

1-1-2014

# Cephalometric regional superimpositions -- digital vs. analog accuracy and precision : 3. the cranial base

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CEPHALOMETRIC REGIONAL SUPERIMPOSITIONS – DIGITAL VS. ANALOG  
ACCURACY AND PRECISION: 3. THE CRANIAL BASE.

DOUGLAS R. SHAW, D.D.S.

A Thesis Presented to the Faculty of the College of Dental Medicine,  
Nova Southeastern University in Partial Fulfillment of the Requirements for the Degree  
of  
MASTER OF SCIENCE  
February 2015  
Orthodontics

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By

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University in Partial Fulfillment of the Requirements for the Degree of  
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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.**

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Date

## **DEDICATION**

I would like to dedicate this to my wonderful wife and children who have supported me through this whole process. I could not have done this without you. I love you!

## **ACKNOWLEDGEMENTS**

I would like to acknowledge everyone who assisted me in compiling this manuscript. I could never have done this without you and sincerely thank you all for the time and energy put forth in my behalf. I specifically would like to acknowledge my mentor Dr. Singer for pushing me to limits I never knew existed. I have learned a great deal along the way and am grateful for it. I want to acknowledge my co-residents Glenn Krieger and Kevin McCaffrey for being the help and support needed to complete this manuscript. I am forever grateful to you all.

## ABSTRACT

CEPHALOMETRIC REGIONAL SUPERIMPOSITIONS – DIGITAL VS. ANALOG

ACCURACY AND PRECISION: 3. THE CRANIAL BASE.

DEGREE DATE: DECEMBER 12, 2014

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**Objective.** To assess the accuracy and precision in measurement of pairwise implant displacement across three methods of cranial base superimposition. **Background.** Cephalometric superimposition is the principal radiographic method used to evaluate changes within the craniofacial skeleton. Many studies have examined the accuracy of software intended to produce cephalometric superimposition. Such studies have utilized anatomic landmarks, selected by the respective software manufacturers, as registration points for constructing superimpositions and their analysis. As a result, these studies are only as accurate as the stability and validity of anatomic registration landmarks used. To our knowledge, no other study has utilized metallic implants to critically assess digital vs. analog cephalometric cranial base superimposition. **Methods.** Serial cephalograms from twenty-two patients across three time points containing metallic implants were obtained



from the Mathews Acquisition Group. Each of the sixty-six cephalograms was traced by hand and digitally. Cranial base superimpositions were completed according to the analog structural method proposed by Björk and Skieller, and Johnston, and then by Dolphin version 11.5 and Quick Ceph Studio V3.2.8 digital software according to manufactures instructions. Total displacement measurements of selected implants across paired time points were recorded for both digital methods and analog method of superimposition with analog serving as the reference. **Results:** There were no statistically significant contrasts of mean total displacement of implants by superimposition method ( $p = 0.999$ ). No significant differences are reported in mean implant displacement when comparing digital to analog superimposition methods for contrasts by time, structure, or implant location. **Conclusions:** The results show that there are no significant differences in accuracy and precision of digital and analog cranial base superimposition. The results of this study suggest that cranial base superimpositions on S-Na that are registered on S may be a good approximation of the structural method of cranial base superimposition. There are many methodological differences between digital and analog cranial base superimposition and future research examining such differences is recommended.

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## CHAPTER 1: INTRODUCTION

### 1.1 Cephalometry - Historical Evolution.

Man's desire for understanding stems from innate curiosity about his existence.<sup>1</sup> The human form and the nature of its perception by others has often been the center of such curiosity.<sup>2</sup> Moreover, concepts of proportion have played a vital role in mankind's interpretation of beauty.<sup>3</sup> For many centuries, artists, scientists and lay people alike have invested much thought into the constellation of features that define beauty.<sup>4</sup> The battle over whether perception of beauty is innate,<sup>5</sup> i.e., "in the mind which contemplates them,"<sup>6</sup> or as stated by Margaret Hungerford, "in the eyes of the beholder,"<sup>7</sup> or acquired has received much attention over the history of our existence.

Ancient Egyptians were likely the first to demonstrate a conceptual ideal of facial and body proportions in grid or mathematical form, though most of the earliest theories of beauty date back to the pre-Socratic period in the works of ancient Greek artists and philosophers. Sculptures such as the *Bartlett Head of Aphrodite* (Figure 1) represent the ideal facial proportions according to the ancient Greek civilization.<sup>8</sup> Phidias (circa 480 B.C.- 430 B.C.), an ancient Greek sculptor, architect, and painter during the fifth century B.C., popularized the artistic use of the 'golden' or 'divine' ratio.<sup>9</sup> The golden ratio, denoted by the Greek symbol  $\Phi$  (phi) after Phidias, is still used today and is purported to demonstrate the perfect harmony of horizontal and vertical structures.<sup>9</sup>



Figure 1-The *Bartlett Head of Aphrodite*. (about 330 B.C.)<sup>10</sup>

Historically, measurements have been used to aid the artistic representation of the human form. Leonardo da Vinci's (1452-1519; Italian) *Proportions of Man* more widely known as the *Vitruvian Man*, (Figure 2) is a blend of art and science demonstrating Da Vinci's interest in proportion.<sup>11</sup> In this artistic example of man, the proportionate human form is based on the idealistic standards of Vitruvius, a Roman author, architect, and engineer during the 1st century BC.<sup>12</sup>

Interest in facial proportions continued during the Renaissance period, when Leonardo da Vinci, demonstrated proportions of the face utilizing a grid system illustrated in the drawing of a horseman (Figure 3).<sup>13</sup> Albrecht Dürer (1471-1528), a German artist, employed coordinate systems to demonstrate different facial types; long and short, narrow or broad (Figure 4).<sup>10</sup> Da Vinci (Figure 5a) and Dürer (Figure 5b) both evaluated sagittal and vertical relationships of the face that suggest ideal proportions defining esthetically pleasing profiles.<sup>10</sup>

Petrus Camper, a Dutch physician, anatomist, and painter, introduced angular measurements of facial form in 1768.<sup>14</sup> Camper defined a facial angle that was formed by drawing a line through the “ear hole” and the “wing of the nose” intersecting a line termed *linea facialis* or facial line, drawn from the most prominent point on the forehead to the alveolar margin of the upper jaw (Figure 6).<sup>14</sup> Longitudinal measurements of this angle demonstrated the change in facial profile over time, were illustrated by Camper comparing measurements of the facial angle at infancy and adulthood.<sup>15</sup> Camper’s work was prescient for contemporary orthodontics by demonstrating a decrease in the facial angle now attributed to the normal downward and forward facial growth pattern.<sup>15</sup> However, Camper’s use of the ear hole and wing of nose was inherently imprecise and resulted in Camper’s inability to differentiate facial forms among ethnicities by employing his metric, none the less, his findings served as a foundation for anthropometric methods of ethnographic examination of facial form.



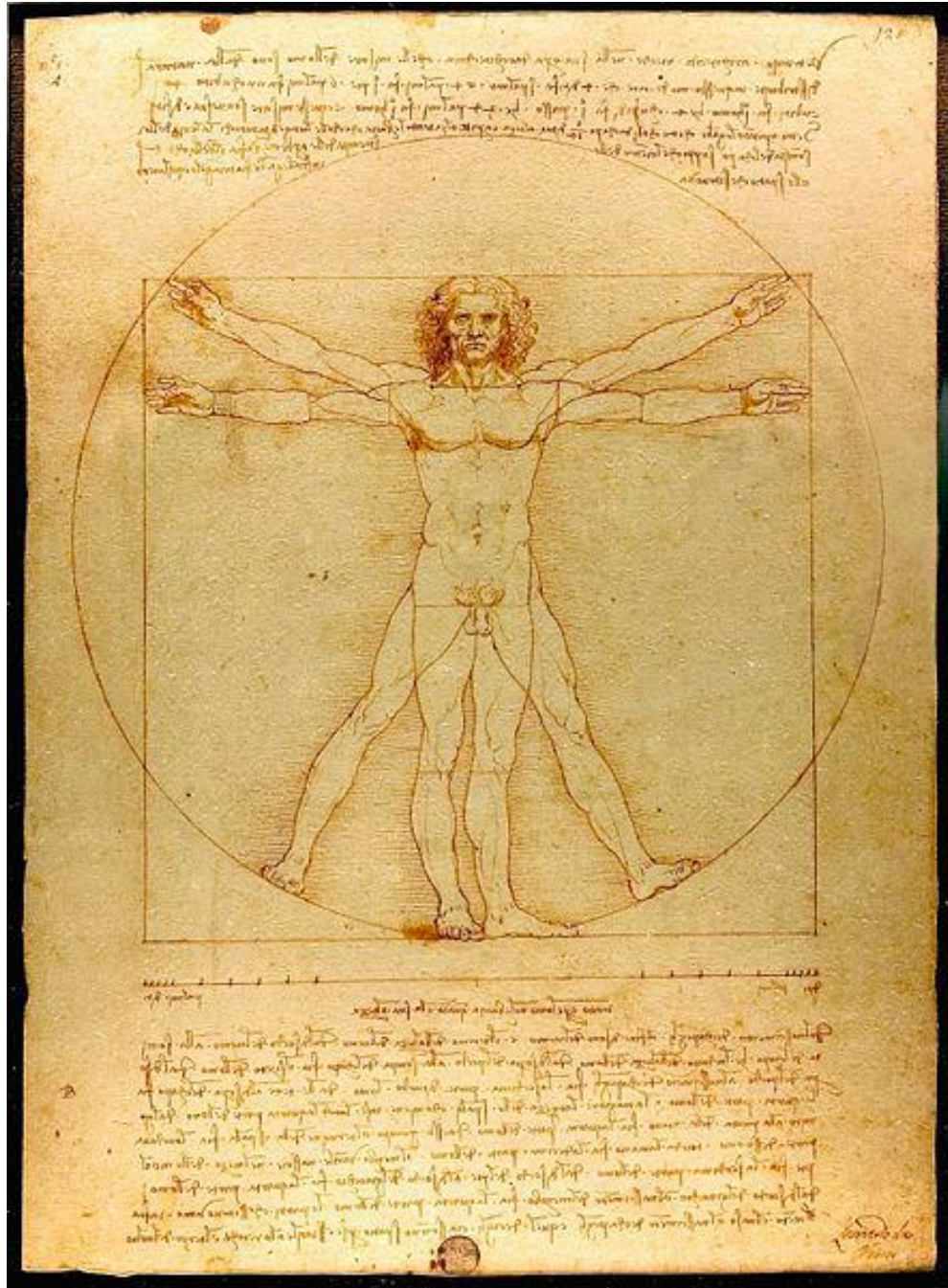


Figure 2 - Leonardo da Vinci's Vitruvian Man (ca. 1485), also known as the Canon of Proportions or the Proportions of Man.<sup>16</sup>



Figure 3 - Leonardo Da Vinci's. The Facial Proportions of Man in Profile; Study of Soldiers and Horses (c. 1490-1504).<sup>13</sup>

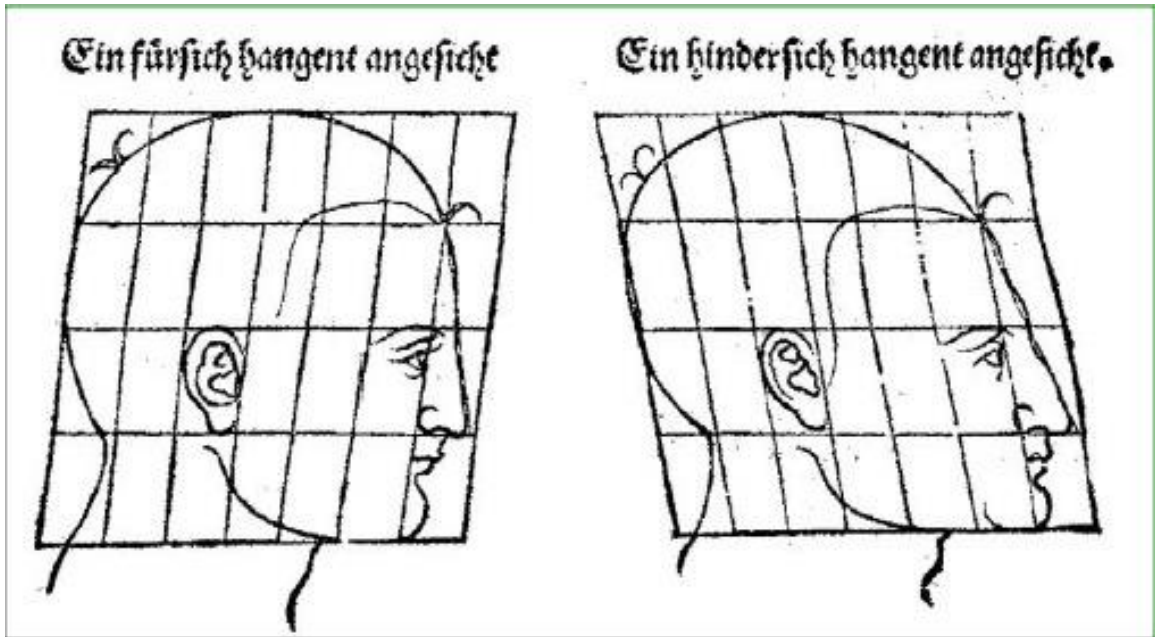


Figure 4 - Albrecht Dürer's (1528) depiction of (a) retroclined and (b) proclined facial contours from the angle formed between the vertical and horizontal axes of his coordinate system.<sup>17</sup>

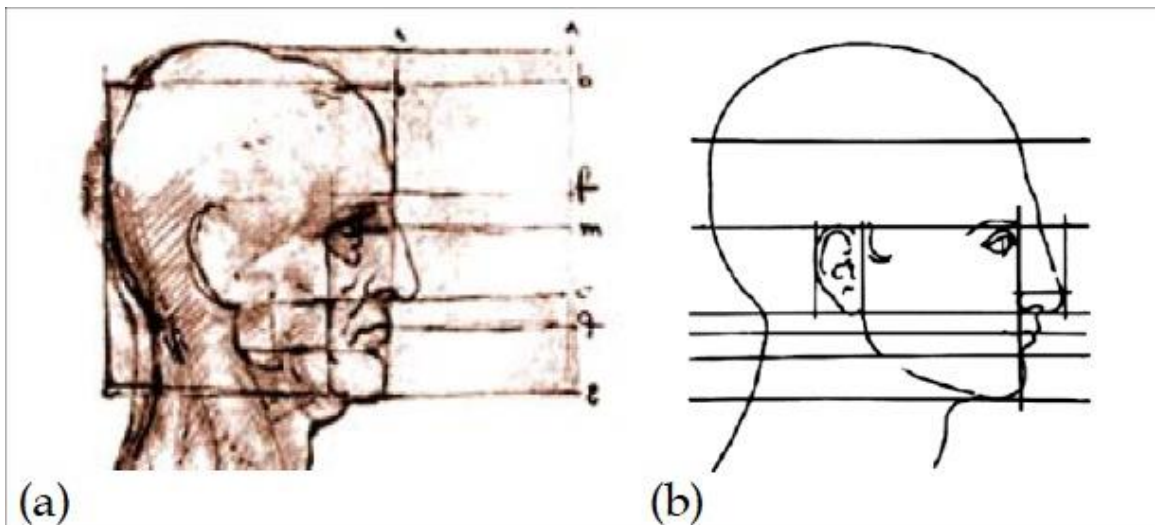


Figure 5 - Vertical and sagittal relationships of the facial profile: (a) Leonardo and (b) Dürer.<sup>10</sup>

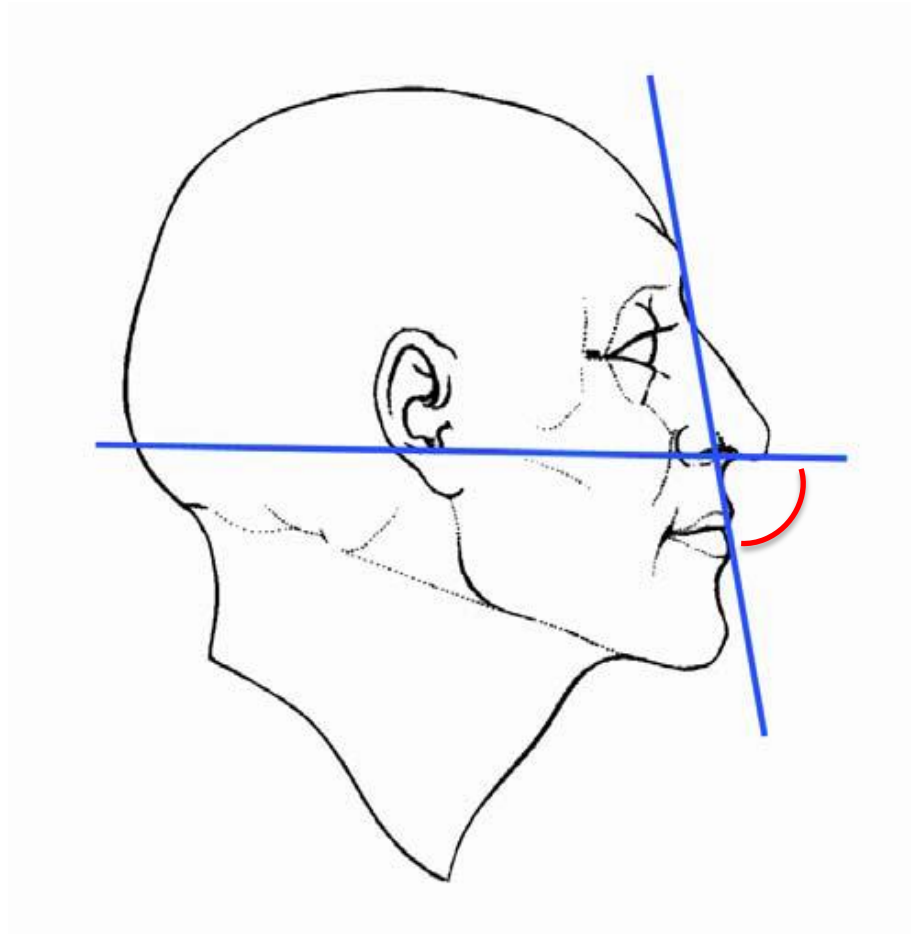


Figure 6 - Camper's facial angle (1768) illustrated by the red arc.

Following Camper's introduction of the Facial Angle, anthropologists expanded anthropometrics (comparative measurement of the size and proportion of the human body) to include study of the cranium and facial bones. The 1884 Congress on Anthropology, held in Frankfurt am Main, Germany selected a universal standard horizontal reference plane used for orientation of the head for scientific study.<sup>18</sup> The Frankfort horizontal plane, introduced by Herbert Von Ihering in 1872, became the new orientation standard for craniometric analysis. Frankfort horizontal is a plane connecting the upper border of each external auditory meatus, and the lowest point of the left infraorbital margin (Figure 7).<sup>18</sup>

Practitioners of “Cranometrics,” a subspecialty of anthropometrics, focused on comparative measurement of the skull, which necessitated the development of a device specifically designed to hold the skull in an oriented position for greater measurement reproducibility. One of the first such devices was the *Reserve Craniostat* developed by T. Wingate Todd.<sup>17</sup>

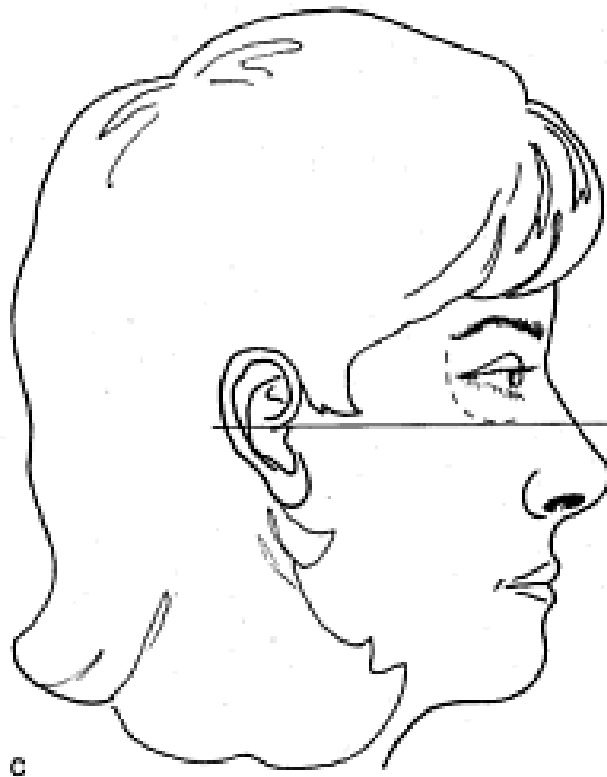


Figure 7 - Illustration of Frankfort Horizontal Plane.

The discovery of the X-ray in 1895 by the German, Wilhelm C. Roentgen, (1845-1923)<sup>19</sup> found application in anthropology, medicine, and dentistry. The Roentgen ray, a form of electromagnetic radiation termed “X-ray,” because of its unknown nature at the

time, could, for the first time, be used to produce an image of the skeleton of living subjects. Roentgen studied the phenomena accompanying the passage of an electric current (cathode ray) through a tube containing a gas of extremely low pressure. He observed that when the discharge tube was enclosed in a sealed thick black carton to exclude all light, that a paper plate covered on one side with barium platinocyanide fluoresced when placed in the path of the rays up to two meters from the discharge tube.<sup>20</sup> Roentgen's subsequent studies led him to observe that objects of different thicknesses interposed in the path of the rays showed variable transparency to them when recorded on a photographic plate. When he immobilized the hand of his wife in the path of the rays over a photographic plate he observed, after development of the plate, an image of his wife's hand which showed the shadows of the bones of her hand and that of a ring she was wearing, surrounded by the penumbra of the flesh, which was more permeable to the rays and therefore displayed a fainter shadow. The resultant image was the first "roentgenogram" (i.e. radiographic image) ever taken.<sup>20</sup>

The study of human skeletal growth and diagnosis of internal pathology of living individuals was facilitated by radiographic images. One year after discovery of the X-ray C. Edmund Kells demonstrated the use of Roentgen rays in dentistry.<sup>21</sup> Kells used X-ray images to disprove the theory of focal infection, which briefly stated, is the concept that a local infection in a small area such as the mouth, spreads microorganisms or their toxins to other locations in the body, which thereupon host secondary infections that initiate, sustain, or worsen systemic diseases. Physicians at the time were frequently prescribing extractions for all focal infections. Kells emphasized that the X-ray was to be used to

enhance the practice of dentistry and not to encourage the “mania for extracting devitalized teeth, whether good, bad or indifferent” in the name of focal infection.<sup>21</sup>

Anthropologist A.J. Pacini received an award from the American Roentgen Ray Society in 1921, for his thesis entitled *Roentgen Ray Anthropometry of the Skull*.<sup>22</sup> Pacini was the first known person to introduce a standardized technique for taking lateral radiographs of the dry skull for anthropologic purposes.

At the same time that roentgenography was maturing, orthodontists adopted craniometric measurements used in physical anthropology for orthodontic research and diagnosis.<sup>19</sup> Van Loon<sup>23</sup> applied anthropometric techniques for orthodontics by inserting oriented models of subjects’ dentition into plaster casts of their faces. Brandhorst<sup>24</sup> reported a method of superimposing oriented and scaled photographs of casts on photographs of the face. The work of early anthropologists and orthodontists provided the foundation for what was later to become roentgenographic cephalometry, that is, the radiographic study of the head and face in living individuals.

T. Wingate Todd (1885-1938), an English surgeon and anatomist, specialized in the study of human skeletal growth and development.<sup>25</sup> Todd assembled a standardized collection of skeletons of known age, race, and gender while serving as a professor of Anatomy at Western Reserve University in 1921.<sup>26</sup> The results of Todd’s studies allowed him to refine the criteria for accurately determining skeletal age.<sup>26</sup> Sponsored by the Brush Foundation, Todd collaborated with Holly Broadbent Sr. to study the magnitude and mechanisms of growth by taking radiographs on more than 4,500 children at Western Reserve University.<sup>17</sup> Todd and Broadbent’s observations resulted in standardized assessments of statural growth and development that served as a reference of “normal”.

Additional contributions by Todd were the use of radiographs of the hand for growth assessment and the development of the *Reserve Craniostat*.<sup>27</sup>

Broadbent introduced the use and application of the radiographic cephalometer to orthodontics in 1931.<sup>28</sup> Longitudinal growth studies of the craniofacial skeleton in living individuals were not possible before the development of the radiographic cephalometer. The radiographic cephalometer designed by Broadbent was essentially a craniostat modified for use on living individuals to capture radiographic images of standardized orientation and magnification of the craniofacial skeleton on film. Also in 1931, Herbert Hofrath, a maxillofacial surgeon in Düsseldorf, Germany, independently and just about simultaneously with Broadbent, developed a cephalometer and technique for acquiring standardized cephalograms with minimal distortion in order to reconstruct faces.<sup>29</sup> The advent of the cephalometer enabled application of anthropometric measurements (both linear and angular) to living individuals by using the standardized radiographic image of the skull for the purpose of diagnosis and analysis of craniofacial structures. The term cephalometry was coined to describe the study of the head and face of living subjects.

Broadbent's<sup>30</sup> first longitudinal study of cephalometric radiographs was based upon a 5-year analysis of craniofacial growth and development of more than 1,000 cases. Broadbent demonstrated "the orderly downward and forward path that is found in the developmental growth pattern of the face of the normal child."<sup>30</sup>

The Bolton-Brush Growth Study Center was established in 1970 at Case Western Reserve University and served to preserve Broadbent's records. Recall of more than 100 of the original patients for additional radiographs during the early 1980s and 2000s makes the Bolton Collection the lengthiest study of craniofacial growth and



development.<sup>31,32</sup> The most interesting finding of the recalls was that craniofacial growth continued throughout all ages of adulthood, as revealed by cephalometric measurements.

## 1.2 Superimposition

### 1.2.1 Overview

Cephalograms used for analysis are manually traced with a sharpened pencil on acetate paper overlaying the radiographic film positioned on a light-box. Linear and angular measurements can be made from the tracing for either anatomic or derived (created from the intersection of two anatomic structures) landmarks for analytic purposes. Tracing of radiographic images in a longitudinal series can then be compared. The method of comparison, known as superimposition, is accomplished by placing a tracing from one time-point atop the tracings from a second time-point in order to observe changes occurring between the two time-points.

Longitudinal (serial) cephalometric superimpositions are used to elucidate the dentofacial changes due to growth and treatment in individual patients. Serial superimposition permits determination of the location, magnitude, and direction of dentofacial changes that may have occurred. The selection of structures used to orient and register serial superimpositions is critical in order for the superimpositions to reflect the changes due to growth and development (and/or treatment) in a valid manner.

Broadbent was the first to describe a superimposition method for longitudinal studies of facial growth and development of living, growing individuals.<sup>28</sup> Broadbent studied the bones of the cranial base radiographically and concluded that, "... subsequent roentgenograms have revealed areas in the cranial base that show no change between certain ages. These areas offer a more stable base for relating our tracings and afford a

very accurate method of measuring changes in teeth, jaws, and face.”<sup>28</sup> Although Broadbent’s statement of “no change” was strictly observational it led him to propose a method for superimposition that oriented the serial radiographs on Broadbent’s interpretation of “stable areas of the cranial base,” namely sella-nasion (geometric center of the sella turcica and the intersection of the frontal bone with the two nasal bones) with registration on sella. Broadbent’s proposal to use sella-nasion was different from the other anthropologic methods presented in the literature, which used porion (the most lateral point in the roof of the bony external auditory meatus) as a stable registration point with Frankfort horizontal as the orientation plane.<sup>28</sup>

Broadbent’s 1937<sup>30</sup> publication illustrates a different method for superimposition of serial cephalograms than Broadbent originally described. Broadbent’s new method of superimposition included a line drawn from basion-nasion (basion being the anterior border of the foramen magnum) with a separate perpendicular line from tuberculum sella intersecting B-Na line. The “Registration Point” or “R” is recorded at the midpoint of the perpendicular line from tuberculum sella to B-Na.<sup>30</sup> Superimposition using B-Na with registration on “R” gave the impression that the head grows in a radial manner from the center out, relative to the cranial base. Broadbent stated, “Recent observations from the data accumulated the last seven years continue to substantiate the stability of the Bolton-nasion plane of orientation and its registration point in the sphenoidal area as the most fixed point in the head or face.”<sup>30</sup>

Considerable disagreement on the selection of structures for superimposition has resulted in a variety of proposed methods.<sup>30,33-36</sup> The *best-fit* method of superimposition involves identification of periosteal contours within the image of the facial skeleton on

the cephalogram that do not appear to change within the time frame of reference. The *best-fit* method is based on visual perception. When linear or angular dimensions of an anatomical structure appeared unchanged they were *assumed* reliable structures for orientation and registration of serial images for superimposition. The idea was that in such conditions neither deposition nor resorption was taking place on the periosteal bone surface of that contour; rather, the surface was stable and thus could be used as a reference for superimposition. De Coster's<sup>33</sup> method for anterior cranial base superimposition was based on the *best-fit* method.

Brodie<sup>34</sup> advocated Broadbent's<sup>28</sup> original use of sella-nasion (S-Na) with registration at sella (S) for superimposition of images along the cranial base. The simplicity of S-Na superimposition with registration on S led to its early adoption and popularity among orthodontists. In contrast to the *best-fit* method, Brodie's suggestion to use easily identifiable landmarks and lines to superimpose eliminates many of the technical errors introduced in visualizing and accurately tracing bony contours of anatomical structures for superimposition.<sup>37</sup>

Keith and Campion,<sup>38</sup> Björk,<sup>39</sup> and Melsen<sup>40</sup> all observed that in fact points sella and nasion were not stable relative to the cranial base, and therefore using them for superimposition produced a biased depiction of facial growth.<sup>41</sup> Ricketts claimed that using S-Na, for cranial base superimposition, did not account for any changes in the posterior part of the cranial base. In order to take into account the changes, if any, which occur in the spheno-occipital synchondrosis, Ricketts proposed a method of superimposition using the nasion-basion (Na-Ba) line, registered on a point formed by the intersection of the Na-Ba line and a perpendicular line drawn from the lower lip of the

foramen rotundum also known as pterygoid point (Pt).<sup>35</sup> Notwithstanding the refuting evidence for superimposing on S-Na, its popularity among orthodontists still persists today.

Three basic aspect of facial growth must be considered to properly interpret superimposition of the serial cephalograms.<sup>42</sup> These include: “(1) the facial composite; (2) remodeling skeletal growth; and (3) articular skeletal growth.”<sup>42</sup> The facial composite is combination of remodeling and articular skeletal growth. Keith and Campion<sup>38</sup> described the facial composite change as complex positional changes of individual growing bones and their effect on each other. Remodeling occurs via bone deposition from osteoblasts and bone resorption from osteoclasts on surfaces that are not in contact with other bones. The remodeling process determines the basic structure of the bony cortex. The use of anatomic landmarks on the surface of the bony cortex for evaluating serial cephalographs can therefore change position over time.<sup>43</sup> Articular growth, describes bony growth that takes place at the borders where the bones meet. It is difficult to discern the growth patterns of individual bones of the facial skeleton, including surface remodeling, from serial cephalometric superimpositions. It wasn't until the implant studies by Björk,<sup>44-48</sup> that stable artificial markers placed in the maxilla and mandible, afforded understanding of where surface bone deposition and resorption take place.<sup>46</sup>

Björk's contributions to the study of growth and development began with his landmark treatise “*The Face in Profile An Anthropological X-ray Investigation on Swedish Children and Conscripts.*”<sup>18</sup> Björk compared the position and movement of defined skeletal landmarks in 12 year-old boys to the analogous measurements among 21 and 22 year-old Swedish army conscripts. Björk conducted an anthropologic and

radiographic study of the variations in the pattern of maxillary and mandibular growth. Björk used linear and angular measurements to explain the affect that growth and development had on the prominence of the face in relation to the skull. The smallest change reported in linear measurement between age groups occurred at sella-nasion.<sup>18</sup> Björk suggested that the S-Na line was suitable for cranial base superimposition during adolescence.<sup>39</sup> However, subsequent studies<sup>40,41,49,50</sup> demonstrated changes in position of S and Na as a result of local remodeling around these points that led Björk and others<sup>40,41,49,50</sup> to question the precision of using S-Na when registering on S for superimposition.

### 1.2.2 Structural Method

Björk<sup>46</sup> conducted a longitudinal cephalometric growth study that included more than 200 human subjects who received tantalum implants placed in both jaws. The tantalum implants served as stable reference markers for serial cephalometric superimposition.<sup>46</sup> Björk's work provided the most accurate interpretations of facial growth available.<sup>44,47,48,51-53</sup>

Birte Melsen<sup>40</sup> conducted histologic studies of the cranial base of deceased children to better understand Björk's results. Melsen stated that the anterior part of the sella turcica demonstrated no active cellular growth activity around 5 to 6 years of age and could therefore be considered stable and should be used to register the superimposed cephalometric tracings horizontally. Additionally, Melsen observed that the cribriform plate of the ethmoid bone and the squamous part of the frontal bone were both stable, after ages 4-years and 1-year respectively, and therefore suggested that such structures could be used to orient the tracings vertically.<sup>40</sup> Melsen's histologic study provided

evidence to select the most stable anatomic reference markers to be used for cranial base superimposition. Building upon Melsen's<sup>40</sup> findings, Björk and Skieller<sup>53</sup> recommended superimposing the anterior wall of sella turcica and its point of intersection with the lower contours of the anterior clinoids, the greater wings of the sphenoid, the cribriform plate, the orbital roofs, and the inner surface of the frontal bone.

According to Johnston,<sup>54</sup> “The process of measuring skeletal and dental displacement involves, either directly or indirectly, some form of superimposition. Superimposition, in turn, consists of registration and orientation, both of which must be based on stable reference structures if the changes that we measure are to reflect only bodily displacement and not a mixture of displacement and remodeling.” Johnston<sup>54</sup> underlined the importance of accurate tracing for the purpose of superimposition by stating, “it must be emphasized that a given subject's cephalograms cannot be traced casually and independently. Rather, they must be traced at a single sitting, side-by-side, and in temporally adjacent pairs (time 1 and time 2; time 2 and time 3; etc.). Each bony detail common to the two films is traced in parallel: a line on one tracing, then the same line, executed in the same way, on the second.” Johnston<sup>54</sup> demonstrated cranial base superimpositions according to the methods of Björk and Skieller<sup>53</sup> and application of ‘fiducial lines’ (Figure 8). Fiducial lines are arbitrary lines with registration crosses on both ends and are added after each tracing has been completed. Fiducial lines are marked adjacent to cranial base, maxilla, and mandible of one tracing and transferred to the second pairwise tracing while the serial tracings are oriented and registered for the respective cranial base or regional superimposition. Fiducial lines allow a simplified way to reproduce cranial base and regional superimpositions by simply superimposing fiducial

lines rather than the corresponding reference structures. Fiducial lines also serve to illustrate the displacement of the maxilla, and mandible from the cranial base. For example, if the cranial base fiducial lines are oriented upon one another, the relative displacement differences of the other fiducial lines at the maxilla and mandible can illustrate translatory growth.<sup>54</sup> (Figure 9)

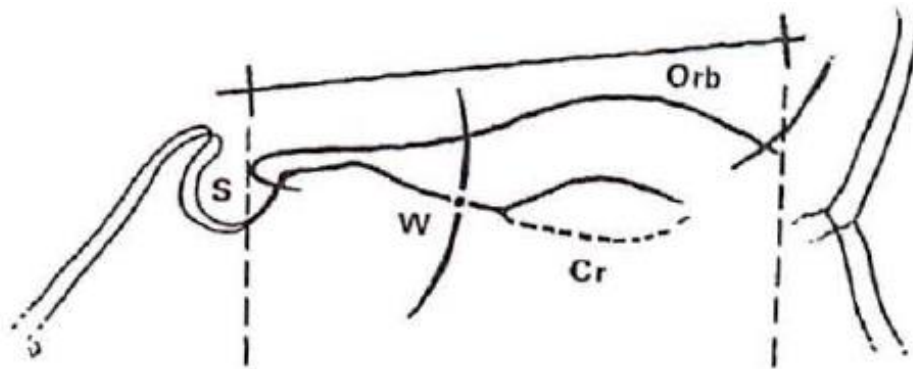


Figure 8 - The Cranial base superimposition.<sup>54</sup> Illustration of reference structures used for cranial base superimposition by Johnston.<sup>54</sup> Note the fiducial line drawn above the cranial base.

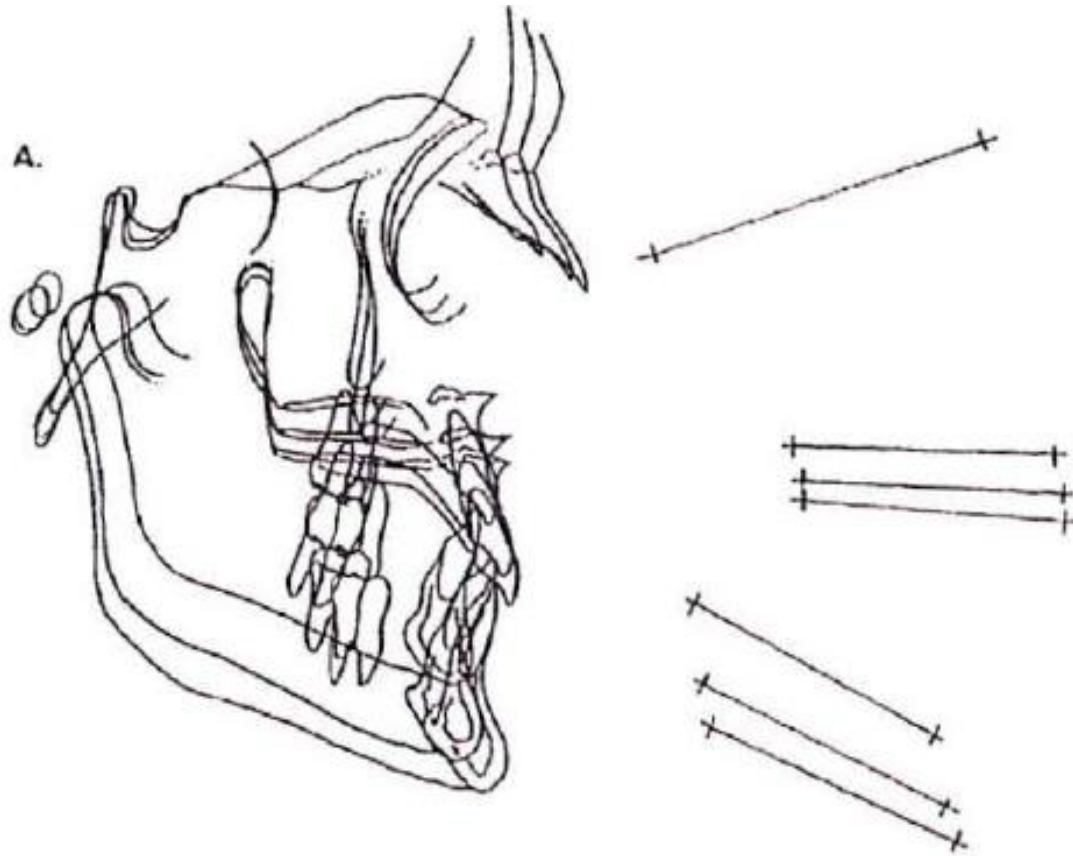


Figure 9 - Pattern of translatory growth illustrated by use of fiducial lines superimposed on cranial base.<sup>54</sup>

### 1.2.3 Regional Method

Cranial base superimpositions demonstrate overall craniofacial changes resulting from growth, and orthodontic treatment. At the level of the teeth, positional changes of the dentition assessed by cranial base superimposition are the sum of two components, namely, treatment induced changes in tooth position within each respective jaw, and changes in the position of the respective jaws relative to the cranial base. Regional superimpositions of the maxilla or mandible when constructed upon stable reference markers can demonstrate the changes in position of dental structures due to treatment alone; the act of superimposition eliminates any effect due to growth, and changes in the



surface of the jaws due to bone remodeling. Björk and Skieller used implants to identify anatomic structures that closely approximated the stability of the implants. Such anatomic structures could therefore be used as surrogates for implants for the purpose of regional superimposition, in all subjects.<sup>53,55</sup> Among the many techniques of maxillary and mandibular regional superimpositions described in the literature,<sup>56-65</sup> Johnston's<sup>54</sup> method for regional and cranial base superimpositions, distilled from the literature, is perhaps the best.

## 1.5 Radiography

### 1.5.1 Analog

Traditional analog cephalograms are characterized by continuous shades of gray, between the extremes of black and white, from one area to the next. Each shade of gray is determined by the amount of light that can pass through the image at a specific site.<sup>66</sup> Analog images are created from the arrangement of silver-halide crystals, known as the emulsion layer, on X-ray films. There is an interaction between the incident X-rays with electrons in the film emulsion that produces a latent image not visible to the eye.<sup>67</sup> The latent image formed is then made visible by processing the film in developer and fixer solutions, followed by rinsing and drying.

### 1.5.2 Digital

Digital radiography is the direct conversion of transmitted X-rays into a digital image using an array of solid-state detectors. The detector converts the energy profile of the incident X-radiation into a binary signal, which, when processed by computer graphic software generates a digital image visible on the computer monitor.<sup>68</sup> It is important to note, that in distinction to film based images, digital images can only display a finite

number of shades of grey. The first direct digital imaging system, RadioVisioGraphy (RVG), was invented in 1984 and first described in the dental literature in 1989.<sup>69</sup>

There are many advantages of digital over film-based radiography. The elimination of darkroom chemicals, reduced radiation dose, and immediate availability of the image are among them.<sup>70,71</sup> The ability to conveniently store, manipulate and enhance the image without permanent change are additional advantages of digital imaging, not possible with traditional film.<sup>71</sup>

Two main systems are primarily used in dentistry for direct digital image acquisition, the charge-coupled device (CCD) sensor and the storage phosphor (SP) image plate.<sup>71</sup> In the CCD system, the image is captured with a sensor connected to a computer and then displayed on the monitor. In the SP system, a phosphor-coated plate, which is comparable in size to film, is exposed. The plate is then scanned and the image information is sent to the computer.<sup>71</sup> The plate can be cleared and reused by exposing it to a strong light source. Both CCD and SP plate technology are known as direct digital imaging techniques.

Indirect digital imaging involves using a digital scanner to scan a radiographic film, with the resulting digital file stored on a computer hard drive, available for future viewing. When scanning film to digitize an image it is important to understand image size and quality. Scanner resolution is a representation of the scanner's enlargement capability. Scanner resolution is the measurement of the deciphering power of the scanner's optics and is expressed as dots per inch (dpi), but it is more accurately described as pixels per inch (ppi). A scanner's sensor captures an analog image by

copying it digitally line by line. The greater number of pixels per inch captured, the larger the image can be displayed by spreading those pixels out.

Digital images, whether directly or indirectly acquired, are composed of pixels. Direct digital imaging systems generally provide diagnostic quality images. Indirect digitization however, requires scanning at the proper dpi to produce a diagnostic quality image. Image resolution (dpi) is important because it can affect the ability to accurately identify anatomic structures for cephalometric analysis. Ongkosuwito, Katsaros, Van't Hof, Bodgom, and Kuijpers-Jagtman<sup>72</sup> reported that the accuracy of landmark identification on scanned cephalograms at 300 dpi is sufficient for clinical purposes and comparable to analog cephalometrics.

Computerized cephalometric systems are used in orthodontics for diagnostic, prognostic, and treatment evaluation, and their popularity has increased steadily since their introduction to the market in the 1970s. In 1992 it was suggested that about 10-15% of orthodontist in North America were using computers for diagnosis.<sup>73</sup> By 2005 that percentage increased to 40 and has continued to increase exponentially.<sup>74</sup> Technological advancements in computers and digital radiographic systems have increased demand for and popularity of software for image database management and analysis. Dolphin Imaging (Dolphin Imaging, Chatsworth, California, USA) and Quick Ceph (Quick Ceph Systems, San Diego, California, USA) are widely used imaging applications in orthodontics that allow radiographic image storage and the ability to digitally trace and perform superimposition of pairwise cephalograms.<sup>75</sup>

## 1.6 Digital Cephalometry

### 1.6.1 Challenges in Cephalometry.

Accurate cephalometric analysis depends on correct landmark identification, which in turn, depends on a quality diagnostic image. Adequate skill and experience of the clinician are essential in each step of accurately producing and analyzing cephalograms.<sup>54</sup>

Baumrind and Frantz studied many of the challenges associated with cephalometric analysis<sup>37,76,77</sup> including errors of image projection and improper head positioning. According to Baumrind and Frantz, the impact of errors in image projection on cephalometric analysis can be minimized by the use of angular rather than linear measurements. Improper head positioning can be corrected when adequate time and attention is applied while taking cephalograms.

In the first of three papers entitled “Reliability of Head Film Measurements,”<sup>76</sup> Baumrind and Frantz described the difficulty associated with landmark identification of analog films. The variability introduced by errors in landmark identification can reflect inaccurate changes in serial cephalogram evaluation. The critical importance of landmark identification in determining the validity of cephalometric measurement and interpretation of cephalometric superimposition data is evidenced by the extensive presence of this topic (referring to both analog and digital imaging) in the literature.<sup>76,78-85</sup>

Baumrind and Frantz described the potential errors associate with the use of a protractor for manual linear and angular cephalometric measurements in a subsequent paper.<sup>77</sup> Measurement errors, according to Baumrind and Frantz, could be “entirely eliminated by the simple expedient of computing the necessary linear and angular relationships algebraically, given the landmark coordinates.”<sup>77</sup> It was predicted by

Baumrind and Miller,<sup>86</sup> and Ricketts, Bench, Hilgers, and Schulhof<sup>87</sup> that the future of cephalometry would be digital.

### 1.6.2 Digital vs. Analog Superimposition

Studies evaluating the accuracy of using digital methods for cephalometric analysis have predominantly evaluated single time-point images.<sup>82,88-96</sup> An even smaller number compared the accuracy of analog and digital methods of constructing overall cranial base and regional superimpositions.<sup>83,97,98</sup>

Bruntz, Palomo, Baden, and Hans<sup>97</sup> compared hand traced cranial base superimpositions versus Dolphin Imaging v.9 generated digital cranial base superimpositions. Vertical and horizontal measurements were made from defined anatomic landmarks between paired time-points using S-Na as a reference plane. Bruntz et al.<sup>97</sup> found no statistical differences in measurements between the defined anatomic landmarks using S-Na registered on sella for superimposition in Dolphin versus analog. The results did show some distortion when the analog film was converted to a digital format. There was a 0.5% enlargement vertically and a 0.3% reduction horizontally when scanned into digital format at 150 dpi. Although no statistical differences were found in this study when evaluating cranial base superimposition it is important to understand that the “standard” for manual superimpositions is the structural method. Bruntz et al.<sup>97</sup> used S-Na with registration on sella for both methods manual versus Dolphin cranial base superimpositions.

Roden-Johnson, English, and Gallerano<sup>83</sup> compared Quick Ceph 2000 v.3.3 generated analyses to the hand-traced method in performing cranial base superimposition. Superimpositions were completed according to the American Board of Orthodontics

instructions as follows: The cranial base superimposition was “registered on sella with best-fit on the anterior cranial base bony structures (planum sphenoidum, cribriform plate, greater wing of the sphenoid).” The only measurement reported with a statistically significant difference between methods (<1mm) was the vertical displacement of nasion also reported as not clinically significant. Roden-Johnson et al.<sup>83</sup> concluded: “...there is no difference on the regional superimpositions on the mandible, the maxilla, and the cranial base, manually or digitally.” Roden-Johnson et al.<sup>83</sup> used Frankfort horizontal as the reference plane in which measurements of selected landmarks were made on a Cartesian coordinate system. A potentially important limitation of this study was the use of a non-parametric statistical analysis (Mann-Whitney) for parametric data for comparisons. Normalization of the data and use of independent *t* test may have delivered different results. Another limitation to this study is that no inter-operator reliability test was done to ensure the accuracy of landmark identification, tracing, and superimposition.

Huja, Grubaugh, Rummel, Fields, and Beck<sup>98</sup> compared the accuracy and precision of overall and regional superimpositions constructed in Dolphin Imaging v.10 to analog superimpositions. Huja et al.<sup>98</sup> found no significant differences between cranial base and regional superimpositions produced by Dolphin Imaging v.10 and those completed by hand. Huja et al. used defined anatomic landmarks as reference points to measure displacement. Using anatomy rather than implants as stable reference markers introduce the potential for false representation of landmark displacement due to surface remodeling between time points. Huja et al. reported that when comparing the digital S-Na cranial base superimposition to the digital *best-fit*, there were statistical differences when the time interval between cephalograms exceeded three years. Huja et al. used

custom settings in Dolphin to perform a *best-fit* superimposition to compare to the analog *best-fit* method. As a result, Huja et al.'s results may not be generalizable to the usual clinical practice use of the software.

The studies previously mentioned have utilized anatomic structures as references in which displacement is measured across paired time-points.<sup>83,97,98</sup> Anatomic structures have potential to incorporate error as a result of displacement by surface apposition and resorption which can lead to false measurements and assessments of changes from growth and treatment.

### 1.7 Importance of the study

Assessment of orthodontic treatment outcomes requires methods to interpret the affect of growth and mechanotherapy on the craniofacial skeleton. Cephalometric superimpositions are the principal technique in which such changes within the craniofacial skeleton are evaluated. The advent of digital cephalometry motivated many studies that have examined the accuracy of software intended to produce diagnostic and treatment outcome information.<sup>83,97-99</sup> Such studies have utilized anatomic landmarks, selected by the respective software manufacturers, as registration points for constructing superimpositions and their analysis. As a result, these studies are only as accurate as the stability and validity of anatomic registration landmarks used. Our study has taken advantage of a pre-existing data set of cephalograms of individuals in which tantalum implants were placed in the maxillae and mandibles. These implants can serve as stable reference landmarks whereby nearly absolute measurements can be made, due to the fact that such implants exhibit both dimensional and positional stability within the growing

craniofacial skeleton. To our knowledge no other study has utilized metallic implants to critically assess digital cephalometric cranial base superimposition.

## 1.8 Purpose, specific aims and hypothesis

### 1.8.1 Purpose

The purpose of this study was to evaluate whether differences exist in the magnitude of pairwise landmark displacement measurements utilizing digital vs. analog methods of cephalometric cranial base superimposition.

The intent is to assess the accuracy and precision of digital methods of cranial base cephalometric superimposition relative to the analog structural method of superimposition, while using tantalum implants as reference measurement landmarks. The results of this study should provide insight into the capabilities and limitations of digital cephalometry generally and digital cranial base superimpositions specifically.

### 1.8.2 Specific Aims

The specific aims for this study focus on assessing the accuracy and precision of cranial base superimposition of serial cephalometric radiographs constructed by two prevalent digital software programs compared to analog cranial base cephalometric superimposition. This study will utilize cephalometric radiographs from the Mathews Acquisition Group<sup>100</sup> taken of patients with Björk type tantalum implants<sup>46</sup> placed in the maxilla and mandible, and used as stable reference landmarks for measurement of displacement of the maxilla and mandible between two series of cranial base superimpositions, each across two paired time points (i.e. T<sub>1</sub>-T<sub>2</sub> and T<sub>2</sub>-T<sub>3</sub> superimpositions). Total implant displacement across paired time points will be recorded for both digital methods and analog method of superimposition. The analog structural



method as described by Björk and Skieller,<sup>52</sup> and Johnston<sup>54</sup> will serve as the reference. As such, this study aims to assess the accuracy and precision of each digital software program in constructing cranial base superimpositions compared to the analog method as described. The cephalometric software programs will include Dolphin v11.5 (Dolphin Imaging, Chatsworth, California, USA), the most widely used Windows-based cephalometric software, and Quick Ceph v3.2.8 (Quick Ceph Systems, San Diego, California, USA), the most widely used Apple Mac OS X-based cephalometric software.

Numerous studies comparing digital to analog cephalometrics exist,<sup>72,80-83,89-92,101-103</sup> however, to our knowledge, this is the first such study to utilize metallic implants to assess accuracy of digitally constructed overall cranial base superimpositions. This study utilizes tantalum implants as landmarks as opposed to anatomic landmarks utilized in previous studies.<sup>83,98,99</sup> The tantalum implants are not subject to changes in morphology or position due to the physiologic changes during growth or treatment across time points. Rather, they exhibit dimensional and positional stability and serve as optimal referential landmarks.

### 1.8.3 Hypothesis

Ho: The null hypothesis is that there are no differences in the magnitude of pairwise implant displacement measurements across methods of cranial base superimposition.

Ha: The alternative hypothesis is that there are differences in the magnitude of pairwise implant displacement measurements across methods of cranial base superimposition.

## 1.9 Location of Study

The design and preparation of this study took place at: Nova Southeastern University  
College of Dental Medicine South University Drive Fort Lauderdale, Florida 33328

## **CHAPTER 2: MATERIALS AND METHODS**

### **2.1 Study Design**

This study utilized pre-existing cephalometric radiographic records from the Mathews Acquisition Group.<sup>100</sup> These records are curated by the Craniofacial Research Instrumentation Laboratory (CRIL) at the University of the Pacific, Arthur A. Dugoni School of Dentistry Department of Orthodontics, 2155 Webster Street, Suite 617 San Francisco, CA 94115. Dr. J. Rodney Mathews while at the University of California, San Francisco, originally collected this data between the years 1967 and 1979.<sup>100</sup> As stated by Dr. Mathews, “It was the first and only long-term U.S. study of growing children with metallic implants.” Dr. Mathews selected patients for his study that were examined, had complete orthodontic records, and whose parents were willing to sign a consent form for implant placement. Three to five tantalum implants, of the Björk type,<sup>46</sup> were then placed in both the maxilla and mandible of each subject. Cephalometric radiographs were then taken annually on the selected patient sample from 7 years of age to 18 years of age.<sup>100</sup>

Dr. Richard Singer (Director MSCDM Program, Associate Professor for the Department of Orthodontics at Nova Southeastern University, Davie, FL.) accessed the Mathews Acquisition Group radiographs, with permission from the Craniofacial Informatics Laboratory and exemption after review of the Nova Southeastern University IRB, to select the subject cephalometric radiographic records for this study. The following inclusion criteria was used to select the sample for this study from the thirty-six patients that comprise the Mathews Acquisition group: (1) radiographic resolution and quality to permit consistent and reliable landmark identification, (2) at least two implants remaining in both the maxilla and the mandible across included time points, and (3)

radiographic records of male subjects encompassing the ages 12, 14, and 16 years;  
radiographic records of female subjects encompassing ages 10, 12, and 14 years .



Figure 10 - Arrows pointing to tantalum implants present in maxilla and mandible on a lateral cephalometric radiograph.

## 2.2 Tracing and Analog Cranial Base Superimposition

The radiographic records of twenty-two subjects comprise the sample for this study. All landmarks and structures needed for cranial base superimposition were identified and traced with a 0.3 mm drafting pencil on tracing acetate for each patient (according to the respective age time-points above). The outlines of implants in both maxilla and mandible were also traced. (Figure 11) Tracings for each time point ( $T_1$ ,  $T_2$ ,

T<sub>3</sub>) were constructed side by side in a dark room under magnification to decrease chance of error in landmark identification. Overall cranial base superimpositions using T<sub>1</sub>-T<sub>2</sub> and T<sub>2</sub>-T<sub>3</sub> for each patient were then constructed with the tracings using the structural method described by Björk and Skiller,<sup>53</sup> and Johnston.<sup>54</sup> (Figure 12) The landmarks used for structural superimposition were “the anterior wall of sella turcica (and its point of intersection with the lower contours of the anterior clinoids), the greater wings of the sphenoid, the cribriform plate, the orbital roofs, and the inner surface of the frontal bone.”<sup>54</sup> Fiducial lines were recorded adjacent to the cranial base on each tracing for ease of superimposition replication as described by Johnston.<sup>54</sup>

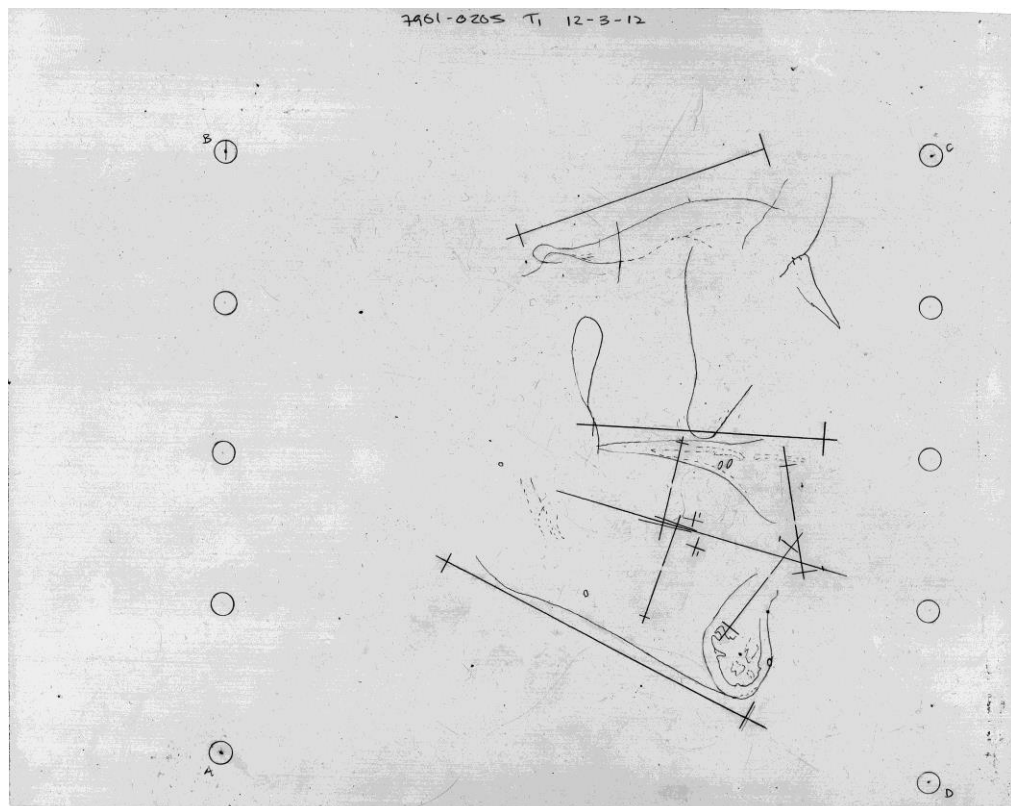


Figure 11 - Analog tracing with selected implants outlined in maxilla and mandible.

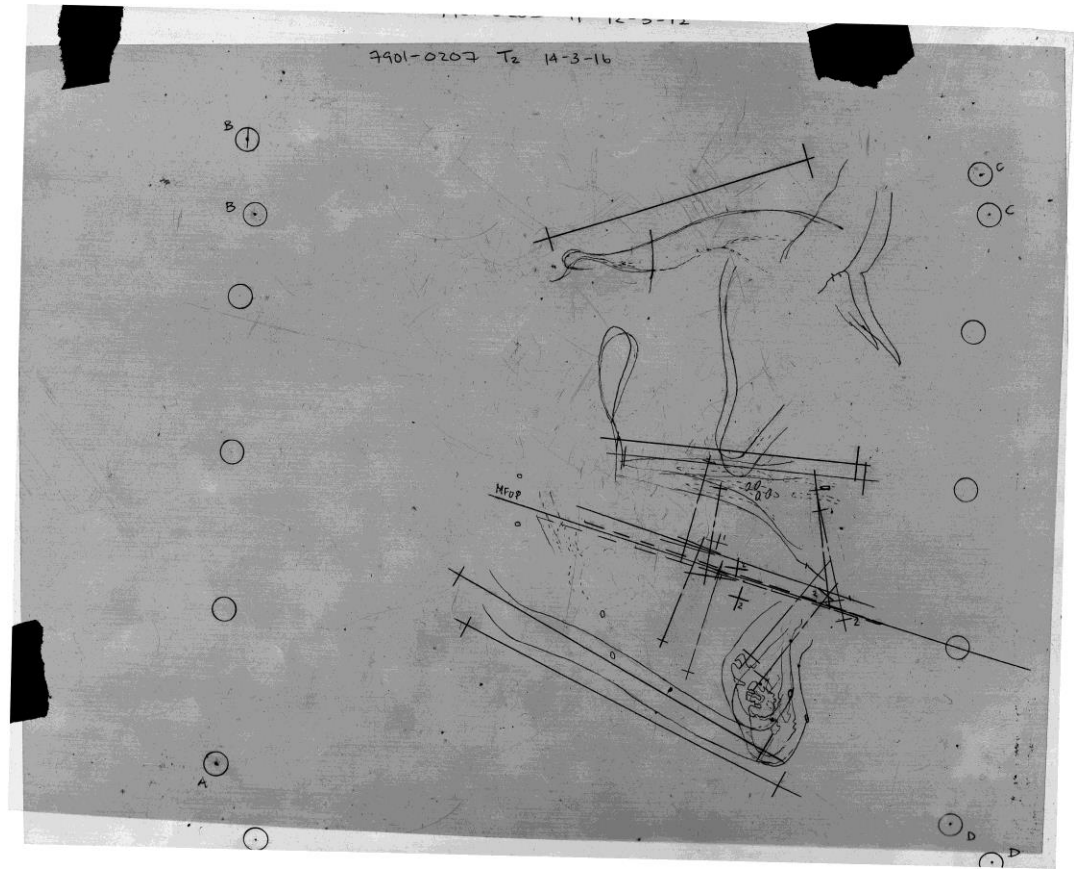


Figure 12 - Analog structural superimposition of cranial base.

### 2.3 Digital superimposition

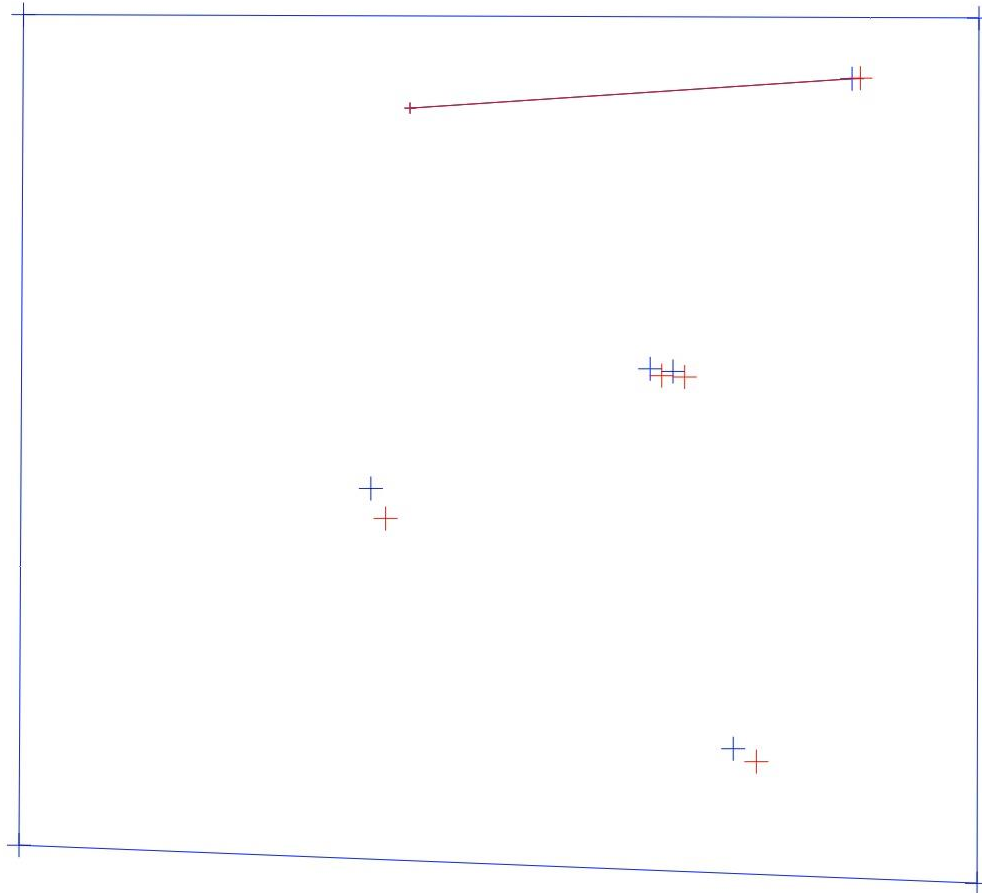
The sixty-six cephalometric radiographs were scanned into digital jpeg format at 300 dpi<sup>104</sup> using an Epson V750-M Pro Perfection Scanner (Epson USA, Long Beach, California, USA). These images were imported into Dolphin Version 11.5 and Quick Ceph V3.2.8, the most current versions available at the time of this study. Tracings and cranial base superimpositions ( $T_1$ - $T_2$ ,  $T_2$ - $T_3$ ) for each patient were executed using S-Na with registration on S. (Figure 13-14) Superimposition along S-Na with registration on S is according to manufacturers default settings in Dolphin. By default, the first superimposition displayed in the main window for Quick Ceph comparisons show the full

lateral tracings superimposed on a pre-specified landmark parallel to pre-specified lines. To keep the digital methods consistent S-Na registered on S was selected for Quick Ceph superimpositions. The customized landmark settings in each program were used to record the implant positions and fiducial markers on each digital tracing.



Figure 13 - Dolphin cranial base superimposition (T1-T2) using S-Na registered on S. Implants and fiducial points are registered using color coded cross hairs to indicate time-point. (T1, T2, T3)

### Sella-Nasion@Sella (Auto)



T2  
T3

Figure 14 - Quick Ceph cranial base superimposition (T2-T3) using S-Na registered on S. Implants and fiducial points are registered using color-coded cross hairs to indicate time-point. (T1, T2, T3)

#### 2.4 Implant Displacement Measurements

All superimpositions were subsequently exported from each software program as a digital jpeg file and imported into Adobe Photoshop CS5 (Adobe Systems Inc, San Jose, California, USA). The analog superimpositions, previously completed by Dr.



Singer, were scanned into digital jpeg format at 300 dpi<sup>104</sup> using the same Epson V750-M Pro Perfection Scanner as above and imported into Photoshop as well. All images in Photoshop were then calibrated using the software's scale tools.

Pairwise implant displacement measurements across each method of superimposition (Structural, Dolphin, and Quick Ceph) were calculated using the ruler tool in Adobe Photoshop. Measurements of pairwise implant displacements from the structural superimposition method served as reference for comparison.

All of the measurements were recorded on a Microsoft Excel (Microsoft Corporation, Redmond, Washington, USA) spreadsheet and stored on the secure Nova Southeastern College of Dental Medicine server.

## 2.5 Statistical Analysis

A mixed-effects, generalized linear model [GLM] (Gaussian family with an identity link function), with robust standard errors was employed as the method of statistical analyses in assessing differences in measured implant displacements across superimposition methods. In this manner our study aimed to assess the accuracy and precision of current digital methods of overall cranial base superimposition relative to the analog structural method.

## 2.6 Reliability

In order to assess intra-rater reliability for the measurements utilized in this study, the entire tracing, superimposition, and measurement process was repeated on a set of 10 randomly selected records from the sample for Dolphin and Quick Ceph and an interclass correlation coefficient was calculated (ICC).

Figure 15 - Flow chart for materials and methods.



### CHAPTER 3: RESULTS

Table 1 presents the descriptive statistics, by study variable, of the overall mean displacements of implants measured. The largest difference in mean displacements between analog and digital superimposition methods was found between Quick Ceph (mean (M) = 4.07mm, standard deviation (SD) = 3.03mm) and Structural (M = 4.04mm, SD = 3.01mm). Ranges were of larger magnitude for each of the digital methods compared to analog.

Table 2 displays the descriptive statistics of mean displacements by superimposition method across each variable. No patterns were observed for means of measured displacements by method across variable. The standard deviations accompanying the mean measured displacement of implants for every variable were smallest for the Dolphin superimpositions.

Table 3 presents the linear contrasts of mean displacement by superimposition method and the 95% confidence interval for each contrast. There were no statistically significant contrasts of mean total displacement of implants by superimposition method ( $p = 0.999$ ). The results for mean total displacement of implants suggest there are no significant differences between analog and digital methods used in constructing cranial base superimpositions.

Tables 4-6 present the linear contrasts, p-values, and 95% confidence intervals for the variables, time ( $T_{12}$ ,  $T_{23}$ ), structure (maxilla, mandible), and implant location (posterior, anterior), respectively. No significant differences are reported in mean implant displacement when comparing digital to analog superimposition methods for contrasts by time, structure, or implant location. The results from evaluating the linear contrasts by

individual variable provide additional support to the overall finding that no significant differences were demonstrated between measurements produced as a result of the analog and digital methods superimpositions.

The intraclass correlation coefficient (ICC) calculated independently to evaluate intra-rater reliability for the analog and digital tracing were: analog (structural) method 0.33,  $p=0.468$ , Dolphin 0.99,  $p=0.999$ , and Quick Ceph 0.82,  $p=0.810$ , respectively. The ICC's calculated were a measure of operator consistency and demonstrated the operators' ability to execute the cephalometric tracings in a reproducible manner across all methods. Note that the ICC reported for analog tracing was not derived directly from this study, but from a parallel study of regional superimpositions with repeated tracings available for ICC calculation.

## CHAPTER 4: DISCUSSION

The specific aims for this study focused on assessing the accuracy and precision of cranial base superimposition of serial cephalometric radiographs constructed by two popular digital software programs compared to an analog method of cranial base cephalometric superimposition. To our knowledge, this is the first study to assess the accuracy between digital and analog methods of cranial base superimposition by using the displacements of metallic implants (placed in maxillae and mandibles of sample subjects) measured across paired superimposed cephalograms.

The results from this study suggest that there was no significant difference in accuracy between the digital methods (Dolphin, Quick Ceph) and the analog (structural) method of cranial base superimposition. These findings are consistent with the available literature on this topic.<sup>83,97,98</sup> Tables 4-6 demonstrate that pairwise implant displacement contrasts measured across each variable (time, structure, and implant location) for analog and digital cranial base superimposition methods were not statistically significant.

Critical assessment of orthodontic treatment outcomes requires a methodologically accurate technique to accurately interpret clinical changes in dental and skeletal relationships occurring over time, as demonstrated by serial cephalograms. Baumrind et al.<sup>37</sup> described two approaches for assessing such changes over time, i.e. individual and superimposition methods. The individual method for a given patient requires that specific measurements are acquired individually from each serial cephalogram between two relevant time points and the differences between like-measurements are taken as a measure of between time-point changes. The superimposition method requires placement of the tracing of a cephalogram from one

time-point upon the tracing of the cephalogram from the second time-point by registering both tracings on anatomic structures or reference planes in a valid manner. The superimposition method then visually demonstrates the changes occurring between the two time-points (presumably due to growth and/or treatment) that can be measured directly from the superimposed images.

In a recent systematic review of the literature on growth of the anterior cranial base, the finding that the cranial base as whole was not stable, was consistently reported.<sup>105</sup> “Sella turcica remodels backward and downward, and nasion moves forward because of the increase in size of the frontal sinus. This leads to a continuous increase in the length of the cranial base from birth to adulthood.”<sup>105</sup> Afrand, Ling, Khosrotehrani, Flore-Mir, and Langravere-Vich also reported, “The presphenoid and cribriform plate regions can be considered stable after age 7, making them the best cranial-base superimposition areas.”<sup>105</sup> Afrand et al.<sup>105</sup> suggested support, after a thorough review of the literature, for the use of the structural method as proposed by Björk and Skieller<sup>53</sup> and Johnson<sup>54</sup> as the best technique for cranial base superimposition.

Although popular, digital software designed for cephalometric analysis contains many limitations in constructing cranial base superimpositions. One limitation is the inability, employing the standard settings in both digital softwares used in this study, to intimately trace bony outlines of cranial base structures known to be stable over time and thereby generate accurate cranial base superimpositions on those structures. The standard or “auto” cranial base superimposition settings in both Dolphin 11.5 and Quick Ceph v3.2.8 utilize reference planes e.g., S-Na, as opposed to the structural method of

superimposition, wherein tracings are superimposed on anatomic cranial base structures known to be stable.

In order to provide information from this study that would most represent conventional use of the digital softwares, we followed the respective manufactures recommended settings in constructing digital cranial base superimposition along S-Na that are registered on S, for both digital methods. The fact that the findings of the present study demonstrated no statistically significant differences between superimposition methods may suggest that cranial base superimpositions on S-Na that are registered on S (i.e., digital methods), are a close approximation to structural method of cranial base superimposition.

Huja et al.<sup>98</sup> compared the computer-generated S-Na superimposition in Dolphin 10 to a digital structural superimposition that required the use of the custom structure and free-form features of the software package. Huja et al.<sup>98</sup> reported differences between the two digital methods of superimposition, especially when the time between serial cephalograms increased. The differences were predominantly found in subjects whose treatment duration was more than 3 years. Such findings may be attributed to the changes that occur in the frontonasal area of the cranial base. The serial cephalograms selected for our study were dated approximately 2 years apart, therefore, the expectation was that errors attributed to the time interval between serial cephalograms and cranial base superimposition using S-Na should have been minimized, according to observations of Huja et al.<sup>98</sup>

The analog cephalograms from the Mathews acquisition group and corresponding analog tracings required indirect digitization i.e., scanning, in order to be used for this

study. Bruntz et al.<sup>97</sup> showed that when analog cephalograms were scanned at 150 dpi, a vertical enlargement of 0.5% and horizontal reduction of 0.3% occurred, however, the authors were unable to identify the source of distortion (i.e. dpi, scanner type, measurement tool). Ongkosuwito et al.<sup>72</sup> reported that scanning at 300 dpi is sufficient for clinical purposes and comparable to analog cephalometrics. Ongkosuwito et al.<sup>72</sup> took cephalometric radiographs of 20 patients at the start (T1) and end (T2) of treatment. Twenty-four cephalometric variables were selected and measured at T1 and T2 on each analog cephalogram and then measured again digitally, after scanning each cephalogram at 300dpi and 600dpi. Reliability coefficients and the total error between the digital and analog methods were compared and the results suggested that not only were cephalograms scanned at 300 dpi comparable to the analog method, but also, there was no additional advantage when images were scanned at 600 dpi. The cephalograms in this study were scanned at 300 dpi following the conventions in the literature.<sup>72</sup> A significant incidental finding of this study was an observed discrepancy in accurately setting the measurement tool in Photoshop.

The measurement tool in Photoshop uses a pixel-based calibration of a known distance on the image to set the scale for successive measurements. When we attempted to calibrate the superimpositions in Photoshop we found errors that exceeded 1.5% in some cases. We used known distances between fiducial punch holes registered in each corner of the cephalogram to set the measurement scale and found errors in the vertical dimension when we calibrated and oriented horizontally. Conversely, when we used the vertical fiducial punch holes to orient and set the scale, errors were observed in horizontal measurements. Possible explanations for this incidental finding include distortion of the



original cephalograms and analog superimpositions during the digitization process i.e., scanning, or inherent errors with the “measurement scale” tool in Adobe Photoshop.

In order to account for the observed measurement discrepancy, a correction factor was applied to the raw data. The diagonal measurements across fiducial punch holes in each corner were recorded for 10 cephalograms for each method, and a ratio (scale) correction factor calculated based upon the known distances. The correction factors (which differed by less than a factor of  $10^{-5}$  millimeters) were averaged among the 10 measurements. The computed mean correction factor was then used to adjust the raw data. The adjusted data was used for all statistical analyses.

Orthodontics, like all clinical disciplines, must come to terms with understanding how to translate research findings into the clinical realm. The concept of clinical significance serves as a useful construct as it relates to cephalometric measurements. One can clearly consider a point, beyond which, when the magnitude of a cephalometric measurement exceeds a given value, that it alters decisions relative to diagnosis and/or treatment planning. Baumrind and Frantz<sup>77</sup> defined “clinical significance” related to cephalometric radiography as the threshold at which one can correctly attribute cephalometric changes to treatment or growth effects rather than landmark identification error alone. Baumrind and Frantz examined estimating errors for identification of lateral cephalometric landmarks and were the first to propose a threshold for clinical significance: “It seems obvious that for the observed difference to be considered real (that is, biologic) it must exceed by a consequential margin the measurement error for that measure. Only then can one say with reasonable certainty that the observed difference is real and not simply the product of estimating errors.”<sup>77</sup> Baumrind and Frantz suggested

that the aforementioned threshold for determining when a cephalometric measurement difference is “real”, (i.e. clinically significant), is best determined when the difference exceeds two standard deviations for said measurement.<sup>77</sup> Baumrind and Frantz stated, “This is not an unreasonably rigorous demand, particularly when we remember that in each comparison there are two estimations made and hence two opportunities to err.”<sup>77</sup> The following example illustrates this concept; consider measurement of the ANB angle from two serial cephalograms of a given patient. If each measurement is different, a guideline is necessary to determine if the observed change is biologic, i.e., from growth and/or treatment, or due to measurement error. According to Baumrind and Frantz,<sup>77</sup> if measured difference was greater than 2 times the standard deviation of ANB, then the change could be considered biologic (i.e. “real”) and not due to measurement error. At the time that Baumrind and Frantz suggested the threshold for clinical significance of two standard deviations, advanced cephalometric computing was not available. Baumrind and Frantz recognized however, that with modern computer technology utilizing coordinate systems on which landmarks are plotted: “...we would have markedly sharpened the cutting edge of our measuring instrument and would be able to ascribe biologic significance to observed changes half the size of those we can properly consider significant at present.”<sup>77</sup> Considering the advanced digital technology used in our study, it may be appropriate to set one standard deviation outside the reference mean (i.e., structural) as an appropriate measure of significance. The magnitude of the measures of mean pairwise implant displacement across the variables used in our study (method, time, structure, implant location) did not exceed one standard deviation of the reference method (structural) measurement means.

Others have suggested  $\pm 1\text{mm}$  as a clinically acceptable level of error in landmark identification.<sup>83,88,91,106</sup> McClure, Sadowsky, Ferreira, and Jacobson<sup>106</sup> found statistically significant differences between digital and analog landmark identification in both X and Y coordinates for 3 of the 19 landmarks identified in their study. McClure et al. concluded, “These statistically significant differences, as well as those found to be not statistically significantly different, were all below 1mm, indicating that even the statistically significant differences between the two methods of image acquisition were unlikely to be of clinical significance.”<sup>106</sup> Liu, Chen, and Cheng<sup>88</sup> stated, “In practice, a landmark location with an error below 1mm is considered a precise measurement.” In no instance did the mean implant displacement across each variable (method, time, structure, implant location) in our study exceed  $\pm 1\text{mm}$  from the reference method.

The statistical power of tests performed was low due to the relatively small sample size for the mixed-effects, generalized linear model analyses employed in the present study (N = 175 for global analyses and less for component analyses). A post-hoc power analysis revealed that on the basis of the mean between group contrasts the power of the analyses was 49%. Power informs the probability of rejecting the null hypothesis when it is in fact false, and the low power found in our analyses necessarily calls into question the decision to do so. Additionally, an increase in the power could inform whether failure to reject the null hypotheses of no difference in pairwise contrast of implant displacements by method tested in this study was in fact a correct decision or if actual differences do exist between digital and analog method of cranial base superimposition. Although, an increase in the sample size could help to obtain statistical power at the conventional 80% level,<sup>107</sup> the Mathews database used for this study is the

only one of its kind readily available, and so the prospect of replicating the current study with a larger sample size does not appear possible.

A limitation of this study was the inability to obtain an intraclass correlation coefficient (ICC) for the analog method of cranial base superimposition. The ICC is a descriptive statistic that can inform intra-rater reliability. For this study it describes how consistently each rater could reproduce tracings. The original intent at the inception of the analog-tracing portion of this study was to examine maxillary and mandibular regional superimpositions and not cranial base superimpositions. Therefore, randomly selected re-tracings of the cranial base were not completed. The two originally intended parallel studies of the same analog tracings to evaluate regional superimpositions were conducted at the same time and repeated tracings in each were available. ICC from each of the parallel studies was not significant. It is reasonable to assume that the accuracy and precision at the regional level for each of the tracings was equivalent at the cranial base, particularly given the common detailed methods applied to each study. Separate operators performed the analog and digital tracing used in our study. The results could be better interpreted if inter-rater reliability tests had been performed. Due to the time, funding, and location of the Mathews implant database, obtaining the data to retrospectively perform inter-rater reliability tests was not possible.

Although the current study cannot be replicated with a larger sample, if one researcher had completed all tracings for all methods, the ability to compare the tracing reliability between the analog and digital tracings would have been a positive methodological improvement. Additionally, a reference line on the cranial base such as S-Na, used to orient a Cartesian coordinate system would have allowed pairwise implant

displacement to be evaluated along both the horizontal and vertical dimensions and provided greater detail in describing accuracy and precision of serial measurements. Historically, alternative reference planes for cranial base superimposition (e.g., Na-Ba) have been reported.<sup>108</sup> Future studies utilizing our data set of cephalograms could be designed to evaluate the accuracy and precision of alternative methods of cranial base superimposition (e.g., Na-Ba), and use the structural cranial base superimpositions generated in our study as a reference.

Notwithstanding the limitations previously discussed, the results of our study indicated that measurements resulting after digital and analog methods of cranial base serial superimposition demonstrated no statistically significant differences. Moreover, particularly in light of the suggestions of Baumrind and Frantz,<sup>77</sup> all three methods employed were well within the limits of accuracy and precision required for application in clinical use.

## CHAPTER 5: CONCLUSIONS

The results of this study show that there are no significant differences in accuracy and precision between digital and analog cranial base superimposition. Both digital methods (Dolphin, Quick Ceph) show a mean displacement of measured implants within .03mm of the mean analog implant displacements.

The results of this study suggest that cranial base superimpositions on S-Na, which are registered on S, are a close approximation of the structural method of cranial base superimposition. The use of implants for pairwise measurements and resultant findings provide valuable support to the existing literature recommending the use of S-Na registered on S as a valid method for cranial base superimposition.

The low power of this study (49%) would indicate the need for a larger sample size thereby potentially increasing the interpretive and inferential value of the results.

There are many methodological differences between digital and analog cranial base superimposition (e.g., accurate reproduction of anatomic structures, etc.) and future research examining such differences is recommended.

## TABLES

Table 1. Descriptive Statistics – Overall measured displacements (mm)

Variable		Mean (SD)	Range (Min, Max)
<b>Method</b>	Structural	4.04 (3.01)	16.48 (0.00, 16.48)
	Dolphin	4.02 (2.93)	17.10 (0.00, 17.10)
	Quick Ceph	4.07 (3.03)	16.72 (0.34, 17.06)
<b>Structure</b>	Maxilla	2.09 (1.10)	5.26 (0.00, 5.26)
	Mandible	6.03 (2.97)	16.39 (0.71, 17.10)
<b>Serial Time Points</b>	Time <sub>12</sub>	4.40 (2.72)	11.72 (0.58, 12.30)
	Time <sub>23</sub>	3.69 (3.19)	17.10 (0.00, 17.10)
<b>Implant Location</b>	Posterior	4.19 (3.12)	17.10 (0.00, 17.10)
	Anterior	3.90 (2.83)	16.48 (0.00, 16.48)

All values in millimeters

Table 2. Descriptive Statistics – Measured displacements (mm) by Method

Variable	Structural		Dolphin		Quick Ceph	
	Mean (SD)	Range (Min, Max)	Mean (SD)	Range (Min, Max)	Mean (SD)	Range (Min, Max)
Time <sub>12</sub>	4.39 (2.78)	11.47 (0.58, 12.05)	4.31 (2.65)	11.28 (0.96, 12.24)	4.49 (2.76)	11.26 (1.04, 12.30)
Time <sub>23</sub>	3.70 (3.20)	16.48 (0.00, 16.48)	3.73 (3.18)	17.10 (0.00, 17.10)	3.65 (3.23)	16.72 (0.34, 17.06)
Maxilla	2.09 (1.11)	5.26 (0.00, 5.26)	2.10 (1.06)	5.07 (0.00, 5.07)	2.07 (1.16)	4.73 (0.34, 5.07)
Mandible	6.02 (3.03)	15.77 (0.71, 16.48)	5.97 (2.93)	16.08 (0.98, 17.06)	6.10 (2.99)	16.01 (1.05, 17.06)
Posterior	4.21 (3.15)	16.28 (0.00, 16.28)	4.18 (3.09)	16.86 (0.24, 17.10)	4.19 (3.16)	16.58 (0.48, 17.06)
Anterior	3.88 (2.87)	16.15 (0.33, 16.48)	3.86 (2.76)	16.20 (0.00, 16.20)	3.95 (2.90)	15.79 (0.34, 16.13)

All values in millimeters

Table 3. Linear Contrasts of Method Mean Displacements

Method		Method	Difference*	P-Value	95% Confidence Interval
Dolphin	vs.	Structural	-0.02	0.999	(-0.21, 0.17)
Quick Ceph	vs.	Structural	0.03	0.999	(-0.17, 0.23)
Quick Ceph	vs.	Dolphin	0.05	0.999	(-0.12, 0.22)

\* All values in millimeters

Table 4. Linear Contrasts of Method Mean Displacements by Time

Method		Method	Time	Difference*	P-Value	95% Confidence Interval
Dolphin	vs.	Structural	T <sub>12</sub>	-0.07	0.550	(-0.30, 0.16)
Dolphin	vs.	Structural	T <sub>23</sub>	0.03	0.697	(-0.13, 0.20)
Quick Ceph	vs.	Structural	T <sub>12</sub>	0.11	0.448	(-0.17, 0.38)
Quick Ceph	vs.	Structural	T <sub>23</sub>	-0.05	0.580	(-0.22, 0.12)

\* All values in millimeters



Table 5. Linear Contrasts of Method Mean Displacements by Structure

Method	Method	Structure	Difference*	P-Value	95%Confidence Interval	
Dolphin	vs.	Structural	Maxilla	0.01	0.897	(-0.14, 0.17)
Dolphin	vs.	Structural	Mandible	-0.05	0.577	(-0.22, 0.13)
Quick Ceph	vs.	Structural	Maxilla	-0.01	0.889	(-0.21, 0.19)
Quick Ceph	vs.	Structural	Mandible	0.07	0.354	(-0.08, 0.23)

\* All values in millimeters

Table 6. Linear Contrasts of Method Mean Displacements by Implant Location

Method	Method	Location	Difference*	P-Value	95%Confidence Interval	
Dolphin	vs.	Structural	Posterior	-0.03	0.699	(-0.17, 0.11)
Dolphin	vs.	Structural	Anterior	-0.01	0.898	(-0.18, 0.16)
Quick Ceph	vs.	Structural	Posterior	-0.02	0.778	(-0.15, 0.11)
Quick Ceph	vs.	Structural	Anterior	0.08	0.468	(-0.13, 0.29)

\* All values in millimeters

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