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Cephalometric regional superimpositions -- digital vs. analog accuracy and precision : 1. the maxilla

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CEPHALOMETRIC REGIONAL SUPERIMPOSITIONS – DIGITAL VS. ANALOG ACCURACY AND PRECISION: 1. THE MAXILLA.

GLENN D. KRIEGER, 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
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Orthodontics

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By

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Orthodontic Department
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DATE SUBMITED: November 20, 2014

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:____
Glenn D. Krieger, D.D.S. Date

DEDICATION

I dedicate this thesis to:

My wife, Alissa and my children, Jordan, Zachary and Devin who quietly allowed me to work on weekends and evenings and supported me when I thought I could go no further. I could not have completed this arduous task without their understanding, love and patience. Thank you for allowing me to follow my dream of becoming an orthodontist and while I can never truly repay what you have meant to me during my time at school, I can at least promise all of you straight teeth for the rest of your lives.

To my mother and father, who taught me to continually ask questions and seek knowledge, to never give up and be a lifelong student. I thank them for always supporting me and being my biggest fans.

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Dr. Abraham Lifshitz, my program Chairman and thesis committee member, whose door has always been open to me, and whose clinical lessons will stay with me for the rest of my career. Dr. Lifshitz has always been the consummate gentleman, demonstrating patience and kindness and most importantly, empathy when I felt that I couldn't go on. I will never forget Dr. Lifshitz' support for my candidacy and for giving me the opportunity to pursue my dream of becoming an orthodontist. For the rest of my life, I will not be able to put on a pair of S-O-C-K-S without smiling and thinking of Dr. Lifshitz. (Think Spanish translation.)

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Drs. Doug Shaw and Kevin McCaffrey, who worked closely with me while completing their own projects. Only they can truly understand what it was like to complete this journey. I couldn't ask for two better and more patient friends with which to complete the process. While both Doug and Kevin kept telling me that I helped them with their projects, it's actually the other way around; I couldn't have completed this manuscript without their friendship and support. I can't say that the process of completing my thesis was in any way easy, but when it was fun, it was usually because of Doug and Kevin.

Raj Jaglal and Keith Simon, my research assistants. Raj and Keith were there for me on short notice, no questions asked, at night and on weekends as I measured displacements and called off over two thousand separate numbers for them to put into a spreadsheet. I have no doubt that both of them are going to be assets to our profession and I wish them lifelong success upon their graduation from dental school next year.

ABSTRACT

CEPHALOMETRIC REGIONAL SUPERIMPOSITIONS – DIGITAL VS. ANALOG
ACCURACY AND PRECISION: 1. THE MAXILLA.
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Introduction: The purpose of this study was to measure the displacement of defined dental structures, as a result of superimposition of cephalometric images across paired time-points by both digital and analog methods. The magnitudes of such displacements across three methods of superimposition were compared to each other and to a reference method constructed by registering superimposed cephalometric images on tantalum markers implanted in the study participants' maxillae. The defined dental structures were: 1) First molar mesial contact point; 2) First molar apical root bisection; 3) Central incisor root apex; 4) Central incisor crown incisal edge. **Methods:** Lateral cephalograms of 22 patients containing tantalum implants from the Mathews acquisition group were digitized, traced and superimposed using analog (implant and structural) and digital (Dolphin and QuickCeph) methods. Superimpositions were exported to Adobe

Photoshop where they were scaled and displacement of defined dental landmarks measured using a Cartesian coordinate system. A random-effects, generalized linear model with Bonferroni adjustment was used to compare the different methods. **Results:** The structural method ($p < 0.01$) showed statistically significant differences versus the implant method and demonstrated the smallest 95% confidence interval range compared to Quick Ceph and Dolphin (0.45mm, 0.75mm, and 0.95mm, respectively). The four structural method landmarks demonstrated statistically significant differences versus the implant method ($p<0.05$) and had smaller 95% confidence interval ranges compared to the corresponding landmarks for Dolphin and Quick Ceph. **Conclusions:** Our study demonstrated that there are differences in the accuracy of digital and analog methods of maxillary regional serial superimposition. Structural, Dolphin and Quick Ceph methods showed a mean overall displacement of defined dental structures within 0.5mm of the displacement measured against implant-registered superimposition (reference method). Only the structural method demonstrated a statistically significant difference compared to the implant method and also exhibited the smallest standard error relative to the mean for every measurement. The low power of this study (0.18) and large standard errors relative to the means for the digital methods suggests that a larger sample size may result in significant differences regarding Dolphin and Quick Ceph vs. implant methods.

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CHAPTER 1: INTRODUCTION

1.1. Background

Among all of the species to ever inhabit the earth, Mankind is unique.[1] Though upright posture and the ability to control fire are undeniably monumental evolutionary accomplishments, the human race boasts an unparalleled capacity for reason and analytical thought. It has been argued[2] that Man's self-awareness is what sets him apart from the rest of the animal kingdom, and it is this trait that has led to an inherent curiosity about his personal identity. Biologists and Philosophers alike have used Descartes'[3] question "But what, then, am I?" as a stepping-stone for analysis and discourse regarding Man's place in the universe. Though currently impossible to definitively answer the question of "personhood" from a metaphysical perspective, history is replete with examples of the search for the anatomical answer to Descartes' query.

Ancient anatomical study dates back to circa 1500 BCE evidenced by the *Edwin Smith Papyrus*, which documented the ancient Egyptians' attempt to better understand the human body and the functions of the internal organs.[4] Nearly 1000 years later, Hippocrates[5] and Aristotle[6] developed an understanding of the musculoskeletal structure of the human body; more than 400 years later, with Galen[7] continuing their work in the 2nd century. However, parallel to the efforts of early anatomists to catalog and understand the inner systemic mechanisms of the human body, others were exploring mathematical insights to better define standards for proportions of the human body.

Marcus Vitruvius Pollio, a 1st century BCE Roman architect, stated that a well-designed structure must exhibit the three qualities of "*firmitas (solid), utilitas (useful) and venustas* *(beautiful)"* - later known as the "Vitruvian Virtues".[8] Vitruvius further described the human figure as the "principal source of proportion among the Classical orders of architecture."[8] The concept of defined proportions in human beings was so influential that nearly 1500 years later Leonardo Da Vinci employed Vitruvius' standards to create his *Canon of Proportions*, more widely known as the *Vitruvian Man*.[9] Da Vinci stated in unequivocal terms, specific dimensions for the proportions of the human body,[9] and thereby provided the world quantifiable standards against which the proportions of every person could be measured. While *Vitruvian Man* described many details of human form and function, it did not, however, elucidate the standards related to facial form and balance. For this, the world would have to wait another 250 years.

Petrus Camper was born into a wealthy Dutch family and was an accomplished artist and draftsman before becoming a Surgeon[10]. In 1770, bothered that his art students were painting the Black Magus from the nativity scene with Caucasian facial features, Camper developed the "facial angle" to demonstrate the differences in facial form among the races.[11] Camper asserted that the angle formed by the intersection of a line drawn horizontally form the nostril to the ear and one from the advancing part of the upper jawbone to the most prominent part of the forehead was unique for each race.[11] Camper's primary interest was the artistic component of facial form, and although Camper's angle was later discredited,[12] his attempt at defining a standard metric for facial form was the first of its kind. Camper's efforts inspired others to look at ways of quantifying standards for evaluation of facial characteristics for scientific analysis.[13]

In August, 1882, at The World Anthropological Congress of Anatomists and Physical Anthropologists in Frankfurt-am-Maine, Germany, the term "Frankfort Horizontal" was first used[14] to describe the line that extended from the upper rim of the external auditory meatus to the lowest point on the margin of the orbit.[15] Terms like Camper's "Facial Angle" and the "Frankfort Horizontal" exemplify early attempts to define specific starting points for the analysis of facial form. The points and lines utilized for these early attempts to quantify descriptions of facial form were not related to facial growth via biology, but rather simply selected for technical convenience.[16] To more completely analyze facial form, one would need to see within the soft tissue and evaluate skeletal patterns of growth. In 1895, the accidental discovery of X-rays provided a pathway for significant advancement in the analysis of facial form.

The first-ever Nobel Prize was awarded in 1901 to William Roentgen for his discovery of electromagnetic radiation in a wavelength range known today as "X-rays".[17] For the first time, researchers were able to visualize hard tissues in living individuals, including the underlying skeletal framework that contributed to facial appearance. In 1922, August Pacini married roentgenography with human cranial analysis.[18] Pacini captured lateral radiographic images of the head with the subject's median sagittal plane positioned parallel to the film plane,[19] the technique was standardized in order to maintain a fixed distance from X-ray source to the film cassette.[19]

1.2. Origins of Cephalometry

1.2.1. The Cephalometer

In 1922, Spencer Atkinson introduced the idea that “Key Ridge*”,* the lowest point of the zygomaticomaxillary ridge,[20] known as the infrazygomatic crest,[21] was the first reference point for radiographic analysis of the teeth relative to the facial skeleton.[22] Atkinson introduced the term to indicate “the functional role of the infrazygomatic crest in dissipating the forces of mastication.”[21] Anatomists of Atkinson’s era studied growth and development through examination of the skulls of diseased children,[22] and some recognized the value of taking the “study of anatomy out of the dead house”.[22] In 1931 T. Wingate Todd, one of the most respected anatomists of his time,[23] recognized and expressed the potential of radiographic analysis by the following statement:

> “A dead child is a defective child in whom there has occurred an interruption or a prohibition of developmental growth for some time before death, unless, of course death is due to an acute disease like intussusception or pneumonia or to accident such as injury or burns. The interpretive study of actual skulls must be tempered by recognition of this fact. If we are to investigate healthy skulls we must do it on the living.”[24]

The “cephalometer” or “cephalostat”,[25] an instrument that allowed investigators to reproducibly position the head in a standardized orientation for measurement and radiographic examination,[26] was invented nearly simultaneously in 1931 by B. Holly Broadbent Sr. and T. Wingate Todd who worked together in the U.S[17,24] and Hofrath, who worked independently in Germany.[20] The introduction of standardized cephalometric radiography meant that for the first time, investigators could study craniofacial development longitudinally in living subjects, rather than having to rely on cross sectional data procured from the examination of dry skulls.

1.2.2. Identification of Landmarks and Analyses

Broadbent[26] and Brodie[27] stated that cephalometry should be used solely for serial evaluation, yet others were employing it for diagnosis as well as treatment planning.[28] Hofrath[29] and Maves[30] used cephalometrics for demonstrating potential benefits for both monitoring change and planning prosthetic treatment.[28]

Cephalometric analysis is the study of angular and linear measurements of a lateral headfilm (i.e., cephalometric radiograph) for descriptive and diagnostic purposes.[31] In 1948, the first standardized cephalometric analysis describing facial form and denture relationships[32] was presented by Downs.[33] Steiner[34] subsequently distilled various sources to "express our concept of the normal American child of average age."[34] Steiner stated that he did not draw his numbers from a particular sample but rather from those he felt useful for his clinical goals and therapeutic outcomes.[35] Steiner's measurements were clinical guides and had no means or standard deviations.[36] In 1954, Tweed[37] presented an analysis derived from a sample of 95 cases of individuals whom he described as "having a face that I thought was pleasing".[37] Sassouni, 1955,[38] developed cephalometric norms based upon a sample of 50 white children ages 7-15 with normal occlusions and Ricketts, 1960,[39] described skeletal and denture variation by a clinical study including over 1000 treated cases.[32]

Baumrind and Frantz[40] observed that regardless of the type of cephalometric evaluation chosen, there are three types of errors common to all cephalometric radiographic analysis: (1) projection errors, (2) landmark location errors and (3) "mechanical errors in drawing lines between points on tracings and in measuring with ruler or protractor."[40] The authors went on to state that errors in projection are all but impossible to prevent unless the positions of landmarks are known in three dimensions.[41] Baumrind and Frantz[40] suggested the use of angular, rather than linear measurements wherever feasible, because angular measurements remain constant, regardless of enlargement factor.

1.3. Serial Superimposition Techniques

1.3.1. Cranial Base Superimpositions

The measurement of lateral cephalometric radiographs may be used to categorize craniofacial patterns by type, wherein an individual subject is denoted as a "case" (i.e.- "a high-angle case" or "a case with an ANB angle of 6 degrees")[31], to describe the degree to which an observed case[31] departs from an accepted norm, or to characterize the changes during treatment.[31] Dr. Broadbent's Bolton Study (1929-1959) evaluated subjects' facial growth and dental development longitudinally with annual radiographs.[42] The initial Bolton study, the first database for radiographs related to longitudinal growth of the face and teeth published in 1937, was based on 5 years of accumulated data that included more than 1000 subjects.[19] Broadbent observed that while a child's brain is developing, and before it reaches final maturity, there are areas of the cranium that appear to remain fixed during growth.[22] Broadbent also detected areas "above the face" in the cranial base which were more stable than areas of the rapidly growing lower face.[24] Broadbent stated that cephalometric superimposition should occur (by using the relatively more stable landmarks) "on the base lines found by connecting such points as the sella turcica and nasion as well as the ear hole and the eye point, thereby disclosing somewhat more clearly the changes in the teeth and jaws during orthodontic treatment."[22] Broadbent demonstrated that the Bolton point (intersection of the occipital condyle and foramen magnum)[43] to Nasion (the most anterior point of the frontonasal suture)[43] formed a "plane" that was a stable line of orientation upon which subsequent roentgenograms of one subject could be superimposed.[26] Broadbent further stated that if one drew a perpendicular line from Sella (the midpoint of the cavity of sella turcica)[44] to the Bolton-Nasion plane, the midpoint of that perpendicular line, named point "R",[26] could serve as the point upon which a patient's roentgenographic superimpositions from different timepoints (serial superimpositions) could be registered.[26] However, Noyes[45] stated that additional landmarks were necessary in order to measure the "anterior extremities of the face" as well as "the breadth and height of the bones".[45]

Noyes presented a lecture in 1942 to the Chicago Association of Orthodontists,[45] regarding the future of facial analysis.[12] Noyes affirmed that Broadbent had described landmarks that had been proven stable in adolescents and that the pattern and direction of growth of the bones that directly supported the dental arches had yet to be discovered.[45] Noyes stated: "…we may be led to discover a proportionality expressed in the form and position of dental arches, facial bones and cranial base, revealed by the measurement of spaces and angles established by anatomic landmarks."[45] Five years after Noyes' comments, Arne Björk, an orthodontist from Sweden, provided the most expansive study of facial growth and development yet, and answered some of Noyes' questions.

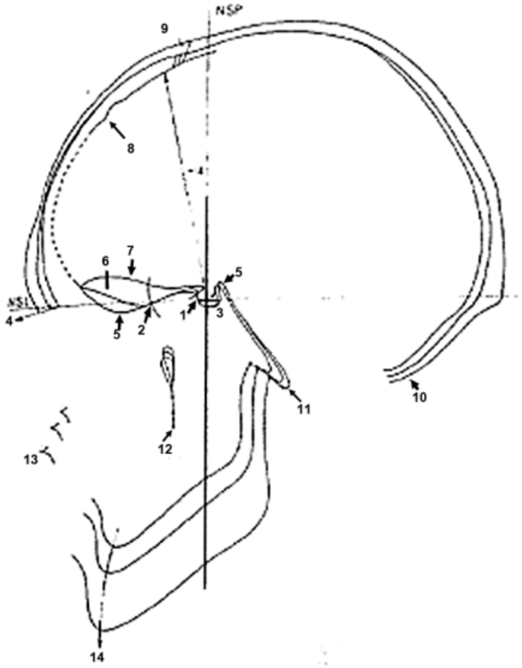
Björk[12] 1947, quantified longitudinal developmental changes in facial structure while investigating the impact of growth and development on prognathism. Björk[12] demonstrated the value of serial superimposition of radiographs to study growth and development, but stated that the radiographic location of Bolton point was compromised by the asymmetric position of the occipital condyles.[12] Björk emphasized the need to determine the most appropriate anatomic structures for cephalometric superimposition, evidenced by his statement that it was essential to determine "…which measurements, linear and angular, would provide the smallest error…in the accuracy in which the various points may be located in the films."[12] Regarding his methodology, Björk further stated:

> "…those measurements which give the smallest errors have been selected and it has been possible to establish a method of measuring the length and height of the face and the cranial base from X-ray films; a method in which the errors of individual measurements are the smallest possible and where the order of these errors is known."[12]

Björk precisely used the same methods to capture all lateral head films during his study to "maintain the same level of distortion throughout".[12] Björk compared the position and movement of defined skeletal landmarks (which provided the smallest errors) among a sample of 12 year-old Swedish boys to that of a sample of Swedish army conscripts aged 21 and 22.[12] It is interesting to note that although the Frankfort line has been broadly accepted by many in craniometry,[33,46,47] Björk chose to not use Frankfort as a reference point. Björk stated that Porion, and subsequently the Frankfort line, was an "inferior reference point".[15] Björk's study[12] was a broad analysis of the growth of the facial bones and cranium. Though numerous angular and linear measurements associated with skeletal landmarks were evaluated, Björk found that the line connecting Sella-Nasion (S-

N) showed only a 6.5% increase between the age groups in the study, the smallest linear change of any of the constructed planes he studied.[12] Although, one could have concluded that the S-N line's linear stability would make it a prime candidate for serial superimpositions of lateral radiographs, Björk[12] had not yet made that inference. Björk's study concentrated on the angular and linear measurements related to the prognathic growth pattern he observed in boys from ages 12 to 21-22[12], and not the possible usefulness of the data for defining stable landmarks for radiographic superimposition. The clinical application of Björk's work[12] was not immediate, and in 1948, a year after Björk had published *The Face in Profile*, Downs presented a cephalometric analysis using techniques for superimposing serial cephalograms developed by Broadbent[22] more than a decade earlier.[33] In 1951, Krogman[46] also cited Broadbent's approach[22] as the proper way of aligning overall superimpositions, he referred to the S-N line as the "Broadbent Plane",[46] and moreover, stated that Björk[12] did not have landmarks designated for "orientational axis".[46] A follow-up study by Björk[20] in 1955 evaluated 243 boys at ages 12 and 20; Björk concluded that the S-N line would be the most suitable reference line for superimposition during "the adolescent period in man", a finding that supported Brodie's work on cranial changes during growth.[48] Björk's subsequent studies[49,50] elucidated growth patterns and reinforced his contention that S-N line was a stable plane upon which serial superimposition could be performed. Björk[49] specified the use of the contour of the anterior wall of sella for superimpositions performed during the juvenile growth period, and the anterior contours of the middle cranial fossa (the internal base of the skull posterior to the sphenoidal ridges and limbus and anterior to the crests of the petrous part of the temporal bone)[51] for superimpositions involving radiographs of subjects after growth cessation.[49]

However, other authors[50,52-54] have suggested that local remodeling around sella and nasion, due to growth, calls into question the validity of simply using S-N for cranial base superimpositions. Johnston[55] stated that the literature[49,56,57] "argues that the bony anatomy from the anterior half of sella turcica to the region of foramen caecum and the internal outline of the frontal bone is sufficiently stable to support meaningful anterior cranial base superimpositions."[55] Björk and Skieller added[49] that serial cranial base superimpositions can be oriented vertically on the contours of the cribiform plate, the contours of the bilateral fronto-ethmoidal crests and "possibly" also by the cerebral surfaces of the orbital roofs and the trabecular system of the anterior cranial base and the inner contour of the frontal bone. (Figure 1)



1.Anterior wall of sella turcica
2. Anterior contours of middle cranial fossa
3. Mean intersection of lower contours of anterior clinoid processes and the contours of the anterior wall of sella turcica
4. Inner surface of frontal bone
5. Contour of the cribiform plate
6. Contours of the bilateral frono-ethmoidal crests
7. Cerebral surfaces of the orbital roofs
8. Inner contour of the frontal bone
9. Frontoparietal suture
10. Occipital bone
11. Articulare
12. Pterygomaxillaire
13. Anterior nasal spine
14. Tip of the chin

Figure 1: Landmarks associated with Björk and Skieller's cranial base superimpositions[49]

Björk's original endorsement of S-N as a stable landmark for overall cranial base superimpositions is still widely used, however, Björk discussed a deficiency when relying upon overall superimpositions in the analysis of regional growth when he added:

> "The age changes in the facial pattern which emerge from an analysis of this kind become significant only through an appreciation of the regional growth changes and mutual displacement of the bone and it is my hope that this article will serve as a contribution toward the solution of these problems."[58]

1.3.2. Implant Method of Superimposition

Brodie[48] demonstrated the need to distinguish the cranium from the facial bones when analyzing growth and development, but Björk stated: "Modern X-ray technique is nevertheless unable to reveal the mechanism governing growth of the individual bone elements in the facial skeleton."[59] The specific periosteal bone growth and resorption affecting each bone composing the face makes cranial base superimpositions alone inadequate for analysis of growth and development of individual bones of the face and jaw.[12,58] It had already been demonstrated that radiographs of the external contours of bones could not be used to analyze the growth mechanisms that contributed to the composite shape.[61-64] Björk ultimately developed a new method of analyzing the growth mechanism of the maxilla and mandible that used metallic implants.[59]

Utilizing three or four 0.62mm x 2.0mm Vitallium pins as references implanted in each jaw, Björk studied the growth in a way never previously performed. The metallic implants served as fixed reference points within the jaws upon which serial radiographic superimposition could be performed and created a "gold standard" for regional superimposition.[59] The implants were placed with their position fixed and without risk of movement due to eruption of teeth, orthodontic treatment or osseous remodeling.[60] This approach was repeated by others,[57,61-70] and by superimposing the Vitallium pins on serial cephalograms, a thorough picture of the growth pattern of each jaw was observed. What Baumrind[29] referred to as: "(1) local remodeling, (2) developmental changes at more distant locations, or (3) the effects of therapeutic intervention" could be thoroughly evaluated employing Björk's implant methods.

The body of literature through the 1950's[35,38,48,52,53,56,58,59,71-76] and 1960's[51,54,55,61-64] elucidated the pattern of growth and remodeling of the facial bones. The "previous implant studies" of Björk[59,60,62,77] and Björk and Skieller[63,64] provided the foundation for superimposition techniques specifically designed to study maxillary growth and development.[77]

1.3.3. Structural Method of Superimposition

Prior to Björk and Skieller's clarification of the pattern, magnitude and direction of facial growth and development[77] there was "a lack of reliable reference structures for superimposition of cephalometric radiographs in longitudinal series".[77] Implants used as such a fixed reference permitted clarification of how the maxilla grew, remodeled and rotated.[77] Due the fact that the maxilla exhibits appositional rather than interstitial growth, once placed, the implants are impervious to movement. Serial radiographs were superimposed upon the unmoving implants and any positional changes of other structures of the face or cranium could be measured precisely and the observed changes attributed to either treatment effects or osseous remodeling or both.

The maxilla grows downward and forward relative to the cranial base, therefore, one could easily presume that such growth occurs solely through apposition of bone in the anterior maxilla. However, the overall downward and forward growth is actually due to bodily translation of the maxilla with apposition at the floor of the nose and simultaneous surface remodeling which is almost entirely resorption in the anterior maxilla.[78] The fact that remodeling and translation are two simultaneous, yet different growth methods in the maxilla can obscure the precise contribution each mechanism plays in the process. When orthodontic therapy is completed in a growing individual, it becomes impossible for one to distinguish final changes attributable to translation, surface remodeling or treatment effects without fixed references upon which regional cephalometric superimpositions can be superimposed and registered.

Physiology and placement of implants in structures undergoing appositional growth allow the understanding that implants are positionally fixed, however, when examining overall superimposition, a phenomenon referred to as "relocation" could make it appear as if the implant has moved, as illustrated in Figure 2. Implants, though fixed within the bone, can appear to be relocated during growth, and when superimposed, demonstrate the true process of remodeling and treatment effects.

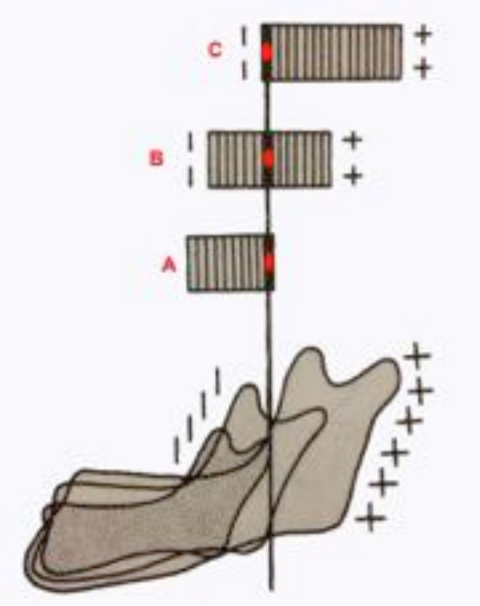


Figure 2:"Relocation" of a fixed object (the red dot) during mandibular remodeling[79]

Implants have served as fixed points for serial cephalometric regional superimposition to determine if there exist anatomic structures that exhibit minimal or negligible displacement during treatment and growth. The existence of such "stable" anatomic structures would permit their use, as surrogates for the implants, for the purpose of serial regional superimposition, thereby allowing a reliable method of serial regional cephalometric superimposition for individual without implants. Serial radiograph registration and orientation upon such anatomic structures known to be the most stable is referred to as the "structural method".[77] Structural method superimposition allows one to visualize those changes attributable to skeletal growth and those related to tooth movement in the antero-posterior dimension using natural reference structures, i.e. a best method in lieu of implants.[55]

Björk and Skieller's structural protocol included superimposing two cephalometric radiographs from a time series on the anterior contours of the zygomatic process (Figure 3).[77] Orienting the radiographs on the S-N line enabled evaluation of the amount of rotation of the maxilla during growth.[77]

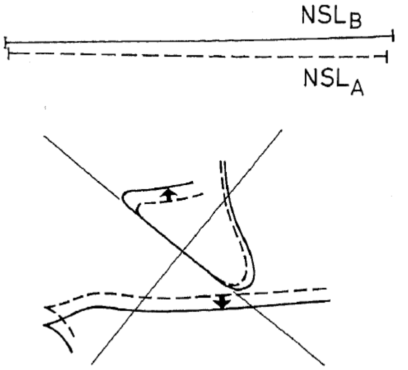


Figure 3: Björk and Skieller's suggested method of maxillary superimposition on the anterior contours of the zygomatic process. (Note the European protocol of cephalometric viewing with the anterior to the left, versus the US method with the anterior to the right.)[77]

Due to the subsequently larger structures in the latter radiograph (due to growth), the two radiographs would need to be adjusted vertically. Björk and Skieller suggested that one should adjust the vertical arrangement keeping in mind that the amount of resorption of the nasal floor is "on average about the same as" the amount of apposition at the orbital floor[77] though this latter supposition was later redacted to a 3:2 orbital floor apposition to nasal floor resorption ratio[80] and subsequently supported by other research.[57]

The lack of a defined vertical registration point to properly align the two radiographs was also problematic because it created an arbitrary component to the vertical alignment. Brodie[81] showed that on S-N registration there was an almost parallel lowering of the nasal floor during development, making the nasal floor a suitable landmark for superimposition. However, Björk and Skieller[63] demonstrated that the downward and forward growth of the maxilla is associated with varying degrees of vertical rotation, making the nasal floor an unsuitable reference structure in maxillary superimposition.

Moss and Greenberg[82] and Koski[83] suggested that the infraorbital canal could serve as suitable a stable landmark, moving in concert with the orbit during growth. However, Björk and Skieller[80] demonstrated that the infraorbital canal, along with the orbit, changes position relative to the anterior cranial base upon application of orthodontic forces, and therefore is not a suitable landmark for registration of serial superimposition of radiographs.

Numerous studies have evaluated the stability of landmarks for maxillary superimposition,[69,70,84-88] but it was Johnston[55] who developed a complete protocol for structural method analysis of maxillary superimposition. Johnston submitted that Björk and Skieller's work[63,64,77,80] provided a useful "approximation"[55] of implant superimpositions, but he added that the anterior surface of the zygomatic process is difficult to see and is too short to achieve reliable control of the palatal plane.[55] The structural method of maxillary superimposition suggested by Johnston included best-fit registrations on both the zygomatic process of the maxilla (right and left sides averaged) and on the bony anatomical details superior to the incisors.[55] Johnston added: "The superior and inferior surfaces of the posterior hard palate assist in orientation, and to minimize the probability of gross errors in antero-posterior registration, care should be taken to ensure that the PTM fissure of the older tracing lies at or behind that of the younger."[55] (Figure 4)

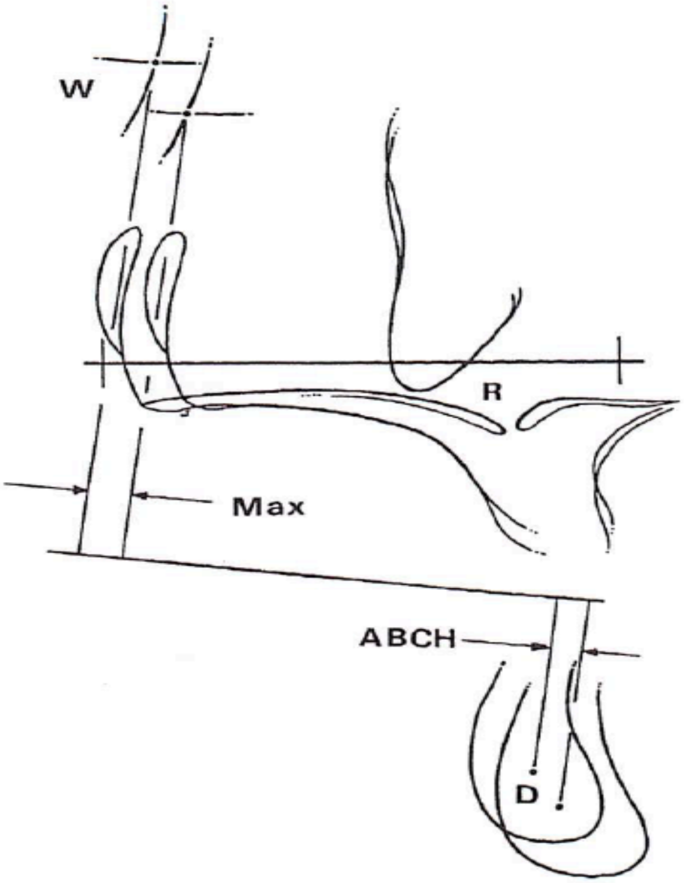


Figure 4: Johnston's structural method of maxillary superimposition. "Registration is based on the zygomatic process of the maxilla ('key ridge') and the curvature of the palate (i.e.-structures in the region of *R*); orientation, on the horizontal structures of the hard palate. Note that care is taken to ensure that the pterygomaxillary fissure of the older tracing is at or behind the younger. Once again, the superimposition is recorded by an arbitrary fiducial line. Maxillary advancement relative to cranial base (*MAX*) is measured at *W*; Mandibular displacement relative to maxilla (*ABCH*) is measured at *D*. Both measurements are executed parallel to *MFOP*."[55]

Johnston introduced the concept of fiducial lines;[55] arbitrary straight lines, ends marked crosswise, to record registered superimpositions (Figure 4). The appropriate regional superimposition carries them forward and back, pairwise, throughout the series.[55] The major advantage of fiducial lines was the simplified process of documenting and repeating structural superimposition and the ease with which one viewed changes from the vantage point of any of three areas: the cranial base, maxilla, or mandible (Figure 5).

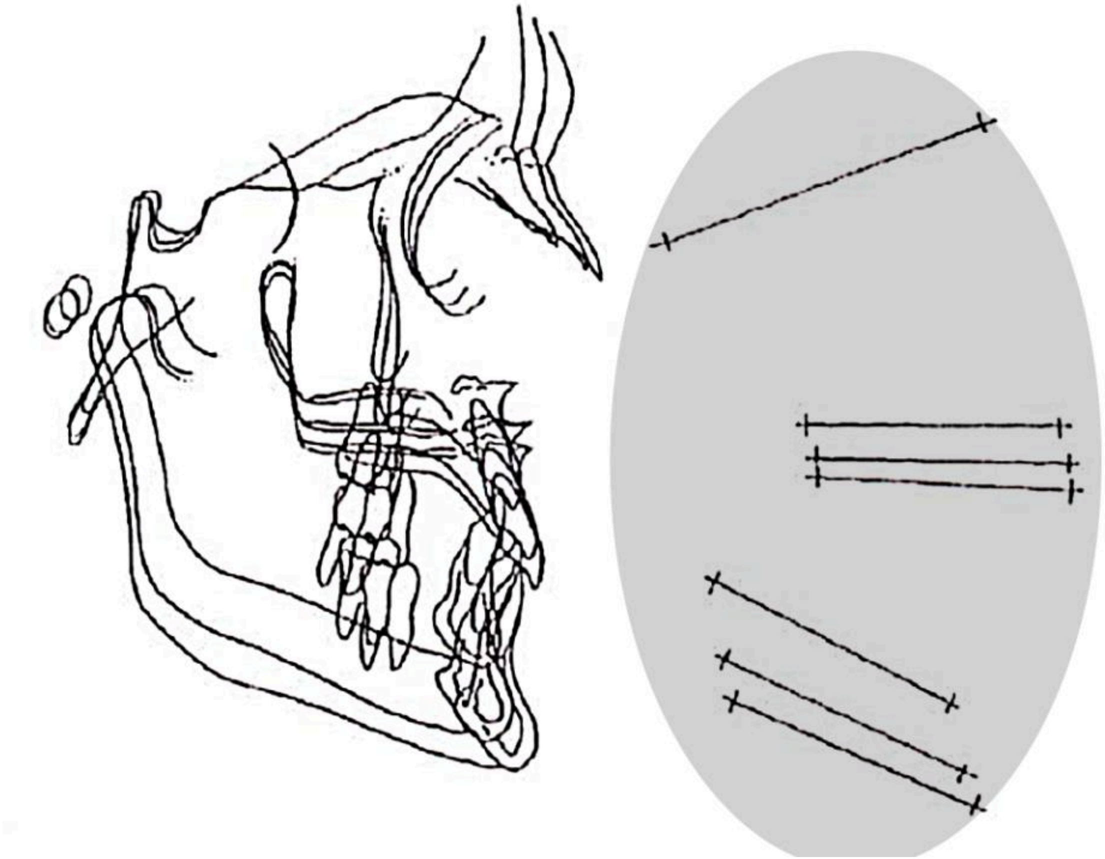


Figure 5: Example of cranial base superimposition of three cephalograms with corresponding fiducial lines on right (shaded oval).[55]

It should be noted that even the most stable natural reference structures are not absolute, that is, such structures demonstrate some degree of movement during growth. Recall that even while Björk advocated the S-N line as a "stable" horizontal point for overall superimpositions, Björk's work demonstrated an average S-N growth in length of 6.5% in boys from age 12 to 21 or 22.[12] It is important to keep in mind that the average of 6.5%

growth of S-N includes all subjects. Some subjects may not have changed at all, while some might have changed considerably more than the average. Consequentially, superimpositions on natural landmarks defined as "stable" will not be as accurate as superimpositions on implants, which neither grow nor move.

1.4. Digital Imaging

Johnston's publication (1996)[55] came at a time when computing power was becoming more affordable and easier to use.[89] The clinical use of computers includes image capture, storage and post-capture image enhancement.[90] When computers are used to facilitate the viewing, display, printing, archiving, printing or transmission of an image, the resultant product is referred to as a "digital image".[91]

There are significant fundamental differences between analog film and digital images with respect to their composite "building blocks". Digital images are composed of a matrix of small squares of color called "pixels" (short for "picture elements")[92] which, when placed together in a mosaic, create the "complete" image.[90] A radiographic film, in contrast, has a nearly infinite number of elements in gray scale.[90] When a radiographic film is converted into digital form, it is composed of pixels similar to any other digital image. Three particular properties related to pixels can play a significant role when the image is sent to a screen or printer for display; total pixels, pixel density and resolution.

The larger the number of pixels, the less apparent they become.[90] An image that is 800 x 800 pixels contains 640,000 pixels versus an image that is 2000x 2000 pixels that which contains 4 million pixels. If a monitor can display 1200 pixels wide by 900 pixels vertically, then the greatest number of pixels it can display is 1,080,000 (1200 x 900). Thus, a 4 million-pixel image will completely fill the screen while the 640,000-pixel image will not have enough pixels to fill the screen. In the latter case, if enlarged to fit the entire width and height, the image appears indistinct, or decomposed, known as, "pixelized"[92] and would need to be reduced in size for better clarity (Figures 6 & 7).

Figure 6: An example of an image with enough pixels to completely fill the screen.[92]

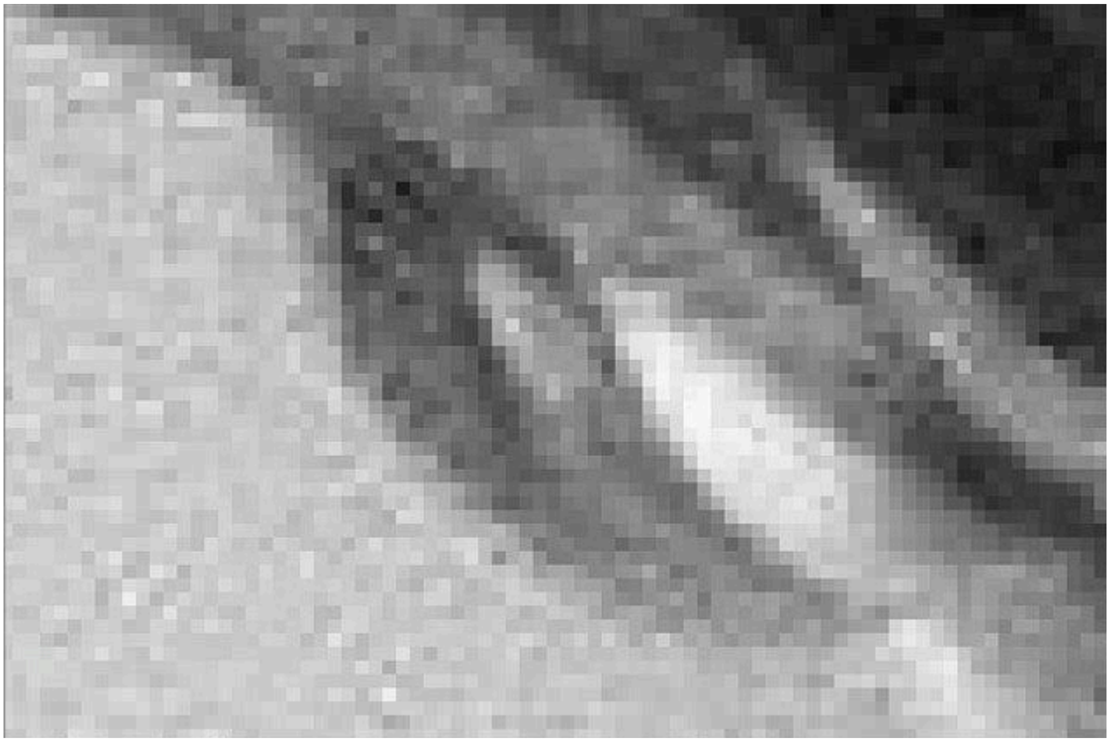


Figure 7: The same image as Figure 6 zoomed in at 1600%. Notice that there are not enough pixels to fill the screen, and as a result, the pixels are visible. The image appears "pixelized".[92]

The number of pixels per inch (ppi) displayed is also known as "pixel density".[93] (Though pixel density can also be known as "resolution", the term "resolution" will be used here solely to describe the <u>overall</u> screen resolution.) Greater pixel density means that each pixel is smaller, resulting in greater visible image detail. However, human visual acuity is limited to 300 ppi[94] and pixel density greater than that is of no humanly discernible value.

Additionally, the size of each individual pixel is a function of the number of pixels displayed on the entire screen and the size of the screen itself. An 11 x 8 inch screen (88 sq inches) with a resolution of 1100 x 800 has a pixel density of 100 ppi. A 20 x 12 inch screen with the same resolution has a pixel density of approximately 37 ppi, a 63% reduction from the 11 x 8 inch screen, resulting in an image with reduced visual detail.

Pixel density also plays a role in the resolution of displayed images. For instance, an image of 792 pixels by 576 pixels (width by height), displayed at a pixel density of 72ppi yields an on-screen image of 11 x 8 inches (792/72 by 576/72). The greater the size of the screen at a given pixel density, the more pixels and subsequently the greater screen resolution necessary to optimally fill the display for increased clarity.

When discussing image preparation for printing, the term "pixels per inch" is replaced with "dots per inch" (dpi).[95] It is suggested that images should be printed with at least 300 dpi for proper print quality.[95] Printing the aforementioned 792 x 576 pixel image at 300 dpi, results in an image only 2.64 x 1.92 inches in size. However, to print an image that is 8.5 x 11 inches at 300 dpi requires an image composed of 2550 x 3300 pixels, or 8,415,000 pixels. Thus, for a given pixel density, the number of pixels composing an image has a dramatic effect on image size and the ability to discern visual detail.

1.5. Digital Radiography in Dentistry

Digital radiography is the conversion of transmitted X-rays into a digital image using an array of solid-state detectors, computer processing and display of the image.[51] In contrast to digital radiography, conventional radiographic film uses silver halide grains in a gelatin matrix to capture an image.[96]

The advantages of digital radiography include the elimination of darkroom chemicals, a reduced radiation dose and immediate availability of the image.[97,98] Additional advantages include facilitated image archiving and enhancement, ready image corrections for over/under exposure, and the ability to quickly share an image while keeping the original.[98,99] Images can be captured through the use of digital sensors (direct imaging), phosphor plates (semi-direct imaging) or through the scanning of analog film (indirect acquisition).[106]

Both the direct and semi-direct imaging methods do not generally include provisions to control resolution. However, when indirect acquisition is utilized, the dpi of a scanned image, as discussed above, will affect its clarity and viewing size.

The literature is replete with investigators reporting a range of scanner setting anywhere from 150 dpi to 800 dpi.[99-113] A study by Ongkosuwito,[121] however, showed no difference in accuracy of landmark identification when comparing scanner resolution settings of 300 dpi to 600 dpi. Therefore, indirect acquisition of images at 300dpi to 600 dpi has no effect upon on-screen visual detail.

1.6. Digital Cephalometry

1.6.1. Digital Cephalometry In Orthodontics

Baumrind and Frantz[40] asserted that the primary challenges with serial superimposition are projection error and the difficulty of "precise replication of skull positioning".[40] The former can be minimized by using angular rather than linear measurements whenever possible, and the latter minimized by operator fastidiousness to a standardized head positioning protocol. However, even Baumrind and Frantz state that perfect alignment of the true anatomic midsagittal plane with the nominal midsagittal plane of the cephalostat happens only “rarely and by chance”.[40] Projection errors can lead to inaccuracies in both angular and linear measurements.[40,114] The variability in landmark identification revealed in other studies[31,115-117] demonstrates the challenge of obtaining accurate data from serial superimposition registered and oriented upon potentially imprecise landmarks.

Baumrind’s[40] third error of headfilm analysis, described as “…errors introduced in drawing lines between points by hand and in measuring with ruler and protractor” was obviated with the introduction of digital technology. In 1971, Baumrind[40] stated:

> “At the present state of the art of machine computation, errors of this type can be entirely eliminated by the simple expedient of computing the necessary linear and angular relationships algebraically, given the landmark coordinates. If only for this reason, we have no doubt that in the relatively near future all head film analyses will be carried out as some form of programmed computer operation.”[40]

Errors produced by drawing lines between points by hand, linear and angular measuring have been reduced with the aid of digital technology, yet the transition from analog tracing has introduced other types of errors. Baumrind’s aforementioned comments regarding the accuracy of linear and angular relationships computed by machine “given the landmark coordinates” relied on accurate landmark identification. Pixel-based images are far from a precise replica of an analog film and do not allow the nearly unlimited freedom of hand tracing. Unlike digital landmark identification, analog tracing allows an operator to identify a landmark anywhere on the acetate, limited in scale only by the size of the marking instrument and the ability to visualize the landmark itself. The simple fact that pixels have a defined size within which a single mark cannot be precisely located limits absolute accuracy in digital landmark visualization and identification. With such limitations in mind, however, there is still perceived value in digital cephalometric analysis.

In 1972, Ricketts[118] espoused the virtues of computerized cephalometric analysis for use in orthodontics but warned: “It should be understood at the outset that a computer can do nothing that the orthodontist cannot do if he is given the time and possesses the knowledge.”[118] Baumrind (1980)[119] added: “It is reasonable to assume that almost all quantitative head film interpretation will soon be done in some sort of computer assisted mode.” Baumrind’s comments proved prophetic, and by 2005, 40% of orthodontic offices in the U.S. reported using computers for cephalometric analysis.[120] However, just because clinicians were moving to digital cephalometric programs did not mean that there was an equal or greater degree of accuracy in either landmark identification or superimposition accuracy.

1.6.2. Digital vs. Analog Landmark Identification

As early as 1971, Baumrind[31] employed a form of computer called the Oscar K “coordinatograph” to asses the reliability of examiners to precisely locate specific cephalometric landmarks. In 1979, Houston[121] demonstrated the clinical application of digital landmark identification for cephalometric analysis. Richardson[122] followed in

1981 with the first study comparing digital and "traditional" methods of landmark identification. Using a "digitizer" first described by Bondevik[123] in his own study, Richardson,[122] and later Houston,[124] were able to compare landmark identification accuracy using direct digitization, finding similar results comparing digital and conventional methods. Digitizers utilize a Cartesian coordinate system to identify landmarks on either a radiograph (direct digitization) or an overlay tracing (tracing digitization), recording the information on a computer for analysis.

Sandler[125] was the first to compare the accuracy of landmark identification in direct digitization versus tracing digitization and compare it to traditional hand tracing, finding that manual tracing was found to yield more reproducible results especially for the points articulare and gonion which are constructed on a tracing, but only estimated using the digitizer.[109]

Lim[126] compared the accuracy of landmark identification between traditional hand tracing and the semi-direct imaging method of capture (phosphor plates). No differences in accuracy of landmark identification were demonstrated when comparing hand tracing and the digital method of landmark identification. Lim stated that "comparable quality digital cephalograms can be taken at 30% radiation reduction, compared to the conventional method."[126] It is worth noting that Lim[126] merely stated that a "conventional film/screen system" was used. The multiple permutations of modern high sensitivity film and intensifying screens could potentially eliminate the radiation exposure differential between digital and analog radiography.

From 1991 to the present many investigators have reported studies[99,102,103,105,106,108-113,127-137] comparing the accuracy of landmark identification using analog and digital methods of images captured at a single timepoint employing a variety of permutations of hand tracing and digital input and output. The following is a summary of the salient findings from the aforementioned studies:

1. Generally, a statistically significant difference has been found in the accuracy of landmark identification of defined structures when comparing analog and digital methods utilizing cephalometric images of a single timepoint.[99,102,106,108,111-113,127,129,131,132,135,137]
    a. Geleen[127] compared landmark identification on conventional film, a printed hard copy and monitor-displayed images. Geleen[127] found the monitor-displayed images to have a lower precision in landmark identification when compared to film and hardcopies. Note that both the printed hardcopies and the on-screen images were digitally enhanced. The author noted that "post-processing algorithms may cause a systemic error in landmark localization" and "…the possibility for this type of error could not be investigated."[127]

    b. Chen[129] found statistically and clinically significant differences for Po in the vertical axis, ANS in the horizontal axis and AR and Upper Molar but specified no axis for the last two. Chen also stated that although the "reliability of landmark identification in digital images was comparable to that in original radiographs” landmarks Po, ANS, AR and Upper Molar “should be scrutinized more carefully” when employing digital cephalometry.

Of concern was the statement: “…the best estimate for each landmark or “gold standard” for determining the inter-observer errors was defined as the mean position identified by 7 observers.” It is difficult to reconcile the use of the terms “best estimate” and “gold standard” interchangeably in the context of measuring error.

2. There were no clinically significant differences found in the accuracy of landmark identification of defined structures when comparing analog images versus on-screen identification of landmarks from a scanned copy of the analog image[102,111,128,131] with the following exceptions:
   a. Chen[130] found that the monitor yields a comparable or better level of performance in landmark identification compared to hardcopy with the exception of the vertical component of Go. However, it is worth noting that “interobserver error” was calculated by measuring the distance from the mean for each landmark, for each of the 12 tracers, rather than re-tracing multiple cephalograms and performing a statistical analysis for interobserver error. The author further states that there were several factors that could have played a role in the outcome including the scanning and printing procedures. There were

no "extra measures"[130] taken to control for distortion during the printing of hardcopies. Additionally, though there was a "calibration operation"[130] performed on the scanner prior to scanning analog tracings, there was no discussion as to the details of the aforementioned operation.

   b. Celik[99] found NLA (Nasolabial Angle) to have "low levels of reproducibility" using digital methods, Vistadent 2.1 AT (Dentsply International Inc, York, PA)) and Jiffy Orthodontic Evaluation (version 5.0, Rocky Mountain Orthodontics, Denver, Colorado, USA), compared to hand tracings.

3. Turner found no demonstrated clinically significant differences in the accuracy of landmark identification of defined structures when comparing direct, semi-direct and indirect image acquisition to one another.[102]

4. There were no clinically significant differences in the accuracy of cephalometric measurements in <u>single</u> timepoint films when analog and digital methods of cephalometric analysis were compared.[99,105,106,109,112,132,136,137] Exceptions included:
   a. Ongkosuwito[128] concluded that hand tracing was more accurate with Wits appraisal compared to a scanned image at 300 dpi and that

indirect acquisition demonstrated more accuracy measuring Facial angle (L1-NB,L1-Apo and Pg-NB).

b. Comparing hand tracing to Dolphin Imaging Software (Version 8.0), Power[108] found “the systematic error in the software’s calculation of LAFH%” for SNA, SN to Maxillary plane, upper incisor edge-apex to max plane and lower anterior facial height as a percent of total anterior face height “resulted in measurements 4% larger than manual techniques, a difference which is clinically significant.”[108]

c. Kubashvili[131] found statistically significant differences in the reliability of measurement of the facial angle using Vistadent Image Management System, v8.0 (Dentsply International Inc, York, PA) while comparing analog versus indirect acquisition and semi-direct imaging in both Dolphin, v7.0 and Vistadent Image Management System. Kubashvili[131] stated that differences could have been attributable to (1) obscurity of porion and orbitale, (2) differences in the algorithms of the two different computer software programs, or (3) to a difference in ability to view various landmarks in Vistadent, all of which appear to be plausible reasons.

5. Based upon calculated intraclass correlation coefficients, cephalometric measurements attained with and without enhancement in digital cephalometric programs were “in agreement”[105] with those measurements

found in hand tracing. Only Li–NB (mm) showed an ICC <0.75 for four out of the five programs tested when the basic features were used.[105]

6. Turner[102] studied the differences in landmark identification between onscreen digitization using ScreenCeph v1.4, hand tracing followed by digitization of the identified point and direct digitization. Turner found that significant differences existed in landmark identification of 15 of 28 measurements comparing ScreenCeph to direct digitization: 6 at the 5% level and 9 at the 1% level, with median score differences ranging from 0.2mm to 0.53mm.[102]

1.6.3. Digital vs. Analog Superimposition

Bill Gates, arguably the standard bearer of the technology movement stated: "…automation applied to an inefficient operation will magnify the inefficiency."[138] To fully understand the gravity of Gate's comment, and what it infers regarding cephalometric analysis, one must examine the essential differences in application of analog and digital technology as it relates to cephalometric superimposition technique.

Accurate analog cephalometric superimposition, though technically arduous in execution is conceptually quite simple. The process includes an operator, a light source, a pencil and a tracing medium such as acetate. The limiting factors include the tracer's ability to properly identify landmarks, draw lines, measure angles and correctly superimpose serial radiographs upon chosen landmarks. Like an artist, the operator has the ability to precisely trace any landmark, and more importantly, the freedom to transfer the landmark in an almost unlimited form to the transfer medium (the tracing acetate).

Digital superimposition, however, has constraints borne from the inherent limitations of digital technology. A pixel is a defined size, meaning that unlike analog technology where a tracer can choose to put pencil to acetate at any position, a digital tracer may only place the cursor upon a pixel in a predefined array. On a 16” x 20” monitor with a resolution of 1000 x 1000, there are 1 million pixels composing a 320 square inch screen, meaning that there are 3,125 pixels per square inch and each pixel is 0.0003” wide. Any point within that pixel can only be represented by that single pixel which will be a representation of the entire space it occupies. The pixel pitch, or the space between pixels, is another component of digital technology, which limits an operators’ ability to pinpoint a precise location on a screen. Such constraints, though small, may reduce the precision of digital landmark tracing and superimposition of images through cumulative summation.

Digital superimposition programs are, by definition, directed by the code, or instructions, which silently instruct the computer about how to execute the software. Unlike analog tracings, which can be superimposed in any manner desired by the operator, the finite, and sometimes limited number of landmarks offered by the program’s software engineers restricts the points upon which digital superimposition can be performed.

One can appreciate the importance of operators refining both tracing and superimposition skills before progressing to digital cephalometric analysis, lest the limitations of the digital medium magnify existing errors.

Bruntz[113] investigated the accuracy of computerized overall superimposition using Dolphin Imaging v.9 (Dolphin Imaging and Management Solutions, Chatsworth, Calif) versus hand tracing. AP changes in molar and incisor position were determined by perpendicular lines to ANS-PNS running through the mesial point of the first molar and incisor tip. Vertical changes were determined from vertical lines to ANS-PNS. No statistically significant differences were found in the distances of measured anatomic structures when comparing the digital and manual superimpositions.[113] Bruntz stated: "Superimpositions made from a computerized cephalometric program [Dolphin Imaging] by using a scanned cephalogram appear to be as accurate as those made from the original cephalogram with conventional manually traced techniques."[113]

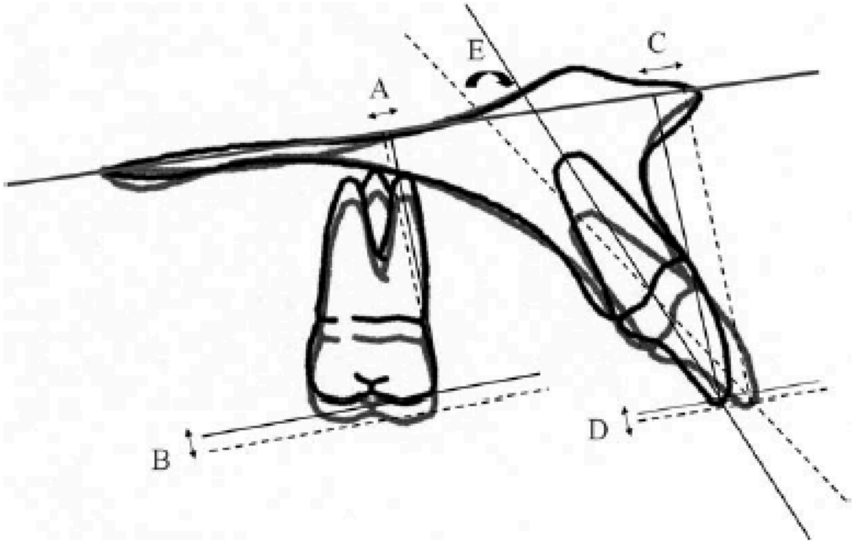


Figure 8: Bruntz' method of maxillary superimposition on ANS-PNS at ANS. Solid lines indicate initial tracing and dotted lines final tracing landmarks. A and B represent AP and vertical changes in molar position, respectively. C and D represent AP and vertical changes in incisor position, respectively. E represents angular change in incisor position.[113]

Roden-Johnson[133] evaluated the measurement accuracy of defined landmarks in maxillary and mandibular regional superimpositions by comparing analog and digital tracing using ABO superimposition analysis guidelines. The ABO standard for superimposition used by Roden-Johnson included "registration on the lingual curvature of the palate and the best fit on the maxillary bony structures."[133] Roden-Johnson found no statistical differences in the values of hand and digital tracing in maxillary regional superimpositions with most values within ± 1mm and ±1° when comparing T1 and T2 values of both methods.[133]

Huja[100] compared hand and digital maxillary regional superimpositions superimposed according to the ABO recommendations. The digital superimpositions were constructed using Dolphin Imaging v.10. Huja found no differences in the accuracy of measurement across two time-points of displacement of the defined landmarks (U1 Tip, U1 Apex, U6 Tip, U6 Apex), between analog and digital methods.

Bruntz[113] and Huja[100] referred to hand traced cephalometric analysis as the "gold standard", however, in the absence of implants, had traced cephalograms are better described as a "control group" rather than "gold standard" as studies[49,59,61,139] have demonstrated that tantalum implants placed interstitially in the maxilla are the only stable, fixed "gold standard" reference points upon which regional serial superimpositions may be aligned and registered for true understanding of changes due to growth and of treatment effects.

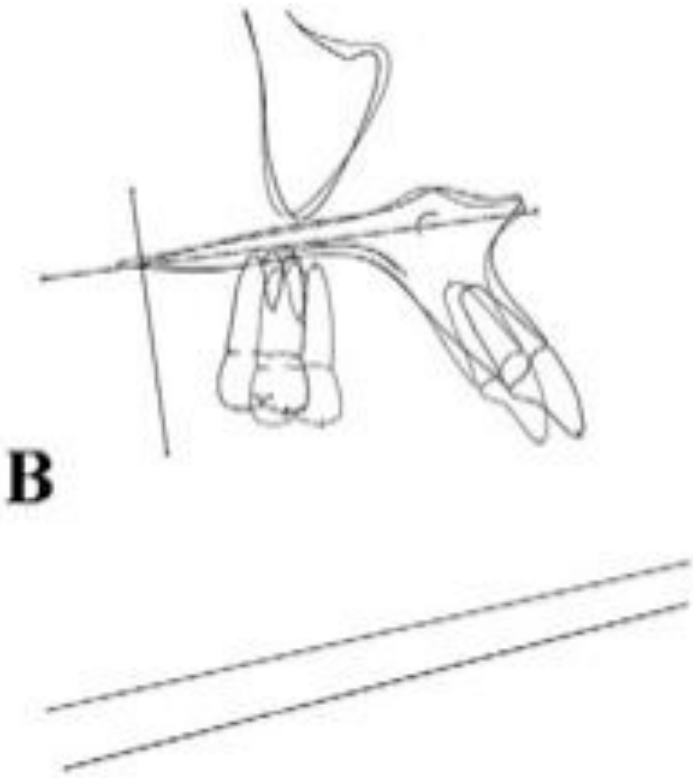


Figure 9: Huja[100] method of alignment for maxillary regional superimposition.

1.7. Purpose

Metallic implants permit construction of reference “gold standard” superimpositions thereby enabling a quantitative evaluation, by comparison, of the measurement accuracy of displacement of selected dental structures derived by analog structural method and digital method of superimposition.

To date, no study has compared the displacement of defined dental landmarks in maxillary regional superimpositions across paired time-points utilizing metallic implants as fixed reference points. Therefore, the purpose of this study is to measure the displacement of the defined dental structures across paired timepoints utilizing tantalum implants as a fixed reference points to determine if the use of the structural method and/or computer-generated regional superimpositions of the maxilla are as accurate as the implant superimposition method, and whether any differences are clinically relevant.

1.8. Specific Aims

Specific Aim 1: To determine if there are differences in the measured displacements of defined dental structures across paired time-points in maxillary regional superimpositions generated in Dolphin, Quick Ceph, and the structural methods compared each other and to the implant method of superimposition.

Specific Aim 2: To determine if differences in in the measured displacements of defined dental structures across paired time-points in maxillary regional superimpositions generated in Dolphin, Quick Ceph, and the structural methods are clinically relevant.

1.9. Location of Study

The design and preparation of this study took place at:

Nova Southeastern University College of Dental Medicine
3200 South University Drive
Fort Lauderdale- Davie, Florida 33328

CHAPTER 2: MATERIALS AND METHODS

2.1. Grant

This study was awarded a grant by the Health Professions Division at Nova Southeastern University.

2.2. Lateral Cephalograms

After review and exemption by the IRB of Nova Southeastern University, the sampling frame for this study was the 36 patient records comprising the Matthews Acquisition Group, accessed with permission, from the Craniofacial Research Instrumentation Laboratory (CRIL), University of the Pacific, Arthur A. Dugoni School of Dentistry Department of Orthodontics, 2155 Webster Street, Suite 617 San Francisco, CA 94115. Mathews originally acquired all of the radiographs for the study he performed in 1978.[66]

In acquiring the data set, Mathews utilized the following inclusion criteria:

1. Participants were patients of record of the Department of Orthodontics, University of California School of Dentistry, San Francisco, CA.
2. The participant's orthodontic records were complete with no missing data.
3. Parental permission allowing the insertion of tantalum implants was granted for each participant.

36 patient records comprise Mathews' acquisition group, including 13 male and 23 female. Patients' ages at the time of records acquisition were 3.6 - 9.1 years and were

recalled annually for between 5 - 14 years. The sample utilized for this study consists of selected cephalometric radiographs of 22 patients from the sampling frame. 14 patient records did not meet the inclusion criteria and were therefore excluded from the study.

Inclusion criteria for the cephalometric radiographs utilized in this study (Figure 10) were as follows:

1. Radiographic quality sufficient to allow detailed analysis.
2. Two or more implants intact in both the maxilla and mandible across all time-points.
3. The patient records were complete and unaltered.

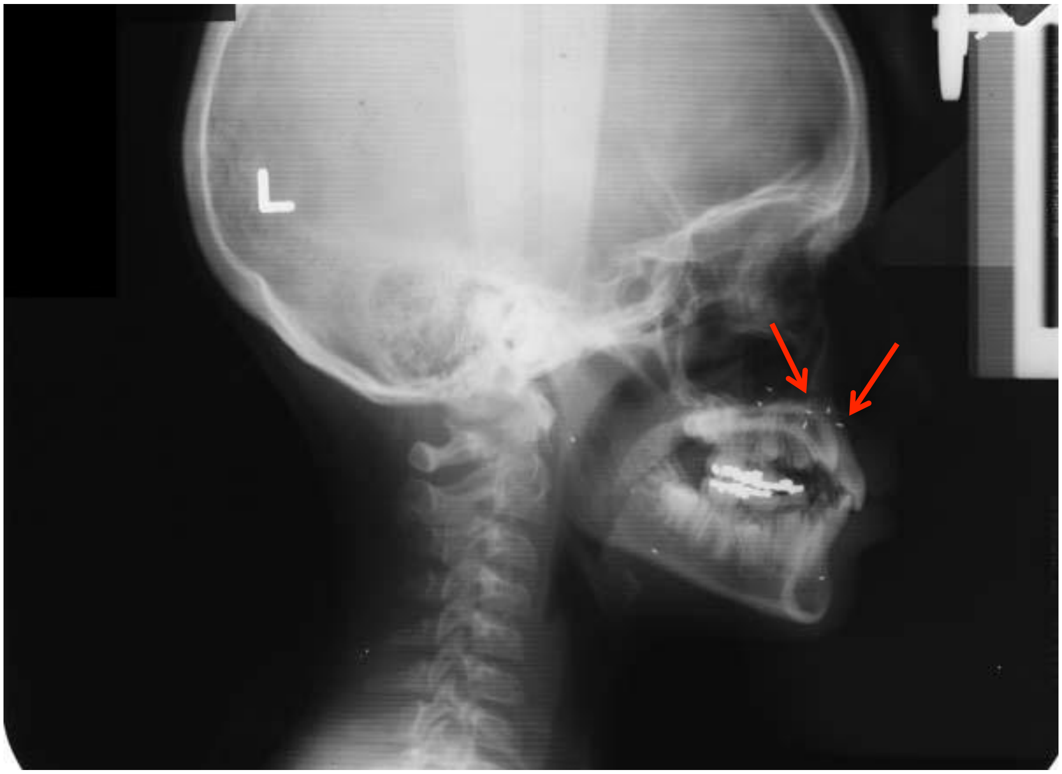


Figure 10: Arrows indicate location of maxillary tantalum implants present in a lateral cephalometric radiographic image.

All radiographs in this study were taken at approximately 2-year intervals, allowing three serial cephalograms for every patient. For males, the images were taken at ages 12, 14 and 16 years (T_1, T_2, T_3) and for females they were taken at ages 10, 12 and 14 years (T_1, T_2, T_3).

No potential ethical issues could be identified as part of this research study. Due to the observational nature of this study no procedures were performed or implemented on human subjects. All data collection complied with IRB and HIPPA regulations and all data was de-identified to ensure confidentiality.

2.3. Analog Method

A diagrammatic summary of the workflow process is outlined in Figure 11.

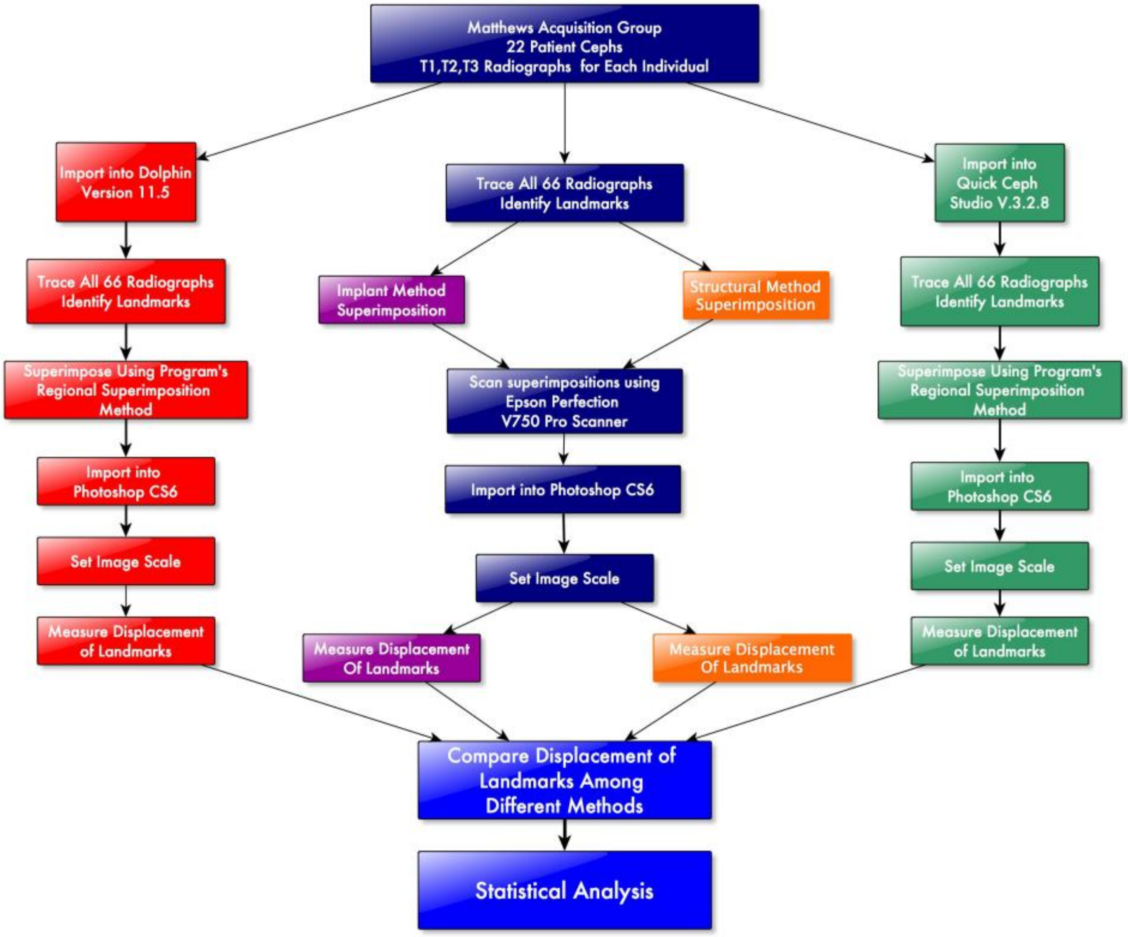


Figure 11: Workflow diagram for the study

Richard Singer, DMD, MS hand traced all patient serial radiographs (T_1, T_2, T_3) on acetate using a 0.3mm drafting pencil. Tracings were performed side by side in order to ensure accuracy in tracing of anatomic landmarks[55]. Landmarks were identified to allow superimposition using the structural and implant methods. The “defined dental structures” traced included central incisor tip and apex, mesial contact of the first molar and an average terminal root length of the first molar centered mesio-distally along the long axis of the tooth. Templates of the most visibly clear teeth were created and transferred to the other films in the series to allow precise duplication of the landmarks for measurement.

The outlines of all maxillary implants were traced at all timepoints using a 0.3mm drafting pencil.

2.4. Structural and Implant Superimpositions

Structural superimpositions were performed as described by Björk[61], Björk and Skeiller[65] and Johnston[55] including "best fit" registration on the zygomatic process of the maxilla and the bony anatomic details superior to the incisors. In addition, the anterior inferior surfaces of the hard palate assisted in orientation, with the PTM fissure of the older tracing lying at or behind that of the newer.[55]

Fiducial lines were drawn adjacent to the maxilla as described by Johnston[55] allowing quicker and more precise superimpositions of tracings forward or backward, pairwise, throughout the series.[55]

Acetate tracings of paired timepoints (T1-T2, T2-T3) for each patient were aligned using the fiducial lines (for structural method) or implants (implant method) and scanned into the designated patient folder, stored on the secure Nova Southeastern College of Dental Medicine server. Tracings were scanned into digital jpeg format at 300 DPI[101,128] using an Epson Perfection V750 Pro scanner (Epson USA, Long Beach, California, USA).

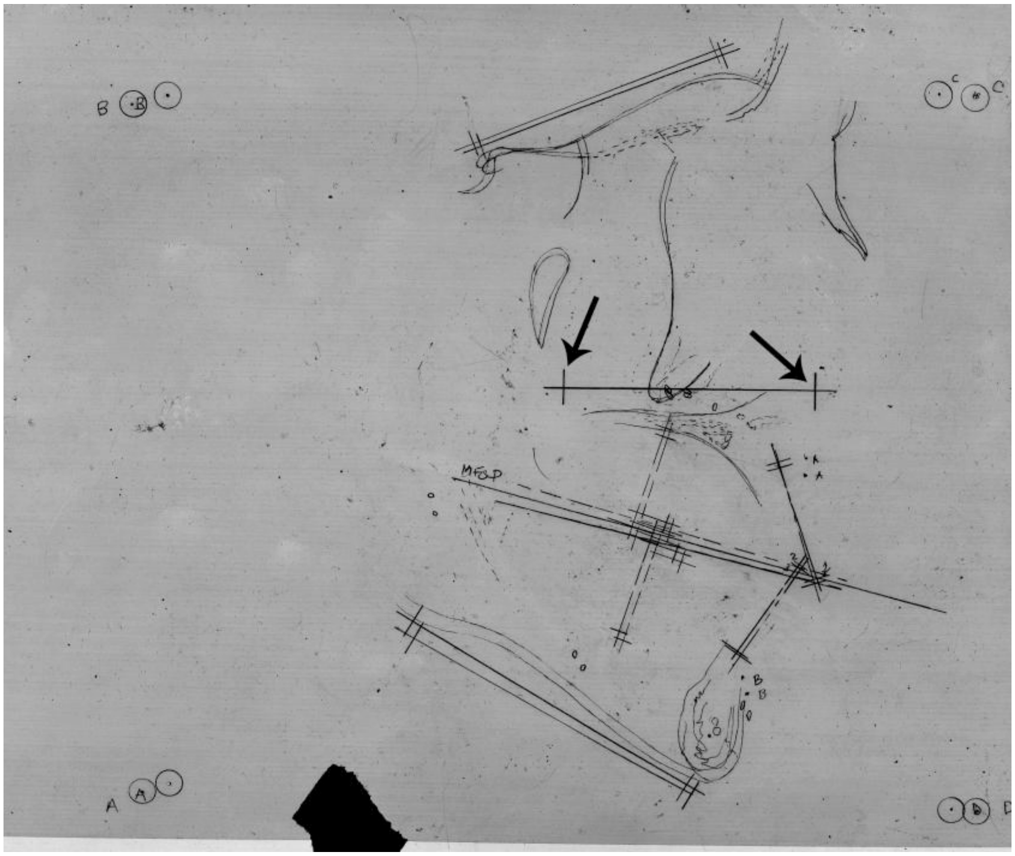


Figure 12: Structural method of superimposition. The arrows demonstrate superimposition of the fiducial lines for the maxillary tracings.

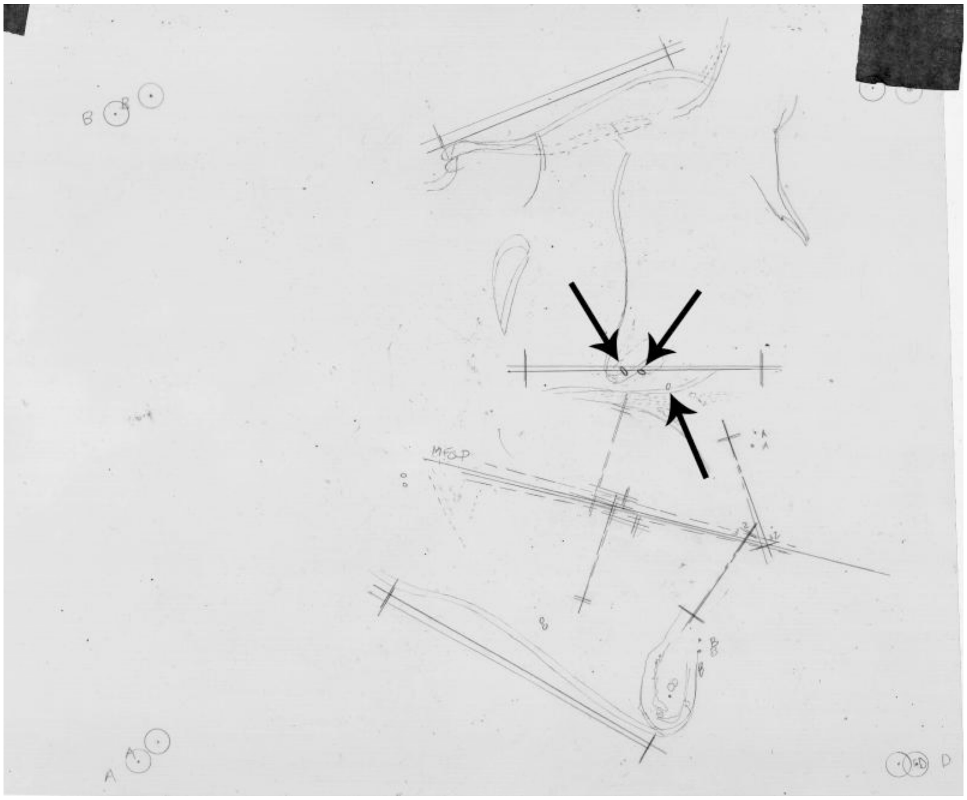


Figure 13: Example of the implant method of superimposition. The arrows demonstrate the implants from different timepoints superimposed over one another.

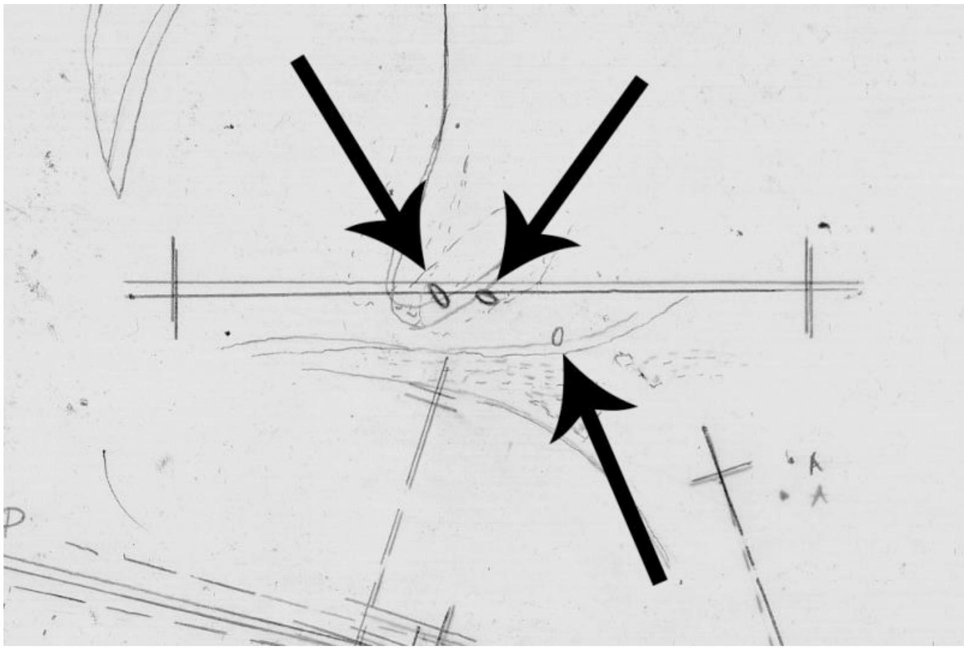


Figure 14: Magnified view of implant superimposition (arrows demonstrate superimposed implants). Notice the changes in the alignment of the fiducial lines.

2.5. Digital Method

All patient original cephalometric radiographs (T_1, T_2, T_3) were scanned into digital jpeg format at 300 DPI[101,128] using an Epson Perfection V750 Pro scanner and subsequently imported into Dolphin Imaging V11.5 (Dolphin Imaging, Chatsworth, California, USA) and Quick Ceph Studio V3.2.8 (Quick Ceph Systems, San Diego, California, USA) cephalometric analysis programs. Landmarks digitally traced included those required to complete maxillary regional superimpositions according to the recommendations of the respective software programs. Outlines of the most visibly clear maxillary central incisor and 1st molar were transferred to the other films in the series to allow precise duplication of the landmarks for measurement.

Maxillary regional superimpositions were performed using the programs' automated functionality according to the manufacturers' instructions.[140,141] Digital superimpositions included paired timepoints (T1-T2, T2-T3) for each patient. Dolphin V11.5 automated maxillary regional superimposition tracings were aligned according to manufacturer recommendations: "to the (ANS-PNS) line, with ANS points overlapping".[140] Manufacturer recommended Quick Ceph Studio V3.2.8 automated superimposition preferences were created similar to Dolphin automated regional superimpositions through superimposition of "ANS-PNS@ANS".[141]

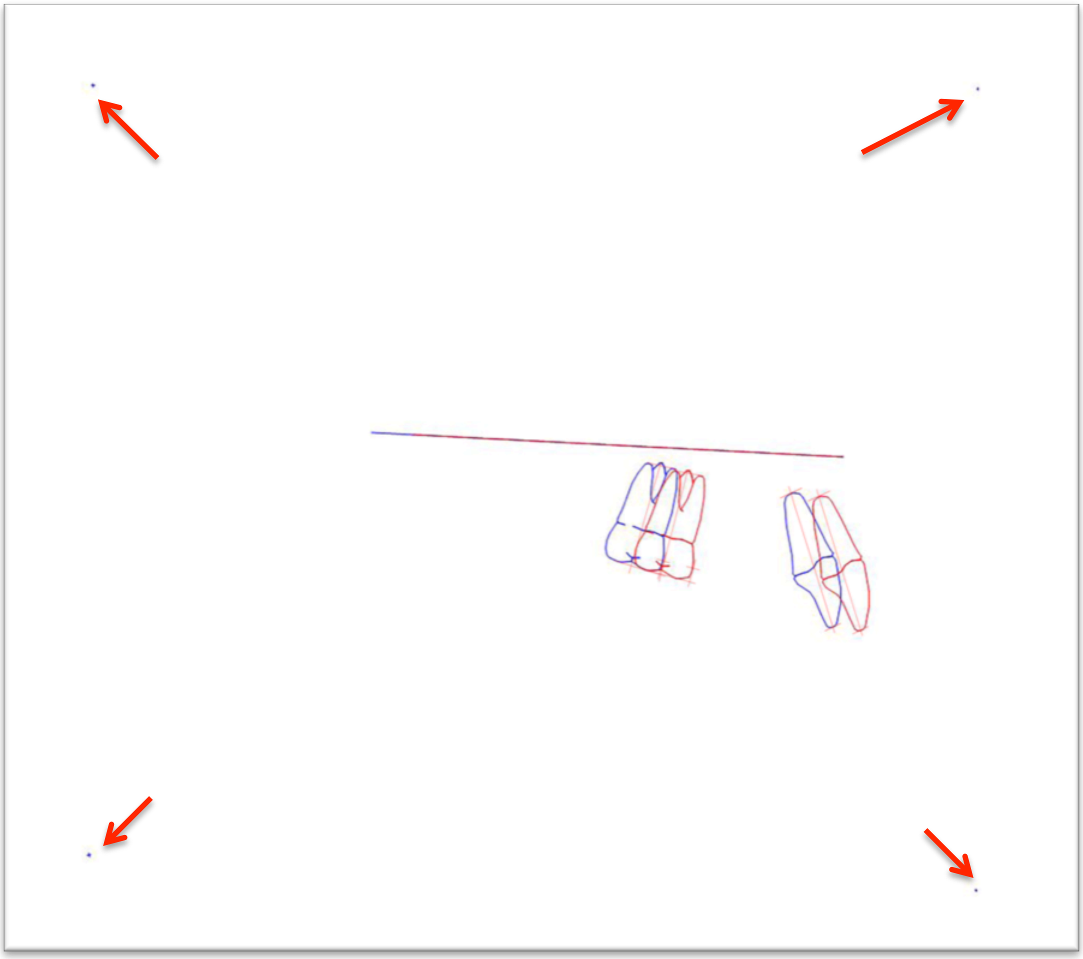


Figure 15: Example of Dolphin method of Superimposition. The crosshairs in the corners (red arrows) are digital duplicates of the punch holes of known distance for scale calibration purposes.

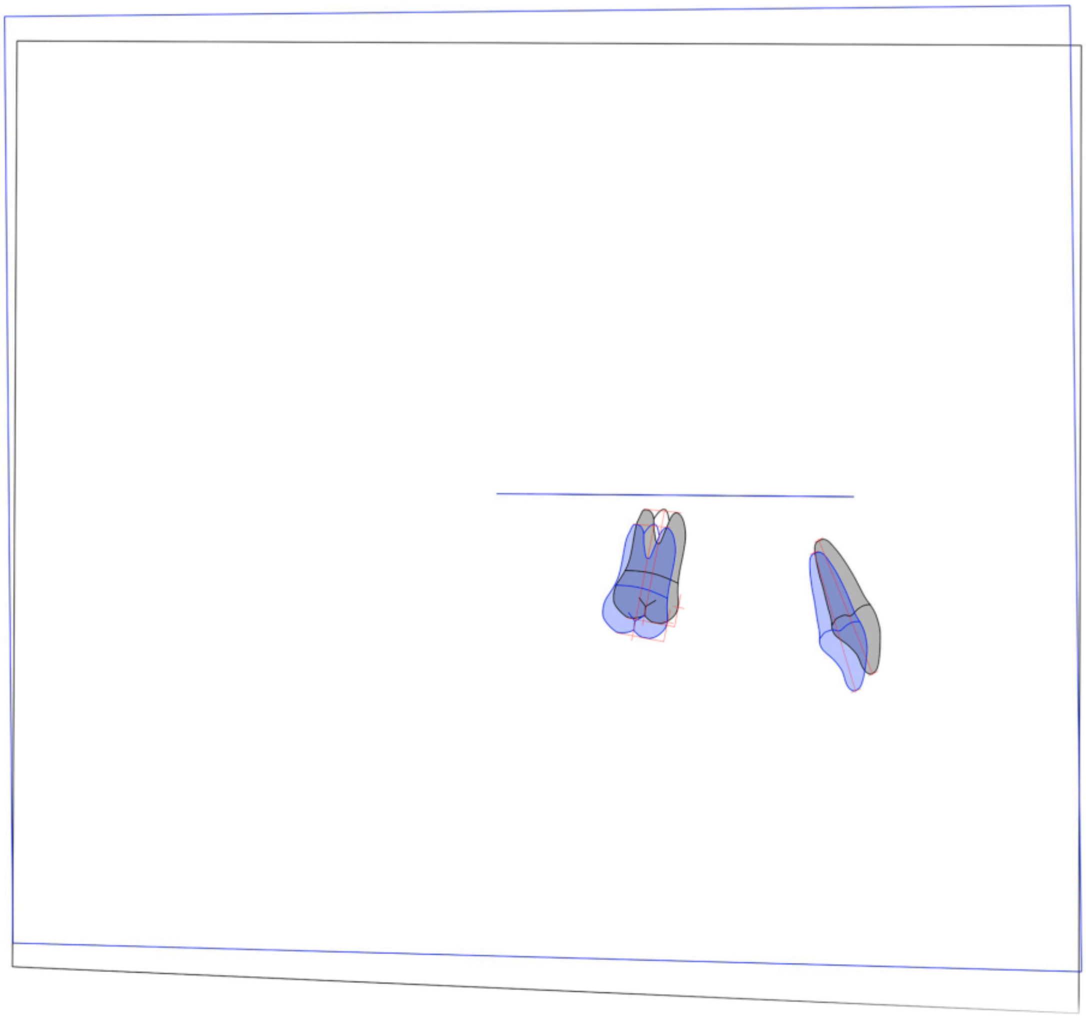


Figure 16: Example of Quick Ceph method of superimposition. For Quick Ceph, lines connect the punch holes instead of crosshairs.

Resultant superimpositions were exported in 1:1 scale and stored on the secure Nova Southeastern College of Dental Medicine server.

2.6. Measurement of Displacement of Defined Dental Landmarks

Superimpositions were imported into Adobe Photoshop CS6 Extended as .jpg files. All digital images were standardized using the scale feature of Adobe Photoshop CS6

Extended (Adobe Systems Inc., San Jose, California, USA) where scale calibration was applied and displacements of the defined dental structures measured.

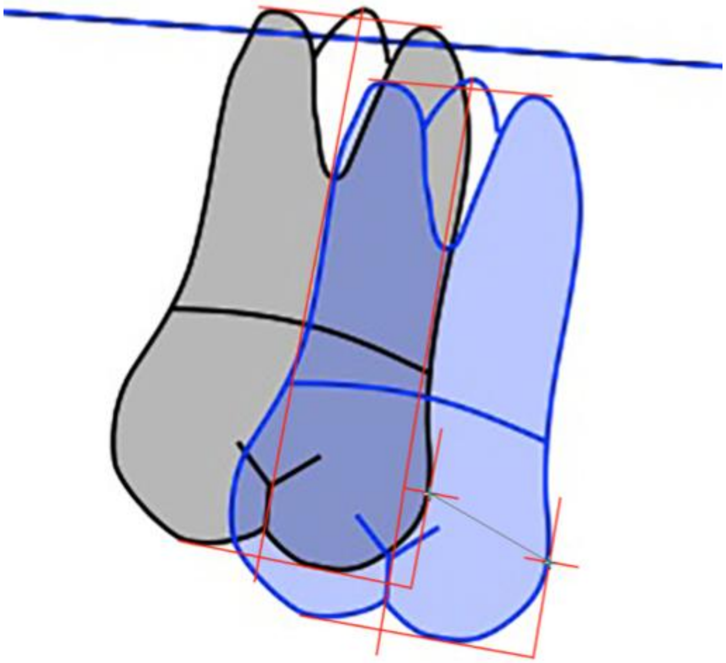
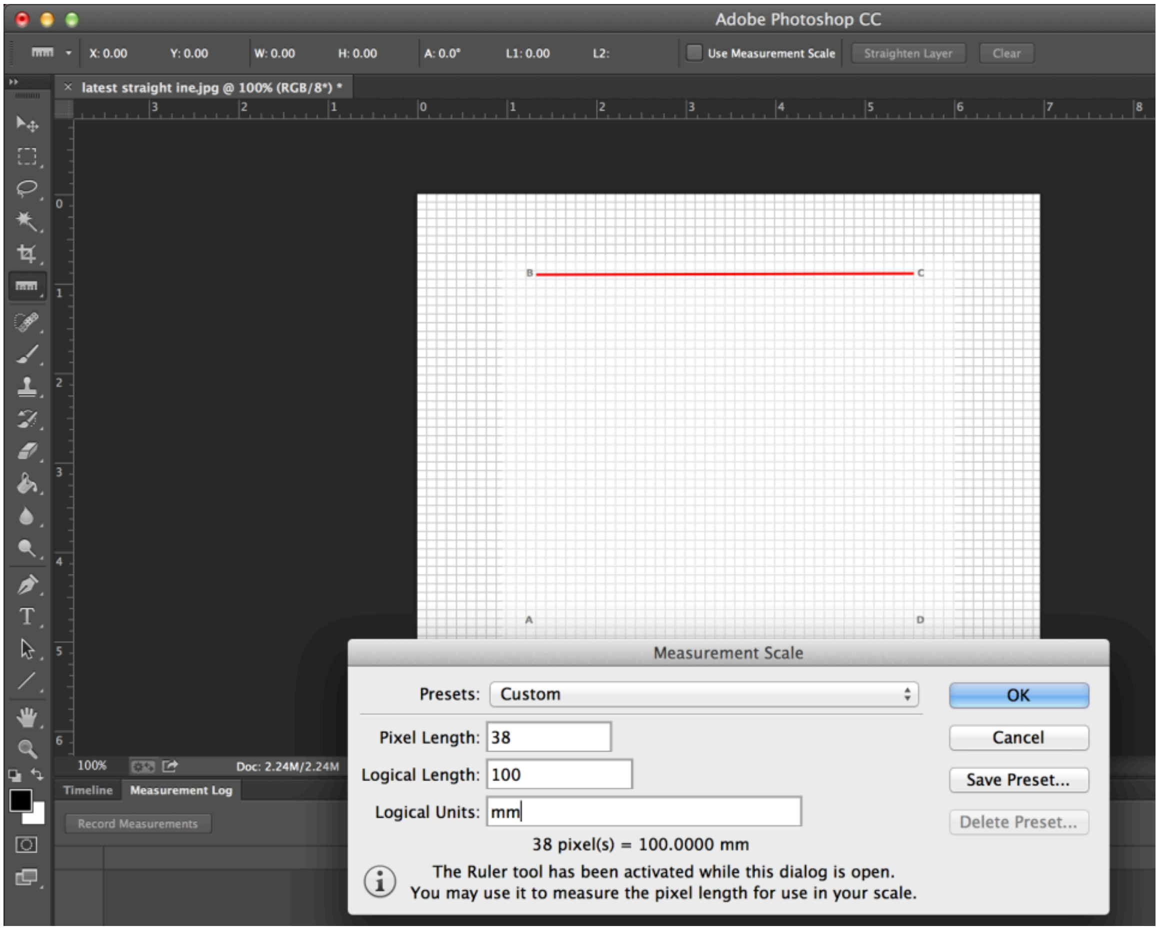


Figure 17: The grey line represents the measured displacement of the mesial molar contact using Adobe Photoshop. This method was utilized for all four methods of analysis (Implant, Structural, Dolphin & Quick Ceph).

A significant incidental finding of this study was an unexpected difficulty in accurately and precisely measuring the displacement of the defined dental structures (the "measurement scale" tool (figure 18)). Photoshop uses a pixel-based calibration of on-screen objects of known distance to scale all other measurements in the image. Adobe states that the measurement scale tool allows users to "accurately measure distance",[142] however, we found errors (in some cases >1.5%) when using this tool, irrespective of monitor, computer or operating system.



Presets: Custom
Pixel Length: 38
Logical Length: 100
Logical Units: mm

38 pixel(s) = 100.0000 mm

The Ruler tool has been activated while this dialog is open.
You may use it to measure the pixel length for use in your scale.

Figure 18- The measurement scale tool in Adobe Photoshop allows one to create a scale against which all other on-screen objects can be measured. In this case, the line of known length (100mm) extends through 38 on-screen pixels (in this case, simulated by the grid) allowing a measurement scale of 38 pixels equaling 100mm.

Photoshop measurement errors were challenging to address due to the unidentifiable nature of the source of the error. Close examination and scrutiny of our methods offered no understanding of extant measurement errors even following on-screen calibration. Calibration of known vertical distances (punch holes A-B or C-D, Figure 19) led to inaccurate horizontal measurements and vice versa. Even corner to corner (A-C) calibration yielded inaccurate measurements for the opposing diagonal (B-D). To our knowledge, no other study utilizing Adobe Photoshop for measurement purposes has reported identifying calibration errors, and we endeavored to find a solution.

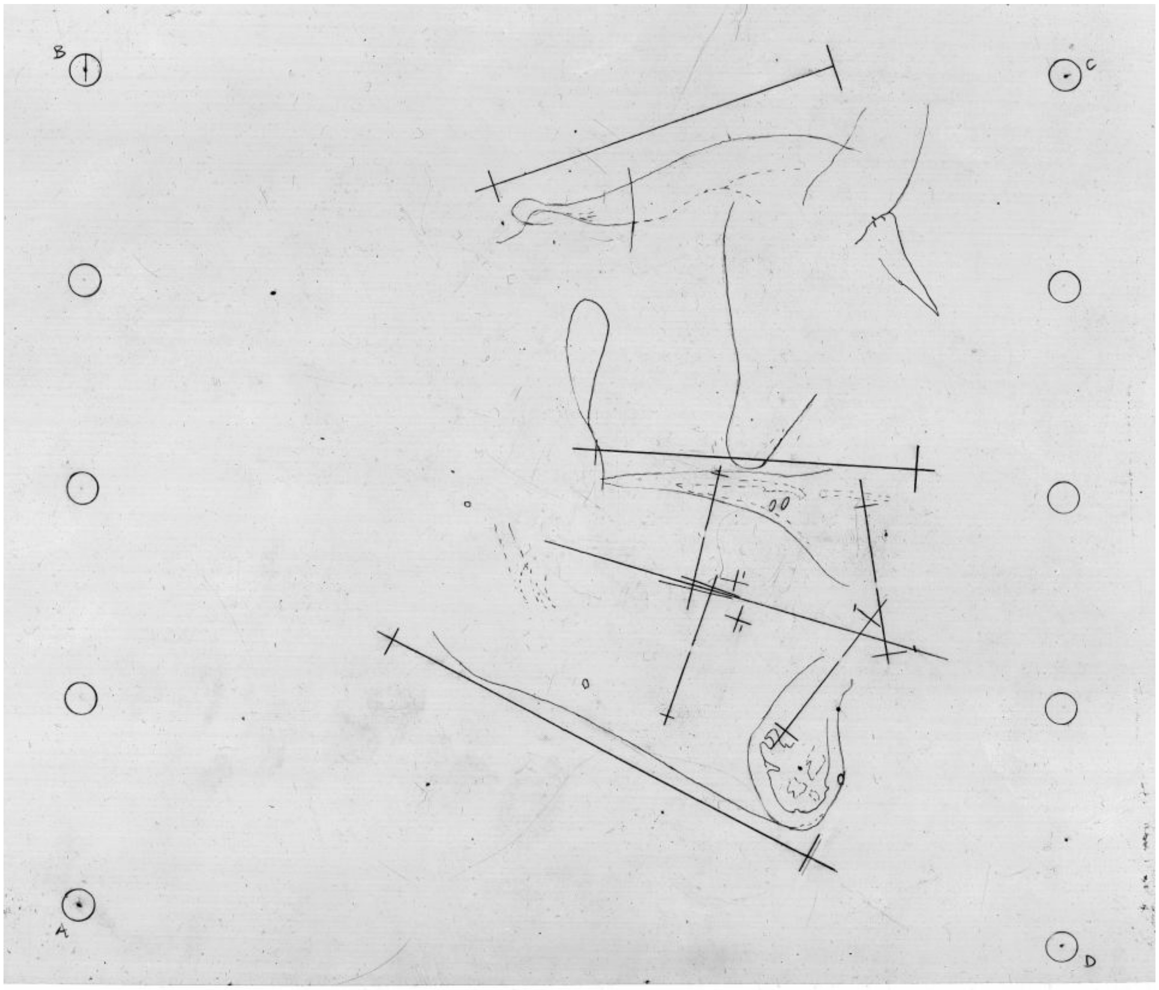


Figure 19: Example of labeled corner punch holes of known distances (A,B,C,D) used in calibration.

An initial thought was that in order to properly use a pixel-based scale, the cephalogram must be perfectly aligned along the horizontal or vertical axis. If one were to set the scale using points B and C and the radiograph was not completely level with respect to the horizontal axis, then the line between the points would pass diagonally through the pixels, which is a longer distance than perpendicularly (figures 20 & 21). Setting the B-C line to a true horizontal, should have created a more accurate scale calibration, but instead continued to yield inaccurate measurements of known vertical distances and calibration using said approach for known vertical distances created errors in horizontal measurement.

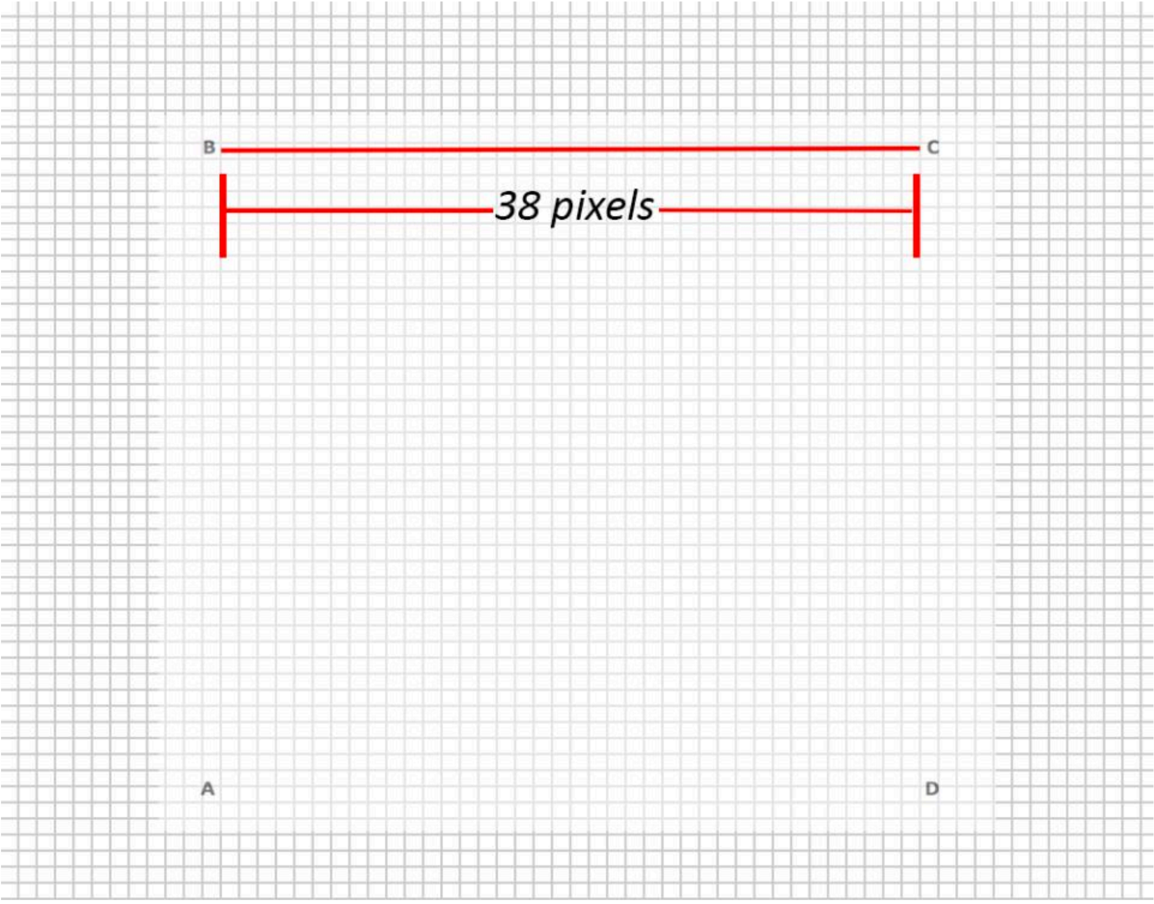


Figure 20- The line crosses the pixels at 90 degrees, traveling the shortest distance through each pixel, extending 38 pixels in total.

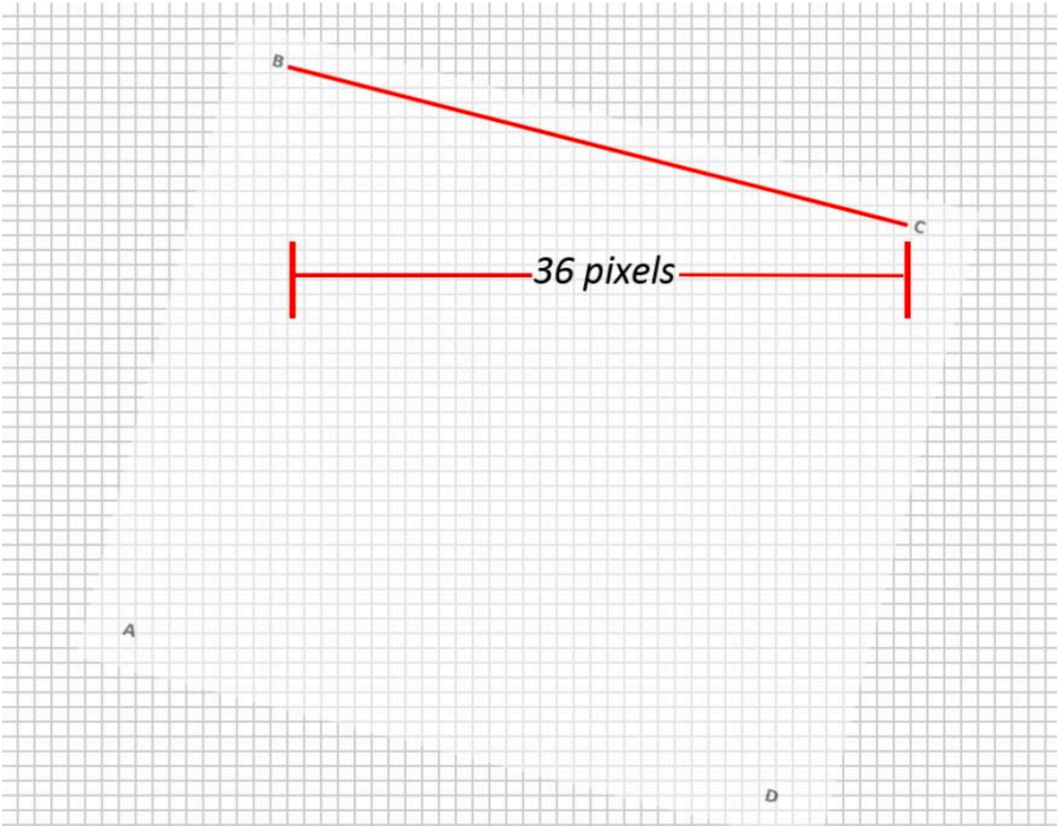


Figure 21- If the cephalogram is rotated relative to the horizontal axis, the line connecting B-C crosses through the pixels diagonally, travelling a longer distance within each pixel. As a result, instead of including 38 pixels (figure 3) it only crosses 36. Measurement scale would therefore change from 100mm=38 pixels (figure 3) to 100mm=36 pixels. The resultant calibration error of 5.3% would be applied to every future on-screen measurement.

The only solution for the problem of measurement inaccuracy was a correction factor applied to the raw data. The diagonal measurements (B-C and A-D) were recorded and averaged for 10 cephalograms of each method, and compared to the known distances. The correction factor, applied to the raw data provided an accurate, final measurement prior to submission for statistical analysis.

All measurement data was stored in a password protected Microsoft Excel (Microsoft Corporation, Redmond, Washington, USA) spreadsheet.

Given that one experimenter, Dr. R. Singer, produced the analog tracings utilized in this study, it is important to estimate the reliability of this individual tracer. To that end, a random sample of 10 tracings were selected and traced at a separate setting in order to independently assess intra-rater reliability. 10 Dolphin and 10 Quick Ceph regional superimpositions were selected and traced at a separate setting to assess intra-rater reliability for the digital method.

2.7. Statistical Analysis

Descriptive statistics as well as a mixed-effects, generalized linear model [GLM] were utilized for analysis of the data and an intra-class correlation coefficient [ICC] was used to evaluate intra-rater reliability.

CHAPTER 3: RESULTS

Table 1 shows mean total displacements of the defined dental structures for all methods (implant, structural, Dolphin & Quick Ceph). All methods exhibited mean displacements ≤ 0.72mm and the Implant and structural methods showed smaller ranges than that of Dolphin and Quick Ceph (6.67mm and 5.97mm vs. 9.19mm and 9.53mm, respectively).

Table 2 presents method displacements relative to the Implant method reference. The structural method ($p=0.00$) showed statistically significant differences versus the implant method and demonstrated the smallest 95% confidence interval range compared to Quick Ceph and Dolphin (0.45mm, 0.75mm and 0.95mm, respectively).

Table 3 displays method displacements by tooth relative to the implant method reference. The structural method incisor and molar measurements demonstrated statistically significant differences ($p=0.00$) with a smaller 95% confidence interval range than Dolphin and Quick Ceph Incisor and molar measurements (0.64mm and 0.56mm vs. 1.23mm and 1.12mm and 1.08 and 1.09mm, respectively).

Table 4 shows method displacements by landmark relative to the implant method reference. The four structural method landmarks (incisor crown and apex, molar mesial contact and apex) demonstrated statistically differences versus the implant method ($p<0.05$) and had smaller 95% confidence interval ranges compared to the corresponding locations for Dolphin and Quick Ceph.

Figure 22 presents scattergrams for total individual measurement differences relative to the reference for each method (n=176). The structural method showed a smaller dispersion compared to the Dolphin and Quick Ceph methods.

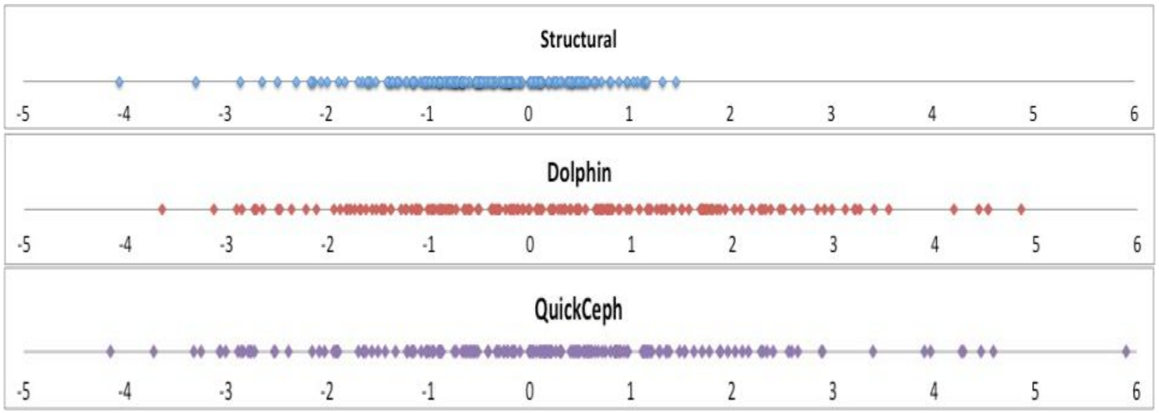


Figure 22- Scattergrams of method displacements relative to Implant method reference*

*All values in mm

The ICC for the analog and digital tracing intra-rater reliability showed non-statistically significant p-values.

CHAPTER 4: DISCUSSION

4.1. Findings

Serial maxillary regional cephalometric superimpositions allow clinicians to visualize maxillary dentofacial changes due to growth and orthodontic treatment separately. Superimpositions may be performed by manual tracing (analog method) or digitally, by the use of computer programs. It is important to understand the accuracy of the method of superimposition employed to estimate the effect of that method upon evaluation of growth and treatment effects.

Accuracy may be determined by comparison of methods to a referent "gold" standard. In the case of maxillary regional superimpositions, such a "gold standard" is obtained by using a database consisting of radiographs of individuals in whom fixed metallic implants have been inserted into the maxilla, namely, the Mathews Acquisition Group. To our knowledge, studies comparing the accuracy of digital and analog methods of maxillary regional cephalometric superimposition, employing an implant reference, have not previously been reported. Utilizing the radiographic data of the Mathews Acquisition Group, this study compared analog, digital, and reference methods of maxillary regional cephalometric superimpositions by measuring the resultant displacement of defined dental structures assessed across paired time points.

The principle finding of this study was that differences in mean displacement of defined dental landmarks were different for the analog (structural) and digital (Dolphin, Quick Ceph) methods of maxillary regional superimposition when compared to the implant method. The three non-reference methods each demonstrated less than 0.5mm mean displacement difference compared to the implant method.

The standard error of the mean displacement from the reference was considerably smaller for the structural method than for the digital methods, for all defined dental structures (landmarks) measured, which was potentially due to the difficulty in accurate digital representation of identified landmarks due to software limitations in the digital methods. There were significant methodological differences in representation of identified landmarks between in the digital and analog methods.

The structural method of superimposition employed an individualized template of the incisor and molar that was traced from the most easily identifiable image of one each participant's three cephalograms. The template permitted transfer by tracing of reproducible incisor and molar representations across each time point. In contrast, it was not possible to create a digital "template" that permitted similar reproducibility across the time points in either of the digital software programs evaluated in this study. Dolphin software creates digital tooth templates (incisor and molar) based upon the identification of the incisor edge and apex and molar apex and crown. Dolphin permitted the tooth outline to be copied forward and backward in a series of cephalograms, however, the generalized shape of the digitally generated template could *not* be manipulated to perfectly match the natural tooth form. The result was a "best fit" of the incisor and molar, rather than a precise outline that was a routine part of the analog template method. The Quick Ceph software approach was somewhat different, in that the tooth "templates" created were based upon the scale of the image. The digital tracings of both the incisor and molar that resulted were generally not representative of actual tooth dimensions; moreover, there was no method available for individualized corrections. Sophisticated diagnosis, treatment planning, and evaluation of treatment outcomes are dependent on accurate cephalometric information. Such information is predicated upon accurate identification and accurate digital representation of dental landmarks that are then used to construct cephalometric tracings and resulting cephalometric measurements. Our observations indicate that Quick Ceph and Dolphin do not provide precise landmark representation in all cases, particularly regarding individual tooth size and shape when performing regional superimpositions.

Digital and analog cephalometric techniques use different methods for detail enhancement to facilitate accurate tracing. Hand-tracing (analog) magnification is accomplished through a set of loupes or a magnifying glass, while digital magnification occurs through digital "zooming" of an on-screen image. The digital method can magnify an image considerably more than the fixed limits of loupes, but there are important issues inherent to the process. Magnifying an image by 400%, 800% or even 1600% results in a pixelated image. A pixelated rendering of a rounded edge in an image acquires the shape of the individual pixels, which are rectangular. Precisely identifying or measuring to the apex of a rounded structure becomes imprecise when there are only sharp edges. No such pixilation occurs in analog images regardless of magnification because pixels play no role. Theoretically, one could use a high power microscope to considerably magnify and trace analog cephalograms, yet curved edges would remain rounded, potentially resulting in more precise identification and tracing of landmarks with curved surfaces, rather than less precise with increased magnification, a feature of the digital techniques.

The smaller standard error of mean displacement relative to the reference for the structural method may also be explained by inherent differences in the superimposition techniques. The structural method superimpositions were performed according to Johnston's guidelines[55], but neither of the digital methods offered a reasonable way of approximating the "bony anatomic details superior to the incisors" as Johnston suggested for maxillary superimposition and used "ANS-PNS at ANS" as a substitute. Current digital software has limited ability to trace the maxillary bony details required for Johnston's superimposition methods.[55] The digital superimposition methods employed in this study strictly followed the recommendations in the respective software user manuals.

The relative standard error (RSE) is a measure of reliability or precision, and is represented by the formula: ((standard error/mean)*100). The RSE for the displacement of defined dental structures versus the reference was 19.57% for the structural method, 76.92% for Dolphin and 320% for Quick Ceph. The RSE values derived from the Dolphin and Quick Ceph methods were almost 4 and 16 fold multiples, respectively, of that of the structural method.

While none of the methods demonstrated mean displacement of defined dental structures versus the reference exceeding the preciously discussed threshold for clinical significance, the digital methods showed the smallest difference. However, the digital methods also exhibited a markedly larger RSE, demonstrating an important difference between the methods. The structural method can be described as generally being "off-target", but more precise (i.e., less scattered and more reproducible) than the digital methods. Conversely, the digital methods are, on average more accurate (i.e. mean values not statistically different from the reference method mean), but imprecise (i.e., more scattered and less reproducible) by multiples of the mean value. Clinical application of our results relative to selecting a method of regional cephalometric superimposition, suggests that the selection is between the structural method that exhibited good precision and accuracy within a clinically acceptable range, or the digital methods, that on average are, more accurate, but also imprecise, such that the magnitude of any single measurement could have a value that exceeds multiples of the mean value.

A power analysis yielded a power of 18% for this study, meaning there was only an 18% chance of not making a Type II error (failing to reject a false hypothesis) when comparing each of the methods of superimposition to the implant method (reference). The null hypothesis tested in this study was the hypothesis of no difference in the displacement of defined dental landmarks resulting from any of the methods of superimposition compared to the implant method. The null hypothesis was rejected for the structural method, but not for the digital methods, however, the low power of our analyses indicates a strong likelihood that Type II errors for the digital methods may have gone undetected. Taking into account the low power and large standard error of the mean displacements would suggest that a larger sample size and greater power might permit evaluation of whether the failure to reject the null hypothesis of no difference from the reference for the digital methods was a correct decision, however, an accessible larger sample does not exist.

Few studies[40,143] in the literature discuss the threshold of clinical significance for measured landmark displacements resulting from cephalometric regional superimpositions. Baumrind and Frantz[40] are alone in explaining their understanding of clinical significance as it relates to cephalometric analysis.

> "The reader may appropriately ask how much error can be tolerated in clinical procedures. Clinical procedures always involve comparisons between values for two head films or between values for one head film and some set of standards or "norms." In either event, it is the difference between the two values for any given measure which is important."
> "…we could not properly ascribe clinical significance to a change in mandibular plane angle of less than 2 x 1.8 or 3.6 degrees [2 standard deviations] or to a change in interincisal angle unless it exceeded 2 x 3.54 or 7.1 degrees [2 standard deviations]. This is not to say that smaller differences are not important to us as clinicians. On the contrary, we all know that they are important. It is, rather, to say that our current measurement instrument, the angular head film measurement, is in most cases too inaccurate to differentiate all but the grossest changes."[40]

Baumrind and Frantz[40] suggested that the use of cephalometric measurements for diagnosis, treatment planning and case evaluation are insignificant unless they are beyond two standard deviations of the measurement error for a landmark, angular or linear measurement.

Other studies have mentioned the term, “clinical significance”, without explicit definition. For example, Bruntz, et al.[113] compared measurements and superimpositions produced on analog radiographs with those made on scanned digital images, and found that “linear distortion was no greater than 1.1mm” and “because the width of the fiducial mark itself was approximately 0.5mm, one might contend that the total disparity between modalities truly is clinically insignificant.”[113] Huja et al[100] compared hand-traced and computer based maxillary regional superimpositions, and stated: “…the differences were small (<1mm) and can be considered clinically insignificant.” Roden-Johnson et al.[133] compared Quick Ceph and hand-traced cranial base and regional superimposition accuracy and concluded: “…the variation was less than 1.5mm for all of them [landmarks]; this leaves the clinical significance questionable because the width of the pencil used to trace the cephalograms was 0.5mm.”[133] Roden-Johnson et al. further stated: “…this study confirms the findings of other investigators[143-145] showing that the differences in landmark identification between hand and computer are not clinically significant.”[133]

The conclusions of Bruntz et al.,[113] Huja et al.,[100] and Roden-Johnson et al.[133] derive from use of a technique artifact to make inferences regarding a physiologically, diagnostically, or biologically meaningful difference in measurements where no such relationship exists. Baumrind and Frantz,[40] elaborated further regarding the clinical significance of errors in landmark identification: “…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."[40] Baumrind and Frantz continued: "Suppose we are not too demanding and require merely that the observed difference be at least twice the standard deviation of the estimating error. This is not an unreasonably rigorous demand…".[40]

Baumrind, Miller and Molthen[146] studied what they called "typical landmark displacements due to error of tracing superimposition", i.e., the displacement of landmarks due to errors in tracing when tracings are superimposed. In the example cited, tracings were superimposed on the palatal plane and landmark displacement was observed. The standard deviations (SD) of the measurements for the upper incisor edge and the upper first molar cusp were 1.33mm and 1.10mm respectively.[146] Application of Baumrind and Frantz's[40] suggestion of 2*SD for changes to be "real" would mean that the upper incisor edge and molar cusp errors would have to be greater than 2.66mm and 2.20mm respectively, in order not to be considered error in landmark measurement alone. While none of the methods of superimposition in our study exceeded Baumrind and Frantz's suggested thresholds, as early as 1976 Baumrind and Frantz stated that by using computers for tracing superimposition: "…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."[40] The terms "biologic significance" and "clinical significance" refer to "real" or "biologic" differences in pairwise comparison of measurements that are not attributed to measurement error alone.

Applying Baumrind and Frantz's approach, we created proposed thresholds for clinical significance using the study results reported by Huja et al.[100] Huja et al. used a computer to measure landmark displacement associated with hand and digital superimpositions for three of the four dental landmarks utilized in our study: upper incisor tip, upper incisor apex and upper 1st molar apex.[100] The ranges for "clinical significance" derived by extension of Baumrind and Frantz's[40] suggestions to the data from Huja et al. are (0.88 – 1.14) and (0.82 - 1.16) millimeters for analog and digital measurements respectively (Table 6). A similar approach applied to our study results by method, indicate that the range of "clinically significance" are (0.88 – 1.14), (0.82 – 1.16), and (0.82 – 1.16) millimeters for the structural, Dolphin, and Quick Ceph methods respectively (Table 7), all comparable to the ranges extended from the data of Huja et al.[100] The measured displacements of the represented defined dental landmarks in our study are of a magnitude clearly less than the "standard" suggested by Baumrind and Frantz[40] needed to meet the threshold of "clinical significance" thereby permitting differentiation of biologic changes from differences due to measurement error. In other words, it would appear that all three methods are accurate enough for clinical use, but as previously discussed, the digital methods demonstrate an imprecision large enough that any single measurement could exceed multiples of their respective mean values.

4.2. Strengths and Limitations

To our knowledge, this study was the first to compare digital and analog methods of maxillary regional superimposition that used a sample comprised of radiographs of patients with maxillary implants as fixed reference structures and that employed implant registered analog superimpositions as the reference for comparison among the methods evaluated.

One limitation of this study was the sample size, which yielded a statistical power of only 18%. Unfortunately, there are only two known cephalometric implant databases in existence: The Matthews database (used in this study) and the Björk database (a larger sample size but with restricted access). Consequently, unless Björk's database can be used in a future study, the sample size for replicating this type of study will not likely be larger, and thereby similarly limited by low statistical power (i.e., limited ability to reduce Type II errors).[147]

A second limitation of this study was that some of the radiographs evaluated in this study had diminished radiographic detail. As such, landmark identification was extremely difficult, but this affected both the analog and digital methods equally.

A limitation resulting from the variability observed in measurements resulting from digital superimposition methods may be partially attributed to the reliance of the digital methods upon anterior nasal spine (a landmark proven to be difficult to precisely identify)[116,117,148,149] for superimposition and registration.

Test results of intra-rater reliability for both the digital and analog methods of superimposition were assessed by intraclass correlation that demonstrated no statistical differences regarding measurements of repeated superimpositions. Only one researcher had access to the CRIL database, thus inter-rater reliability could not be assessed. Future studies could capitalize upon the methodological strength of our study by implementing a design improvement wherein the same operator(s) trace, superimpose, and measure each analog and digital cephalogram.

4.3. Conclusions

The results of this study suggest that there are differences in the accuracy of digital and analog methods of serial maxillary regional superimposition. All three superimposition methods (Structural, Dolphin and Quick Ceph) showed a mean overall displacement of defined dental structures no more than 0.46mm relative to the implant (reference) superimposition method.

The structural method alone, demonstrated a statistically significant mean displacement measurement differences compared to the implant method and yet also exhibited the smallest standard error relative to the mean for every measurement. The implication is that while all three methods show accuracy below the threshold for clinical significance the digital methods lack precision, meaning that any single measurement may have a value exceeding multiples of the mean value, an observation disguised by our finding no statistically significant difference in mean displacements measured by the digital methods compared to the reference method.

The low power of this study (18%) and large relative standard errors for the digital methods suggests that a larger sample size may have elucidated if the failure to reject the hypothesis of no difference in measured displacements for the Dolphin and Quick Ceph methods, respectively, from the reference, were a result of a Type II statistical error, or correct decisions.

This study highlighted many of the issues surrounding registration, accuracy, and interpretation of maxillary regional cephalometric superimpositions. There are methodological advantages and disadvantages to both analog and digital methods each requiring due consideration prior to selecting a method for clinical use.

TABLES

Table 1-Mean total displacements*

Method	Displacement	SE	Min	Max	Range
Implant	2.65	1.36	0.09	6.76	6.67
Structural	2.19	1.16	0.40	6.37	5.97
Dolphin	2.91	1.80	0.35	9.54	9.19
Quick Ceph	2.71	1.62	0.14	9.67	9.53

*All values in millimeters

Table 2-Method displacements relative to implant method reference*

Method	Displacement	SE	p-Value	95% Confidence Interval	CI Range
Implant	-	-	Reference	-	-
Structural	-0.46	0.09	< 0.001	(-0.69, -0.24)	0.45
Dolphin	0.26	0.20	0.56	(-0.21, 0.74)	0.95
Quick Ceph	0.05	0.16	> 0.99	(-0.32, 0.43)	0.75

*All values in millimeters

Table 3-Method displacements by tooth relative to Implant method reference*

Method	Displacement	SE	p-Value	95% Confidence Interval	CI Range
Incisor					
Implant	-	-	Reference	-	-
Structural	-0.45	0.12	< 0.001	(-0.77, -0.13)	0.64
Dolphin	0.07	0.23	> 0.99	(-0.55, 0.68)	1.23
Quick Ceph	0.23	0.21	> 0.99	(-0.32, 0.78)	1.09
Molar					
Implant	-	-	Reference	-	-
Structural	-0.47	0.11	< 0.001	(-0.75, -0.19)	0.56
Dolphin	0.46	0.21	0.18	(-0.10, 1.02)	1.12
Quick Ceph	-0.12	0.20	> 0.99	(-0.66, 0.42)	1.08

*All values in millimeters

Table 4-Method displacements by landmark relative to implant method reference*

Method	Displacement	SE	p-Value	95% Confidence Interval	CI Range
Incisor Crown					
Implant	-	-	Reference	-	-
Structural	-0.54	0.14	< 0.001	(-0.94, -0.14)	0.80
Dolphin	0.04	0.29	> 0.99	(-0.79, 0.86)	1.65
Quick Ceph	0.39	0.25	> 0.99	(-0.31, 1.09)	1.40
Incisor Apex					
Implant	-	-	Reference	-	-
Structural	-0.37	0.12	0.03	(-0.71, -0.03)	0.69
Dolphin	0.10	0.28	> 0.99	(-0.69, 0.89)	1.58
Quick Ceph	0.07	0.23	> 0.99	(-0.58, 0.72)	1.30
Molar Mesial Contact					
Implant	-	-	Reference	-	-
Structural	-0.40	0.13	0.02	(-0.76, -0.04)	0.72
Dolphin	0.50	0.24	0.48	(-0.20, 1.20)	1.40
Quick Ceph	-0.02	0.24	> 0.99	(-0.70, 0.66)	1.36
Molar Apex					
Implant	-	-	Reference	-	-
Structural	-0.55	0.10	< 0.001	(-0.82, -0.27)	0.55
Dolphin	0.41	0.21	0.58	(-0.19, 1.01)	1.20
Quick Ceph	-0.23	0.22	> 0.99	(-0.87, 0.42)	1.29

*All values in millimeters

Table 5-Thresholds for clinical significance based upon Huja's[100] findings

Landmark	Superimposition Method	SD	Threshold for clinical significance
U1 tip	Analog	0.44	0.88
U1 tip	Digital	0.58	1.16
U1 apex	Analog	0.57	1.14
U1 apex	Digital	0.41	0.82
U6 apex	Analog	0.46	0.92
U6 apex	Digital	0.52	1.04

*All measurements in mm

Table 6-Method displacements relative to the reference by landmark relative to threshold for clinical significance* according to the method of Baumrind and Frantz[40]

Method	Mean Displacement	95% CI Range	Threshold for Clinical Significance
Incisor Crown			
Structural	0.54	0.80	0.88
Dolphin	0.04	1.65	1.16
QuickCeph	0.39	1.40	1.16
Incisor Apex			
Structural	0.37	0.69	1.14
Dolphin	0.10	1.58	0.82
QuickCeph	0.07	1.30	0.82
Molar Apex			
Structural	0.55	0.55	0.92
Dolphin	0.41	1.20	1.04
QuickCeph	0.23	1.29	1.04

*All values in millimeters

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