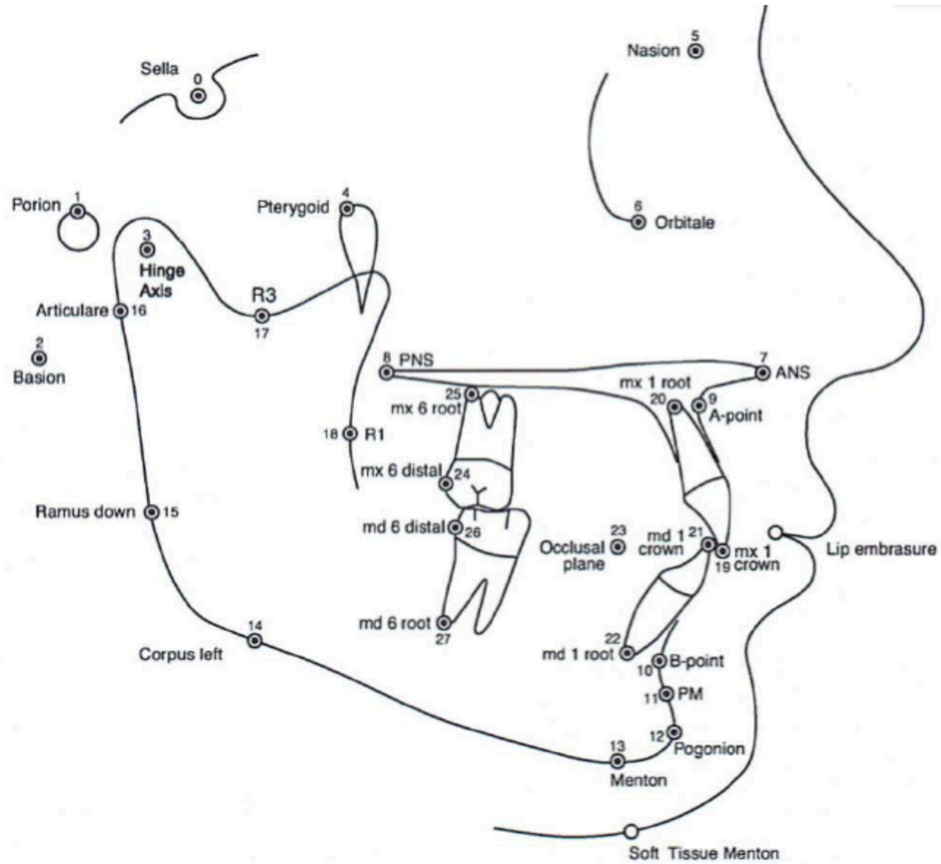

Figure 6. Quick Ceph anatomic landmarks[162]

2.5. Measurement of Displacement of Defined Dental Landmarks

Mandibular regional superimpositions resulting from each of the four methods (analog: structural and implant; digital: Dolphin and Quick Ceph) were imported into Adobe Photoshop CS6 Extended as jpeg files (Adobe Systems Inc., San Jose, California, USA). The digital images resulting from each of the respective methods were scaled using the scale properties of Adobe Photoshop CS6 Extended by calibration to known landmarks embedded in each radiograph and transferred to each digital image. The displacements of each defined dental structure were measured and total displacement and the Cartesian coordinates were recorded for each paired superimposition.

Displacement measurements were completed for a total of 176 superimpositions (twenty-two patients, each with two superimpositions for four methods). The measurements of defined dental structure displacement obtained from the tantalum implant registration method were considered the "gold standard" reference for comparison of the remaining superimposition methods. Data storage for each set of superimpositions was password protected in a Microsoft Excel Spreadsheet (Microsoft Corporation, Redmond, Washington, USA), saved on a password protected secure server.

One researcher produced each of the analog tracings utilized in this study. A random sample of ten tracings were selected and traced at a separate setting in order to independently assess intra-rater reliability. Ten Dolphin and ten Quick Ceph regional superimpositions were randomly selected and traced by the author at a separate setting to assess intra-rater reliability for the digital method.

2.6. Statistical Analysis

The study data was analyzed using a mixed-effects, generalized linear model, with robust standard errors. Mixed-effects models are used where there is correlated data. The generalized linear model was used because it does not require normality of the response variable, nor does it require homogeneity of variances. Robust standard errors are used to account for heteroscedasticity.

Descriptive statistics for mean displacement (SE) in millimeters, for each method of superimposition were calculated. The overall total displacement between each superimposition method was compared to the implant method. The mean difference (SE), upper and lower 95% confidence intervals, and p-value were calculated. Additionally, the displacement measurement of each defined dental structure for each method was compared to the displacement measurement of the same defined dental structure calculated by the implant method. The mean difference (SE) in millimeters, upper and lower 95% confidence intervals, and p-values were calculated for each defined dental structure.

The procedures described above are displayed graphically in Figure 7.

Figure 7. Workflow diagram for the study

Chapter 3: Results

3.1. Descriptive Statistics

Descriptive statistics for the displacement of defined dental structures for each superimposition method are presented in Table 1. The mean total displacements for all of the defined dental structures for implant, Dolphin, Quick Ceph, and structural methods of superimposition were 2.30 (SE: 1.36) mm, 2.31 (SE: 1.25) mm, 2.25 (SE: 1.37) mm and 2.41(SE: 1.30) mm, respectively. No difference between mean total displacement for any method compared to the implant method was greater than 0.11mm.

Table 1. Descriptive Statistics. Mean displacement (SE) in millimeters, by method of superimposition.

	Method			
Measurement	Implant Mean (SE)	Dolphin Mean (SE)	Quick Ceph Mean (SE)	Structural Mean (SE)
Total Displacement	2.30 (1.36)	2.31 (1.25)	2.25 (1.37)	2.41 (1.30)
Incisor		.	.	.
Total	1.93 (1.08)	2.18 (1.23)	2.04 (1.33)	2.17 (1.22)
Crown	1.94 (1.06)	2.23 (1.17)	2.05 (1.22)	2.16 (1.18)
Apex	1.92 (1.11)	2.14 (1.30)	2.04 (1.45)	2.19 (1.28)
Molar		.	.	
Total	2.66 (1.35)	2.43 (1.29)	2.44 (1.40)	2.64 (1.41)
Crown	2.74 (1.38)	2.46 (1.33)	2.44 (1.44)	2.68 (1.48)
Apex	2.57 (1.33)	2.40 (1.25)	2.45 (1.37)	2.59 (1.35)

3.2. Linear Contrasts

3.2.1. Linear Contrasts of Method

The linear contrasts by method are shown in Table 2. There were no statistically significant differences between any of the superimposition methods compared to the implant method.

Table 2. Overall total displacement relative to Implant method reference.

Method	Ref	Measurement difference* (95% CL)	p-Value
Dolphin	Implant	0.01 (-0.28, 0.30)	0.935
Quick Ceph	Implant	-0.05 (-0.34, 0.23)	0.728
Structural	Implant	0.11 (-0.12, 0.34)	0.356

*Measurements reported in millimeters

3.2.2. Linear Contrasts of Method by Defined Dental Structure

The linear contrasts by defined dental structure are shown in Table 3. There were no statistically significant differences between any superimposition method and the implant method for any of the defined dental structures.

Table 3. Displacement by structure relative to respective Implant method reference.

Method	Structure	Measurement difference (95% CL)	p-Value
Dolphin	Incisor Apex	-0.29 (-0.68, 0.10)	0.148
	Incisor Crown	-0.21 (-0.52, 0.09)	0.174
	Molar Apex	0.28 (-0.12, 0.68)	0.173
	Molar Crown	0.17 (-0.18, 0.53)	0.338
Quick Ceph	Incisor Apex	-0.18 (-0.40, 0.05)	0.121
	Incisor Crown	-0.10 (-0.27, 0.08)	0.271
	Molar Apex	-0.03 (-0.32, 0.17)	0.859
	Molar Crown	0.05 (-0.27, 0.38)	0.747
Structural	Incisor Apex	-0.07 (-0.32, 0.17)	0.562
	Incisor Crown	0.05 (-0.18, 0.29)	0.640
	Molar Apex	0.22 (-0.05, 0.49)	0.116
	Molar Crown	0.19 (-0.03, 0.41)	0.084

*Measurements reported in millimeters

To assess the intra-rater reliability, intra-class correlation coefficients(ICC) were calculated. The ICC for analog (p= 0.468) and digital tracing (p= 0.575) showed non-statistically significant p-values.

Chapter 4: Discussion

4.1. Purpose and Principle Finding

This study compared three methods of mandibular regional lateral cephalometric superimposition to an implant registered method.[24,120] The comparisons involved both analog (structural and implant) and digital (Dolphin and Quick Ceph) methods. In each method of superimposition studied, the displacement of defined dental structures (incisal edge and root apex of the most anterior mandibular tooth, mesial contact and apical root bisection of the mandibular first molar) was measured and compared to similar measurements obtained by the implant-registered method of superimposition. To our knowledge, this was the first study comparing analog and digital methods of mandibular regional LCS to a reference method using metallic implants. The principle finding of this study was that there were no statistically significant differences in the measurements of defined dental structure displacements conducted by the structural, Dolphin, or Quick Ceph methods compared to the implant (reference) method of mandibular regional LCS.

The mean differences in the displacement of defined dental structures compared to the implant method were as follows: for structural method mean (m) = 0.11 mm (95% confidence limits [CL] -0.12, 0.34), p =0.356, Dolphin m = 0.01 mm (95% CL -0.28, 0.30), p =0.935, and Quick Ceph were, and m = -0.05 mm (95% CL -0.34, 0.23), p =0.728. The mean displacement differences measured following superimposition by each of the three test methods were not statistically different from displacements resulting from the implant (reference) method.

The results of our study are similar to other studies that reported no statistically significant differences in the magnitude of the displacement measurements of defined dental structures between digital regional LCSs produced by computer-based programs and those produced by hand.[66,69,97] Roden-Johnson et al. compared Quick Ceph 2000 to analog regional LCSs and found no significant difference in the measured displacement of defined dental structures (all mandibular measurements were within 0.5 mm).[66] Huja et al.[69] compared Dolphin Imaging v10 to analog methods to conduct regional LCSs[69] and found the mean difference in landmark displacement was less than 1 mm for all mandibular landmarks. Huja et al. concluded that their study validated the use of Dolphin Imaging v10 for lateral cephalometric superimpositions. Bruntz et al.[97] compared mandibular LCSs using analog and Dolphin Imaging v9 techniques and found no statistically significant differences in the magnitude of the displacement measurements of defined dental structures between methods. Each of these studies was similar to the current study in that they compared digital and analog regional LCS methods and therefore, reported relative results between methods, however, none of these studies utilized implant-registered mandibular regional LCSs as a reference for comparison.

4.2. Analysis of Results

4.2.1. Power

The power of a statistical test refers to the probability of rejecting the null hypothesis when it is actually false. A post-hoc power analysis revealed that on the basis of the mean, between-groups comparison, the statistical power of the analyses utilized in this study was 0.15, which is well below the conventional 0.80 level.[161] A power of 0.15 means that there was an 85% chance that we would fail to reject the null hypothesis when it was actually false (a type II error). While the current study demonstrated no statistically significant difference between the test methods and the implant registered method, the risk of a type II error was more likely than not. The implication of low statistical power for the tests we conducted calls into question the amount of confidence we have in failing to reject the null hypothesis.

Previous studies have shown that mandibular superimposition using structural mandibular landmarks for registration and orientation of serial radiographs, as described by Björk,[10,115,125,162] was more accurate than superimposition on the lower border of the mandible.[146] Given the methodological differences in the way that the digital superimpositions were completed (i.e. orientation toward gonion or corpus left, rather than the inferior alveolar nerve and third molar prior to root formation) it was unexpected that our study demonstrated no statistically significant differences in measurements by technique. The low power of the statistical tests used to analyze our data, and a subsequent type II error, is a possible explanation for our unexpected findings.

4.2.2. Standard Error and Coefficient of Variation

The standard error (SE) is the standard deviation of the sampling distribution of a statistic. Compared to the mean implant measurement, Dolphin had a difference of 0.01mm (SE: 0.15), Quick Ceph had a difference of -0.05mm (SE:0.15), and structural had a difference of 0.11mm (SE: 0.12). The SEs, particularly for the Dolphin and Quick

Ceph methods, are large in proportion to their means, which suggests that while the mean differences were small in comparison to the implant method reference, the dispersion of the data was considerable.

The coefficient of variation (CV) is a standardized measure of the SE that permits comparison of dispersion of the measurements among the superimposition methods. The CV is the ratio of the SE to the mean, where lower CV values indicate higher precision and less variability around the mean. The CV for Dolphin was 15.0 (0.15/0.01), for Quick Ceph was 3.0 (0.15/0.05), and for structural was 1.1 (0.12/0.11). The CV values for Dolphin, Quick Ceph, and structural methods of superimposition indicate that the structural method demonstrated the most precision, followed by Quick Ceph, and finally Dolphin, which was far less precise.

The scatterplots (Figure 8-Figure 10) visually demonstrate the differences in distribution of the data resulting from measurement contrasts between each superimposition method used in this study and the reference implant method. The negative values in the scatterplots indicate measurements where the particular method demonstrated a smaller displacement than the implant method, whereas positive values indicate larger measurements than the reference. The scatterplots show a wide dispersion of data around the mean. Such wide dispersion of data suggests that while the *mean* difference in landmark displacement between any individual method and the reference (implant method) was small, there were individual measurements in each method where the difference relative to the reference method was quite large. The scatterplot representation of the data supports the quantitative description of data dispersion, i.e. CV, and the rank order observed for method precision (from highest to lowest), viz., structural method, followed by Quick Ceph method, followed by the Dolphin method.

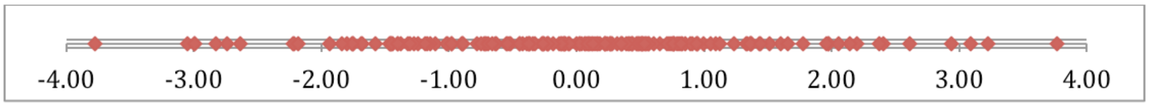

Figure 8. Scatterplot of Dolphin vs. Implant: Measurement differences in mm

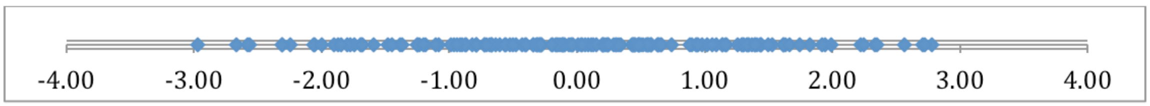

Figure 9. Scatterplot of Quick Ceph vs. Implant: Measurement differences in mm

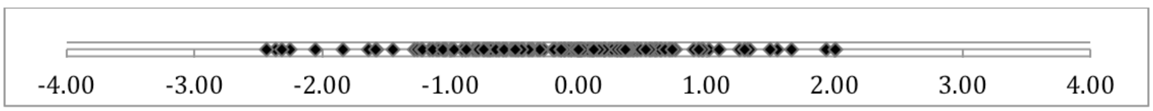

Figure 10. Scatterplot of Structural vs. Implant: Measurement differences in mm

4.3. Digital Tooth Templates

One observation obtained while using the digital cephalometric programs in this study related to the automated tracing of the defined dental structures (teeth) by the software-generated tooth templates. Tracing teeth manually, as in the structural or implant methods, permits tracing the actual anatomy of the tooth (based on the clearest radiographic image) and allows the transfer of that exact traced image from one tracing to another to obtain a clear and reproducible representation of the apical and coronal movement of that tooth in the sagittal dimension. In contrast, Dolphin created incisor and molar templates of variable length, where the width of the template was a fixed ratio in relation to the length, such that the templates that resulted may or may not be representative of the actual dimensions of the tooth being traced. Quick Ceph exhibited greater tracing discrepancies, in that it created molar and incisor templates based on the scale of the image. Quick Ceph tooth templates were often unrepresentative of the dimensions of the actual tooth, and erred by overestimating or underestimating tooth length considerably, thereby creating several issues. One issue related to placement of the digital tooth template over the radiographic tooth image when the tooth template length was inaccurate, i.e., uncertainty whether the coronal portion or the apical portion of the template should coincide with the crown or apex of the radiographic tooth image. Another issue occurred when the angular position of teeth changed between time points. For example, clinically, if a molar were to tip mesially between serial cephalograms, the radiographic appearance of the apex will generally remain in the same position. However, if the Quick Ceph produced template was shorter than the actual tooth, and the coronal portion of the template was aligned on the coronal portion of radiographic molar image, then the template molar would demonstrate a mesial translation of the root apex, thereby creating the spurious observation and measurement of root translation, when none actually occurred. Additionally, both digital methods presented ambiguities when molar teeth with marked dilacerations were digitally traced. The forced choice for the operator was between aligning the software generated tooth template either along the long axis of the radiographic tooth image or toward the root apex, neither of which are representative of the radiographic image of the tooth being traced.

4.4. Operator Error

A random sample of 10 tracings was selected and re-traced (for the analog, Dolphin, and Quick Ceph methods) at a separate setting in order to independently assess intra-rater reliability. Results of the intra-class correlation showed no statistical differences for intra-rater reliability in either the digital or analog methods of superimposition. One investigator produced all of the analog tracings (structural and implant methods) utilized in this study and a second investigator produced all of the digital tracings in this study, as such, inter-operator reliability could not be evaluated.

4.5. Clinical Significance

Clinical significance, as it relates to cephalometrics, refers to the magnitude between two cephalometric values that would cause an orthodontist to alter their patient's diagnosis, treatment plan, or any other clinical decision. Baumrind and Frantz[163] suggested that clinical significance only be ascribed to differences in cephalometric measurements that exceed twice the standard deviation of the error for that particular measurement. Compared to the mean implant measurement, Dolphin had a difference of 0.01mm (SE: 0.15), Quick Ceph had a difference of -0.05mm (SE: 0.15), and structural had a difference of 0.11mm (SE: 0.12). Applying the "double the standard deviation of the error" guideline as suggested by Baumrind and Frantz,[163] none of the differences in our study are clinically significant.

Other researchers[66,69,97] have reported no clinically significant differences in landmark displacement measurements between digital and analog methods of regional cephalometric superimposition. Huja et al.,[69] in their comparison of analog and digital cephalometric superimpositions, concluded that differences less than 1 mm would not be clinically significant. Huja et al.[69] did not provide any rationale for the decision to quantify differences <1 mm as clinically insignificant. Roden-Johnson et al.[99] compared Quick Ceph 2000 to hand (analog) tracing and provided additional support that cephalometric measurements that were within ±1 mm of each other would not be clinically significant. Roden-Johnson et al. did not specifically state why they decided that differences of ±1 mm were not clinically significant; however, they did state "this leaves clinical significance questionable because the width of the pencil used to trace the cephalograms was 0.5 mm." While these authors did not provide a literature-based rationale for the 1 mm threshold, their conclusions would agree with the "double the standard deviation of the error" suggested by Baumrind and Frantz[163] when applied to our data and that the differences found between superimposition methods and the reference method in the current study are not clinically significant.

4.6. Limitations

Three specific limitations were identified in the current study. The first limitation of this study concerns the small sample size used. Placing metallic implants in patients for the purpose of superimposition is no longer possible and there are very few existing data sets that utilize radiopaque metallic implants in cephalometry. We were privileged to have access to the Mathews Acquisition Group for this study, however, using this specific data resulted in a small sample size. The only apparent way to replicate the current study with a larger sample size would be to gain access to Björk's data,[124,125,162,164,165] however, such access is not currently possible.

A second limitation of this study was that only one of the investigators had access to the Mathews Acquisition Group data, and only that one investigator executed all of the analog tracings in this study. A second investigator completed all of the digital tracings. Although the intra-rater reliability (ICC) for each investigator within the respective domains (analog or digital) was acceptable, it was not possible to evaluate inter-rater reliability between methods. It is possible that the difference in tracing experience between the two investigators could account for some of the differences seen in data variance across the different methods of superimposition.

A third limitation of this study relates to the tracing method used in the digital superimposition portion of this study. While the defined dental structures present on the molar tracings were always bisected, the defined dental structures present on the mandibular incisor were not. The most anterior mandibular incisor was traced in every case across all three time-points in both digital methods. While this is not the standard convention in cephalometric tracing, the method was consistent throughout the digital portion of this study.

4.7. Conclusion

The results of this study demonstrate that there are no statistically significant differences in the measured displacement of defined dental structures in serial mandibular lateral cephalometric superimpositions when comparing Dolphin, Quick Ceph, or the structural method of superimposition to the reference implant method of superimposition. The mean difference in displacement of defined dental structures in comparison to the reference (implant) method was 0.01 mm, $p = 0.935$ for Dolphin, -0.05 mm, $p = 0.782$ for Quick Ceph, and 0.11 mm, $p = 0.356$ for the structural method. None of these differences are statistically or clinically significant.

In assessing the conclusions presented here, it is important to consider the high CV values for the mean difference from the reference (implant) method for each of the methods studied (Dolphin: CV= 15.0, Quick Ceph: CV=3.0, Structural: CV= 1.1). A high CV value suggests that the data are widely dispersed. This indicates that while the *mean* difference in the measurement of landmark displacement between any method studied and the reference method was quite small, many individual measurements were considerably different from the reference method (See the scatterplots in Figure 8-10). The CVs suggest that the structural method was more precise than Dolphin or Quick Ceph methods of superimposition. It is also important to consider that the power of our statistical tests was 15%, indicating that the probability of failing to reject a null hypothesis that was actually false was more likely than not, i.e., 85%. To clarify, if there really were differences between methods, there is an 85% chance that we would not have found those differences, and therefore, our confidence in failing to reject the null hypothesis is low.

Additionally, the digital software employed in this study created tooth templates with fixed height/width ratios that apparently did not accurately represent tooth size. The inaccuracy of the digital tooth templates makes the lack of statistically significant differences between methods surprising, although, as stated above, the low power of our study is a possible explanation for this. While Dolphin and Quick Ceph do not currently have options for tooth template customization, such an option would help orthodontists to improve the accuracy of their tracings.

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