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Accuracy of Cephalometric Analyses and Tooth Movements of Conventional vs CBCT-Generated Cephalograms

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LOMA LINDA UNIVERSITY
School of Dentistry
in conjunction with the
Faculty of Graduate Studies

Accuracy of Cephalometric Analyses and Tooth Movements of Conventional vs CBCT-Generated Cephalograms

by

Thanh Khong Ng

A Thesis submitted in partial satisfaction of
the requirements for the degree
Master of Science in Orthodontics and Dentofacial Orthopedics

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August 2018

Each person whose signature appears below certifies that this thesis in his/her opinion is adequate, in scope and quality, as a thesis for the degree Master of Science.

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This thesis would not be possible without the help of my committee members and the support of my husband, family, and co-residents.

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I want to express my deepest gratitude and love to my parents, who have sacrificed immensely to support me through my education. I would not be here today without their passionate encouragements and boundless love.

Lastly, I want to dedicate this thesis to my husband, Derek Ng, who believed in me and pushed me to pursue all my dreams, big and small. His undeniable patience, selflessness, and love have allowed me to achieve everything I wanted for myself and us.

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ABBREVIATIONS

*Alphabetical order

2D	Two-Dimensional
3D	Three-Dimensional
ACB	Anterior Cranial Base
ANS	Anterior Nasal Spine
Ba	Basion
CBCT	Cone Beam Computerized Tomography
CLC(s)	Conventional Lateral Cephalogram(s)
CBLC(s)	CBCT-generated Lateral Cephalogram(s)
Cranial Defl.	Cranial Deflection
FH	Frankfort Horizontal
FMA	Frankfort-Mandibular Angle
Gn	Gnathion
Go	Gonion
LC	Lateral Cephalogram
L1 to APo	Lower Incisor to A Point-Pognoion
L1 to MP	Lower Central Incisor to Mandibular Plane
L1 to NB	Lower Central Incisor to Nasion – B Point
Md	Mandibular
Me	Menton
Mx	Maxilla
MPA	Mandibular Plane Angle

Na	Nasion
Or	Orbitale
PFH	Posterior Facial Height
PM	Protuberance Menti
PNS	Posterior Nasal Spine
Pog	Pogonion
Porion Loc.	Porion Location
SNA	Sella-Nasion-A Point
SNB	Sella-Nasion-B Point
SN-MP	Sella-Nasion to Mandibular Plane
T1	Pre-treatment
T2	Post-treatment
U1 to APo	Upper 1 to A point-Pogonion
U1 to NA	Upper Central Incisor to Nasion – A Point
U1 to SN	Upper Central Incisor to Sella-Nasion
U6 to PTV	Upper molar to PT Vertical

ABSTRACT OF THE THESIS

Accuracy of Cephalometric Analyses and Tooth Movements of Conventional vs CBCT-Generated Cephalograms

by

Thanh Khong Ng

Master of Science
Graduate Program in Orthodontics and Dentofacial Orthopedics
Loma Linda University, August 2018
Dr. Kitichai Rungcharasseng, Chairperson

Purpose: The aim of this study was to compare Ricketts and American Board of Orthodontics (ABO) cephalometric measurements and tooth movements from tracings between conventional lateral cephalograms (Sirona Orthophos XG Plus, Charlotte, NC) and CBCT-generated cephalograms (NewTom 5G; QR srl, Verona, Italy).

Materials and Methods: Patients who had bilateral Angle's class II molar were evaluated. Pre-treatment (T1) and post-treatment (T2) conventional lateral cephalograms (CLCs) and CBCT-generated lateral cephalograms (CBLCs) were traced in Quick Ceph Studio using Ricketts and ABO cephalometric analyses. Linear and angular cephalometric measurements from tracings were compared between the two radiographic modalities using one-sample Wilcoxon signed rank test (α=0.05) and intraclass correlation coefficient. Ricketts superimpositions between CLCs T1 and CLCs T2, CBLCs T1 and CBLCs T2, and CBLCs T1 and CLCs T2 were also measured to assess molar and incisor movements for the maxillary and mandibular arch. Comparison between the three groups was completed using Friedman's two-way analysis of variance of ranks and pairwise comparison, adjusted by the Bonferroni correction (α=0.05).

Results: Records of thirty-eight patients were used in this study. Ricketts and ABO cephalometric measurements between CLCs and CBLCs were statistically significant for 8 out of 26 landmarks. Ricketts superimposition showed that directional tooth movements (DTMs) between the two radiographic modalities were not statistically significant. Total tooth movements (TTMs) showed statistical significance at maxillary molar furcation and maxillary molar root. All statistical significance found in this study did not seem to reach clinical significance.

Conclusions: Statistical significance for cephalometric measurements with landmark identification at porion, orbitale, gonion, gnathion, nasion, and pterygomaxillary point was found. DTMs of CLCs and CBLCs were comparable to one another. TTMs did however show statistical significance, which was potentially due to the superimposition of radiopaque structures and the greater density in the region of the maxillary first molar.

CHAPTER ONE

REVIEW OF LITERATURE

Cephalometry is an important tool used for diagnosis and treatment planning in orthodontics. Broadbent first introduced cephalometric radiography in 1931.[52] The applications of cephalometric analysis consist of case diagnosis, estimating growth for treatment planning, and assessing treatment results.[1]

Traditionally, cephalometric analysis requires specific landmark identification and calculation of linear and angular measurements on a 2-dimensional (2D) lateral cephalograms. These measurements are compared to normative values that have been determined based on sex, age, and ethnic groups.[1, 53-56] Because these 2D lateral cephalograms are depiction of three-dimensional (3D) structures, some inherent limitations exist. Improper patient positioning in a lateral cephalogram machine can be a source of error, as the rotation of the head can result in double images, magnification, and projection errors of these crucial landmarks.[5] Furthermore, non-parallel x-ray projection potentially creates double images along with magnification error. Structures closest to the x-ray source appear more magnified than the structures closest to the detector. Bilateral structures also have appeared at greater risk of error due to superimposition and difficulty determining which side of the face a specific structure is located on.[5] Limitation of observer's experience and training can also affect cephalometric analysis.[57] These factors of radiographic magnification, superimposition of bilateral craniofacial structure, and observer's skills all can contribute to variation in cephalometric values.[5, 58-60]

Although the method of hand tracing on acetate and measuring from those tracings has been widely used among orthodontists, it is time consuming and prone to errors.[3] Linear and angular cephalometric measurements obtained manually with a ruler and a protractor can introduce substantial clinical errors. Moreover, measurements and identifying landmarks due to clinical skills and quality of radiographs can increase the error seen with manual tracing.[3] With the advancement to digital radiography, more orthodontists are creating tracings from digitized lateral cephalograms. Orthodontic software generates values of cephalometric measurements simultaneously as landmarks are identified, thus reducing operator's time spent on tracing and measuring. In addition, digital tracings can be integrated into patient records to take advantage of storage and transmission of data.[61]

Many studies have investigated the similarities and differences between manual and digital tracings. In a research by Roden-Johnson *et al.*, thirty sets of serial cephalometric radiographs were manually and digitally traced using Quick Ceph 2000.[62] It was determined that there was no difference in identification of landmarks made manually versus digitally.[62] When comparing ABO superimpositions using the two methods, the only statistical difference was the vertical position of nasion relative to cranial base, which was reported to be less than 1mm. [62] Thus, no clinical significant difference was seen in identification of cephalometric landmarks between manual versus digital tracings. On the other hand, Albarakati *et al.* looked at pre-treatment records of thirty patients and recorded American Board of Orthodontics (ABO) cephalometric measurements for manual and digital tracings.[3] All measurements had statistically significant differences, except for ANB. This study was further supported by Naoumova *et al.*, which assessed manual versus digital tracings for lateral cephalograms of twenty-five adult patients who had undergone orthognathic treatment.[4] The study indicated that there were differences in soft tissue gonion (Gn'), labrale inferius (Li), mentolabial sulcus (Si), and incisal inferior to labrale inferius (Ii-Li) measurements but these values were determined to be clinically insignificant.[4] Chen *et al.* also showed that cephalometric measurements were statistically different for all skeletal and dental measurements between conventional and digital cephalometric analysis.[25] These differences were believed to be mainly due to landmark identification. With several researchers reporting a range of results, it should be considered that the variations can be due to many confounding factors, including the type of cephalometric analysis programs used, as well as how the radiographs were acquired by the programs.

As the transition to digitally traced cephalometric radiographs becomes more prominent in today's world, the use of 2D cephalometric radiographs has also advanced to 3D imaging. Computed tomography (CT) was first introduced in the medical field in 1971 but it's application in dentistry was limited due to the significantly high levels of radiation and scanning costs.[63] Cone Beam Computed Tomography (CBCT) was then developed to capture maxillofacial regions relevant to dentistry.[21] Following CBCT acquisition, volumetric reconstruction various views can be generated to display the true 3D craniofacial morphology.[63] Since its introduction in 1998 to the dental field, CBCT has improved TMJ treatment, implant placement guidance, assessment of impacted teeth, and orthognathic surgical cases.[65-68]

One of the most important advantages of CBCT when compared to CT is the reduced radiation exposure to patient. The radiation dose with CBCT can be up to 10 times less than medical CT scans.[22] However, assessment of full craniofacial region with CBCT still shows to be 3 to 7 times more radiation than panoramic doses (77.9 μSv from

CBCT NewTom 9000 versus 22 µSv from Orthophos Plus DS).[22] It is important to note that CBCT doses varies significantly with type of devices, field of view (FOV), and type of structures being captured.

Because of the noticeable advantages of CBCT, more orthodontists are choosing to use 3D imaging for assessment of orthodontic patients. It appears that the replacement of 2D imaging with 3D radiographs is on the horizon. To help validate the use and ease the transition to 3D imaging, it is prudent to assess how CBCT-based analyses can be incorporated into the existing tools of treatment planning that co-exists in the 2D world. If CBCT is taken at initial records, orthodontists should be able to directly and effectively compare those records to that of subsequent progress records done with conventional lateral cephalograms (CLCs). Because CBCT volume data can produce lateral cephalograms, along with other views such as frontal and panoramic views, these CBCT-generated lateral cephalograms (CBLCs) can be utilized as supplements or replacements of current orthodontic radiographs.

In a study conducted by Ludlow *et al*., twenty presurgical orthodontic patients were imaged using CLCs and CBLCs. Five observers plotted cephalometric landmarks for both radiographic techniques.[12] Results showed that identification of cephalometric landmarks were more precise on CBCT volume than traditional cephalometric landmarks, specifically at condylion (Co), gonion (Go), and orbitale (Or), which commonly have bilateral superimposition errors on conventional lateral cephalograms.[12] With cephalometric measurements, Ludlow *et al.* demonstrated that CLCs and CBLCs produced angular and linear measurements that were not statistically different.[12] Similar results were seen in Chung *et al.* and Shaw *et al.*, which saw that high reproducibility was demonstrated in all angular cephalometric values between CLCs and CBLCs.[69-70] However in general, differences between the two radiograph modalities were greater in linear measurements than angular measurements.[11,13-17] Moreover, in a study by Kumar *et al.*, ten dry skulls were imaged using both CLCs and CBLCs, and the only measurement that was statistically significant between the two modalities was mandibular length from gonion to gnathian.[12] When linear measurements on radiographs were compared to actual measurements on the skulls, conventional radiographs underestimated the actual skull dimension. On the other hand, CBLCs with 7.5% simulated magnification had overestimated of the actual skull dimension. The research determined that orthogonal CBCT measurements were the closest to actual anatomical measurements. In a follow-up study by Kumar *et al*., this time in vivo with thirty-one patients, there were no significant differences in angular measurements between conventional and CBCT-generated orthogonal and perspective lateral cephalograms, except for Frankfort-mandibular angle (FMA).[13]

Additional studies have revealed other measurements to be inconsistent between the two imaging modalities. Aksoy *et al.* saw poor reproducibility between 2D and 3D lateral cephalogram at condylion-gnathion (Co-Gn), gonion-mentum (Go-Me), and anterior nasal spinamentum (ANS-Me), and Wits.[31] Park *et al.* saw statistical differences in linear measurement for U1 to facial plane distance, as well as angular differences in gonial angle, ANB, and facial convexity.[15] Interestingly, Hilgers *et al*. found all CBCT measurements to be similar to the true anatomical structure but saw conventional lateral cephalogram measurements of condylar height, condylar length, and lateral pole of gonion to be different from true anatomical structure by 1.97 mm, 2.28 mm, and 8.99 mm respectively.[16]

Landmark identification with 2D lateral cephalograms is one of the most important tasks when creating accurate cephalometric tracings.[8-9] Chien *et al.* found that CLCs showed more errors than CBLCs at A-point, ANS, Ba, Co, Po, Or, ramus point, sigmoid notch, midramus and lower 6 to occlusal plane by more than 1 mm.[9] Errors seen in CBCT that were greater than 1 mm were Co, Or, midramus, and Go. Furthermore, Chang *et al.* showed that conventional lateral cephalograms had errors in landmark identification at overlapping structures, specifically ANS, posterior nasal spine (PNS), A, B, and Go point, whereas CBCT-generated lateral cephalograms had errors at Ba.[28] By scrolling through CBCT volume and identifying landmarks from left to right, the data is able to overcome the problem of superimposition of bilateral landmarks, such as Co, Go, and Or which are often time difficult to identify in 2D conventional lateral cephalograms. Go identification is specifically difficult due to poor anatomical outline of the inferior border of the mandible, double images, and its localization away from the midsagittal plane.[26, 43] Chen *et al.* stated similar results, indicating that there were fewer landmark errors in CBCT-synthesized cephalograms than with lateral cephalograms at Me, lower central incisor position, lower central incisor root apex landmarks in the horizontal dimension and at Po, Gn, Me, upper central incisor root apex, lower central incisor root apex, and lower molar landmarks in the vertical dimension.[26] Ludlow *et al.* also demonstrated that in general, CBLCs that are derived from software allowing view of one side of the face provided precise landmark identification.[12] The study noted that there was greatest variability in landmarks in the mediolateral direction for CBCT.[12]

Although literature has shown a range of results for CLCs versus CBLCs, these findings as a whole need to be taken into consideration when deciding which radiograph modalities would be most suitable for the operator’s scope of practice.

CHAPTER TWO

ACCURACY OF CEPHALOMETRIC ANALYSES AND TOOTH MOVEMENTS OF CONVENTIONAL VS CBCT-GENERATED CEPHALOGRAMS

Abstract

Purpose: The aim of this study was to compare Ricketts and American Board of Orthodontics (ABO) cephalometric measurements and tooth movements from tracings between conventional lateral cephalograms (Sirona Orthophos XG Plus, Charlotte, NC) and CBCT-generated cephalograms (NewTom 5G; QR srl, Verona, Italy).

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Introduction

Cephalometric radiograph is one of the most common tools used by orthodontists to effectively diagnose and treatment plan. With serial cephalometric analyses, providers can better measure dental and skeletal growth, track progress of treatment, and understand the effectiveness of orthodontic mechanics.[1] These sequential analyses can also help estimate surgical outcomes, which is crucial in treating complex dentofacial deformities.[2]

Traditionally, cephalometric analysis is traced and measured manually on acetate film used over lateral cephalograms.[3] Specific landmarks and anatomical planes are constructed on the lateral cephalometric tracing. The linear measurements are made between landmarks, and angular measurements are determined by joining specific planes. Manual tracings have been shown to be time consuming, as well as subject to systematic errors.[4] Variation in the accuracy of cephalometric analyses is affected by multiple sources, such as patient positioning in cephalometer, landmark identification, and technical measurements. Literature have indicated that landmark identification is the most common error, which is influenced by radiograph density and clarity, landmark definition, and observer's experience.[5-9]

Digitized records of patients are becoming increasingly popular among orthodontists, who are moving towards paperless management system. Cephalometric measurements can be done efficiently, images processed and stored easily, harmful chemicals used for analog films are eliminated, and better communication can be facilitated between providers, as well as providers to patients.[4] Moreover, serial radiographs can be used for superimposition more effectively and can be carried out in a more cost-efficient manner.

With the transition from manual to digital tracings, orthodontists are also utilizing 3D radiographs more commonly in conjunction with conventional 2D lateral cephalogram. Computed tomography (CT) has been integrated into the medical field; however, it can pose too high of radiation exposure to dental patients for its diagnostic yield and causes increased costs to health care practices.[4] The introduction of cone-beam computed tomography (CBCT) has made 3D imaging more readily available for dentists and specialists. In comparison to CT, CBCT has lower radiation dose, lower cost, and higher spatial resolution.[4, 11] The use of CBCT for orthodontic diagnosis and treatment planning are still under clinical validation. However, CBCT can generate 2D lateral cephalograms, along with frontal, panoramic radiographs and TMJ tomography, thus bridging the gap between 2D and 3D radiographic modalities.[11] Numerous of studies have investigated the similarities and differences between conventional lateral cephalograms (CLCs) and CBCT-generated cephalograms (CBLCs).

Researchers have reported the difference between CLCs and CBLCs tracings, but studies have been limited to landmark identification and cephalometric measurements. According to Ludlow *et al*., identification of cephalometric landmarks was more precise on CBLCs and CLCs cephalometric landmarks, specifically at condylion (Co), gonion (Go), and orbitale (Or) which commonly have bilateral superimposition errors on CLCs.[12] With cephalometric measurements, it has been shown that CLCs and CBLCs produce angular and linear measurements that are not statistically different.[11] One study indicated that the only statistically significant measurement between CLCs and CBLCs was the Frankfort-mandibular plane angle (FMA)[13]. In general, differences between the two radiograph modalities are greater in linear measurements than angular measurements but do not show to be clinically significant. [11, 13-17]

Statement of Problem

Currently, there is a lack of consenuses among studies regarding cephalometric measurements between CLCs and CBLCs. Studies have indicated different landmarks being inconsistent in identifying, as well as differences in cephalometric measurements between the two radiographic modalities. Moreover, normative values have been established for conventional lateral cephalograms by Ricketts, Steiner, Mcnamara, to name a few. However, with CBCT being used more in today's world, it is not well studied whether data obtained from CBCT views are comparable to current population norms and existing databases obtained from conventional lateral cephalograms.

There are no studies assessing tooth movements between CLCs and CBLCs. A study of such would allow for a better comparison of CLCs and CBLCs . By comparing tooth movements, clinicians who decide to utilize 3D imaging for initial records can choose to compare them to progress records taken in 2D or 3D-generated lateral cephalograms.

Purpose of Study

The goals of this study were to:

1. Compare Ricketts and American Board of Orthodontics (ABO) linear and angular cephalometric measurements between CLCs and CBLCs.

2. Compare incisor and molar movements using Ricketts superimpositions between CLCs and CBLCs.

Null Hypothesis

There is no statistically significant difference in Ricketts and ABO cephalometric measurements between CLCs and CBLCs. Furthermore, there is no statistical significance in measurements of tooth movements from T1 to T2 using CLCs and/or CBLCs.

Materials and Methods

This study was approved by Institutional Review Board (IRB) at Loma Linda University, School of Dentistry, Loma Linda, CA (#5170322). This research utilized CLCs (Sirona Orthophos XG Plus, Sidexis XG 2.56) and CBLCs (NewTom 5G, NNT, version 5.1) from patients, who were treated at Loma Linda University, Graduate Orthodontic Clinic. Patients were consecutively treated from December 22nd, 2011 to March 7th, 2018 and fulfilled the following inclusion and exclusion criteria:

Inclusion Criteria

- Comprehensive orthodontic treatment with complete T1 and T2 records
- Presence of only permanent dentition at T1
- Angle's molar class II bilaterally by at least 3 mm

Exclusion Criteria

- Congenitally missing permanent teeth
- Radiographs without reference measurement
- Skeletal asymmetry beyond 5 mm
    - Measured from frontal CBCT view, comparison of horizontal and vertical position of ante gonial notch position
- Orthognathic surgery

Conventional Lateral Cephalogram Tracing

Pre-treatment (T1) CLCs taken with Sirona Orthophos XG Plus were exported from Dolphin^{TM} Imaging (11th edition) and traced in Quick Ceph Studio (Version 4.1.3; Quick Ceph Systems, Inc, San Diego, Calif) (Fig 1). Applying the reference measurement of 45 mm in Quick Ceph Studio standardized the tracing template for central incisors and first molars, regardless of the actual shape and size of the teeth. The software applied the position of the maxillary and mandibular first molars from the operator's placement of a point at distal outline of crown and root tip (Fig 2). For maxillary and mandibular central incisors, the position was determined from the operator's placement of a point at crown tip and root tip (Fig 2). The left molars were traced using T1 plaster models and clinical photographs to ensure correct left-side molar classification. If double images of the inferior border of mandible, angle, and ramus were seen, the left side of the mandible was traced, which is believed to be less magnified and smaller in size. CLCs T1 were traced using landmarks shown in Table 1.

Figure 1. CLC T1 were exported from Dolphin^{TM} Imaging.

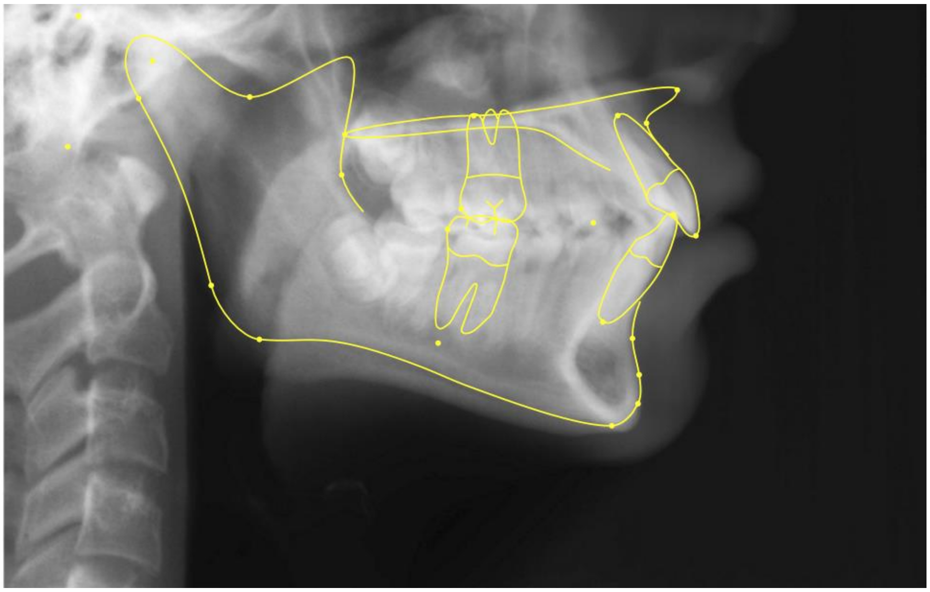


Figure 2. Tracing of molars and incisors using Quick Ceph Studio templates.

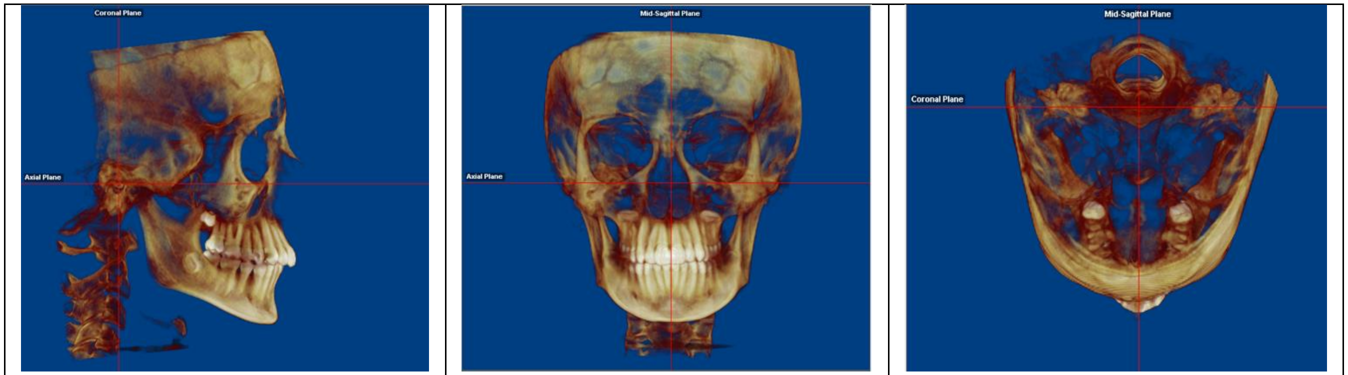
Table 1. Definition of landmarks used in CLCs T1.

Landmark	Abbrev.	Definition
A Point (subspinale)	A	Deepest point on the curve of bone between ANS and the dental alveolus
Anterior Nasal Spine	ANS	Anterior point on maxillary bone
B Point (supramentale)	B	Deepest point on the contour of alveolar projection between superior point of alveolar bone of mandible and pogonion
Basion	Ba	Lowest point on the anterior rim of foramen magnum
Condyle	DC	Point at center of condyle neck along the Ba-N plane
Gonion	Go	Point on curvature of mandibular angle of ramus, located by bisecting the angle formed by lines tangent to posterior ramus and inferior border of mandible
Gnathion	Gn	Point on the chin, located by bisecting angle formed by facial and mandibular planes
Lower Central Incisor	L1	Incisal tip of most anterior mandibular central
Menton	Me	Most inferior point on symphysis of mandible
Nasion	N	Most anterior point on frontonasal suture
Orbitale	Or	Most inferior point on lower border of orbit
Porion	Po	Most superior point of external acoustic meatus
Posterior Nasal Spine	PNS	Posterior limit of bony palate/maxillary bone
Pogonion	Pog	Most anterior point on symphysis of mandible

Protuberance Menti	PM	Point at which shape of symphysis mentalis change from convex to concave
Pterygoid Point	PT	The point intersection of the inferior border of the foramen rotundum and posterior wall of the pterygomaxillary fissure.
Pterygomaxillary Vertical	PTV	Vertical line through PT point
Sella	S	Center point of sella turcica
Upper Central Incisor	U1	Incisal tip of most anterior maxillary central
Xi Point	Xi	Center of ramus, point of intersection of diagonals of the rectangle formed by drawing tangents to the four borders of ramus.

CBCT-Generated Cephalogram Tracing

CBCT scans taken with NewTom 5G were first oriented using lateral, frontal, and top 3D views, as defined by Dolphin^{TM} Imaging (Fig 3). In the lateral view, the axial plane passed through porion (Po) and orbitale (Or) horizontally and the coronal plane passed through porion vertically. In the frontal view, the axial plane passed through the inferior border of bilateral orbits and the midsagittal plane passed through center of glabella, anterior nasal spine (ANS), and genial tubericle. In the top view, the coronal plane went through bilateral Po and the midsagittal plane went through crista galli and center of foramen magnum.



Lateral view: Axial plane through Po or Or. Coronal plane through Po.

Frontal view: Axial plane through inferior border of bilateral orbits. Midsagittal plane through center of glabella, ANS, and genial tubericle.

Top view: Coronal plane through bilateral Po. Midsagittal plane through crista galli and center of foramen magnum.

Figure 3. Oriented CBCT scans for lateral, frontal, and top views.

CBLC T1 were set to orthogonal left side projection with projection center at porion without magnification in Dolphin^{TM} Imaging (Fig 4). Reference measurement was set to 100 mm.

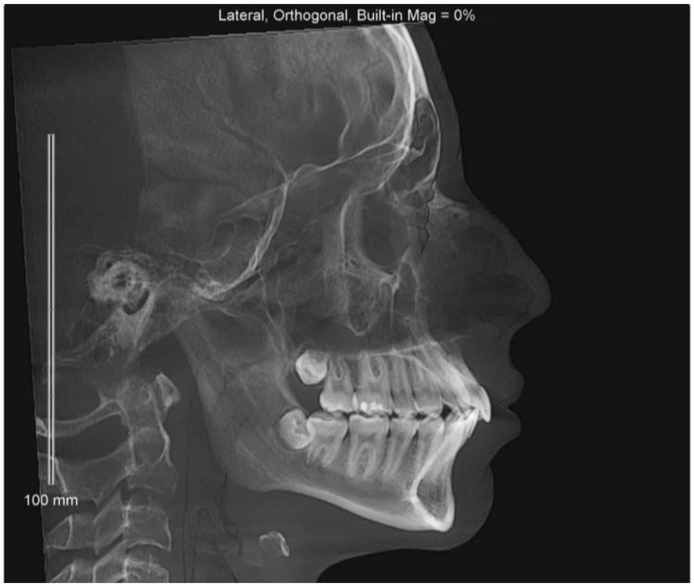


Figure 4. CBLC was set to orthogonal left side projection with projection center at porion without magnification in Dolphin^{TM} Imaging.

Cephalometric tracings were completed in Quick Ceph Studio in the same manner as described for CLCs.

Cephalometric Measurements

Angular and linear measurements from Ricketts (Fig 5, Table 2 and 3) and ABO analyses (Fig 5, Table 4 and 5) were recorded for CLCs and CBLCs T1 in Quick Ceph Studio.

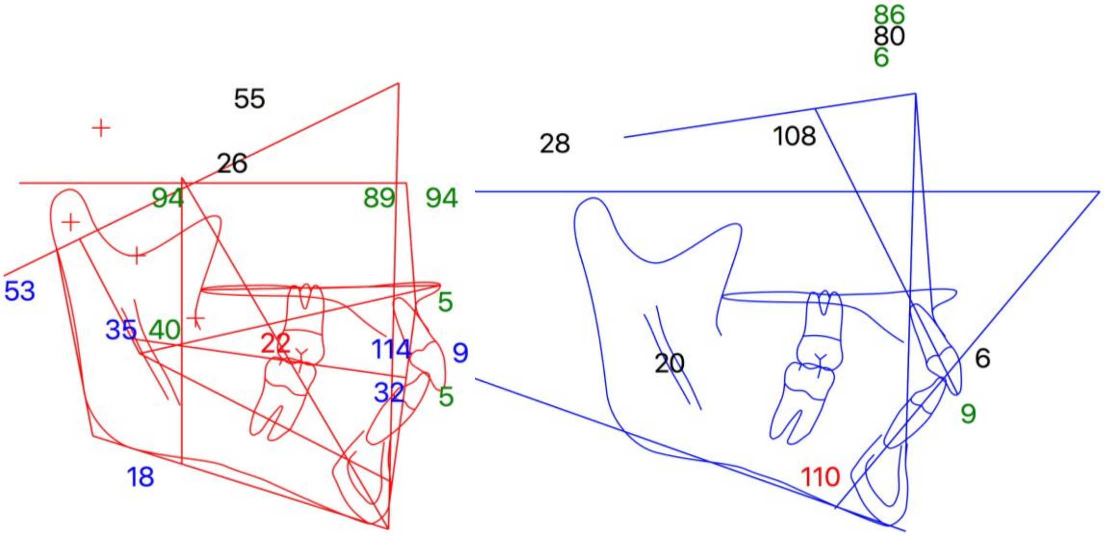


Figure 5. Ricketts (left) and ABO analyses (right) shown.

Table 2. Angular measurements for Ricketts analysis.

Angular Measurements (degree)	**Description**
	Angle between . . .
Cranial Deflection	Nasion-Basion and Frankfort Horizontal
Facial Axis	Nasion-Basion and Pterygoid-Gnathion
Facial Depth	Frankfort Horizontal to Nasion-Pogonion
Lower Facial Height	ANS-Xi point and Xi point-PM point
Mandibular Arc	PM-Xi point and Xi point-DC point
Mandibular Plane Angle (MPA)	Gonion-Gnathion and Frankfort Horizontal
Maxillary Depth	Frankfort Horizontal and Nasion-A point
Ramus Position	Frankfort Horizontal and Xi point-PT point
Total Facial Height (TFH)	Nasion-Basion and Xi point-PM point

Table 3. Linear measurements for Ricketts analysis.

Linear Measurements (mm)	Description
Anterior Cranial Base (ACB)	Nasion to PT point
Corpus Length	Xi to PM
Maxillary Convexity	A point to line from Nasion-Pogonion
L1 to APo	Mandibular central incisal tip to A-Pogonion
U1 to APo	Maxillary central incisal tip to A-Pogonion
U6 to PTV	Maxillary first molar to line of PTV
Posterior Facial Height (PFH)	Sella to Gonion

Table 4. Angular measurements for ABO analysis.

Angular Measurements (degree)	Description
	Angle between…
L1 to MP	Mandibular central incisor axis and Gonion-Menton
U1 to SN	Maxillary central incisor axis and Sella-Nasion
ANB	A point-Nasion and B point-Nasion
SNA	Sella-Nasion and Nasion-A point
SNB	Sella-Nasion and Nasion-B point
SN-MP	Sella-Nasion and Mandibular Plane
FMA	Frankfort Horizontal and Gonion-Menton

Table 5. Linear measurements for ABO analysis.

Linear Measurements (mm)	Description
U1 to NA	Maxillary central incisor to Nasion-A point
L1 to NB	Mandibular central incisor to Nasion-B point

Measurements of Tooth Movements

To measure tooth movements, T1 and T2 tracings were completed and superimposed in Quick Ceph Studio. For patients whose growth were not completed at T1, a growth constant grid (GCG) was constructed on the T1 radiograph. According to literature, female complete growth at an average age of 16 years old and male complete growth at an average of 18 years old.[18] GCG tracing consists of Frankfort horizontal plane (Po to Or), cranial base plane (Na to Ba), and pterygoid vertical (PTV) (Fig 6). The T1 with reference grid was superimposed on the T2 radiograph to best fit. The new T2's Frankfort horizontal plane, cranial base plane, and PTV were identified in referenced to that grid as a template to minimize visual variation.

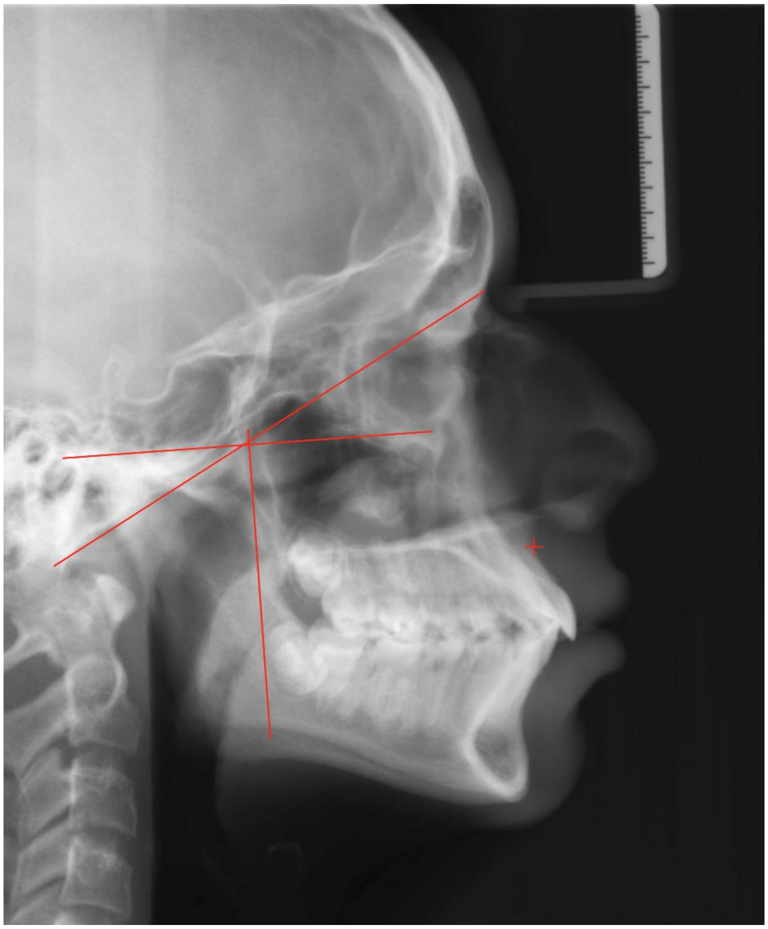


Figure 6. GCG constructed on a CLC which consists of Frankfort horizontal plane, cranial base plane, and pterygoid vertical.

Ricketts landmarks were superimposed at the following areas in Quick Ceph Studio (Fig 7):

- **Mandibular superimposition**
    - Corpus length (Xi to PM) at PM
- **Maxillary superimposition**
    - Palatal plane (ANS to PNS) at ANS

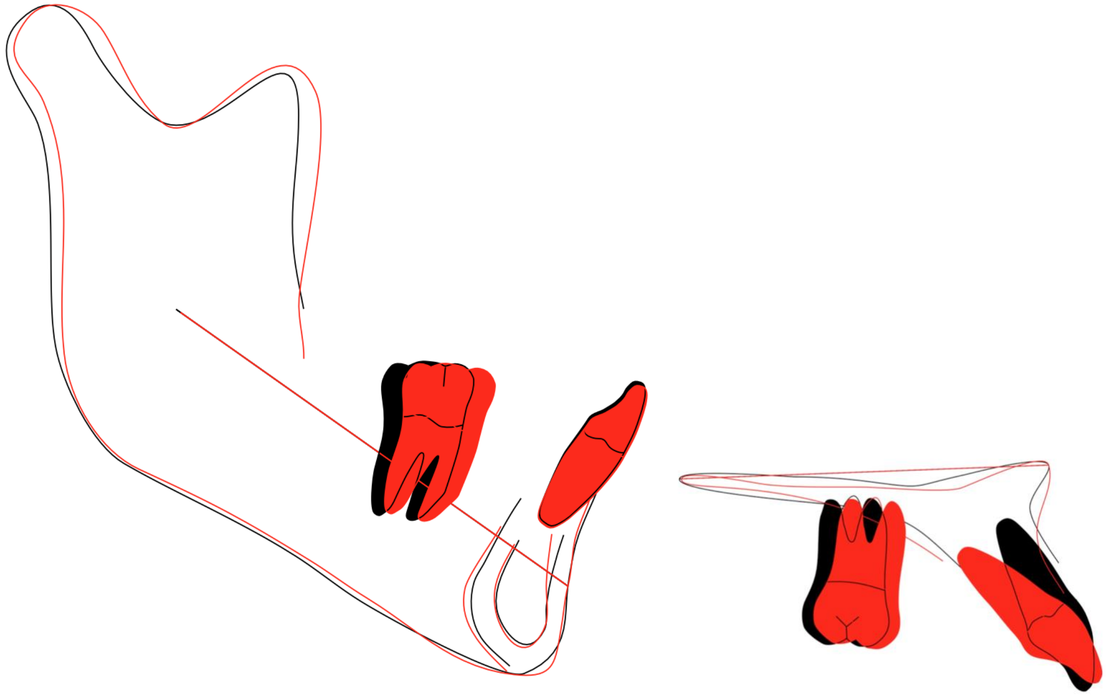


Figure 7. Superimposition of mandible (left) at corpus length at PM and maxilla (right) at ANS to PNS at ANS were completed in Quick Ceph Studio. CLCs T1 shown in black and CLCs T2 shown in red.

Ricketts superimpositions were completed between:

1) CLCs T1 and CLCs T2 (Group 1)

2) CBLCs T1 and CBLCs T2 (Group 2)

3) CBLCs T1 and CLCs T2 (Group 3)

For each superimposition, a ten millimeter reference length was drawn in Quick Ceph Studio and exported as a JPEG image (Fig 8). The JPEG image was imported into Keynote (Version 8.0.1; Apple Inc.). Once in Keynote, a corresponding measurement of the reference length was recorded in pixel, which was represented as points (pt) on software (reference pixel) (Fig 9).[19]

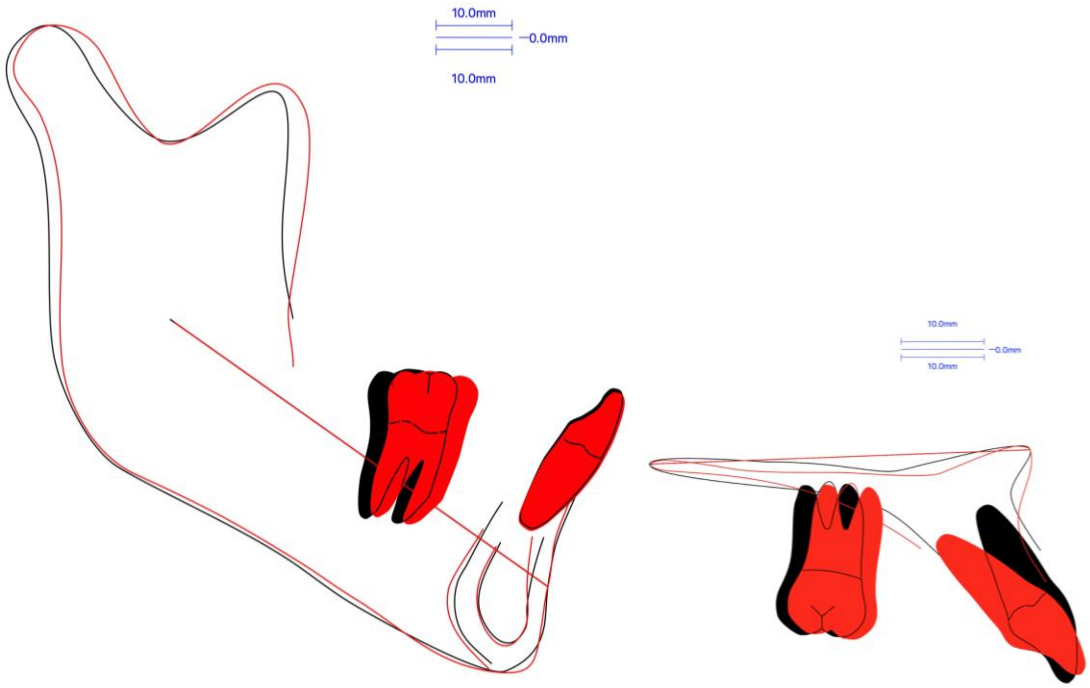


Figure 8. A ten millimeter reference length for mandibular and maxillary superimpositions were drawn in Quick Ceph Studio.

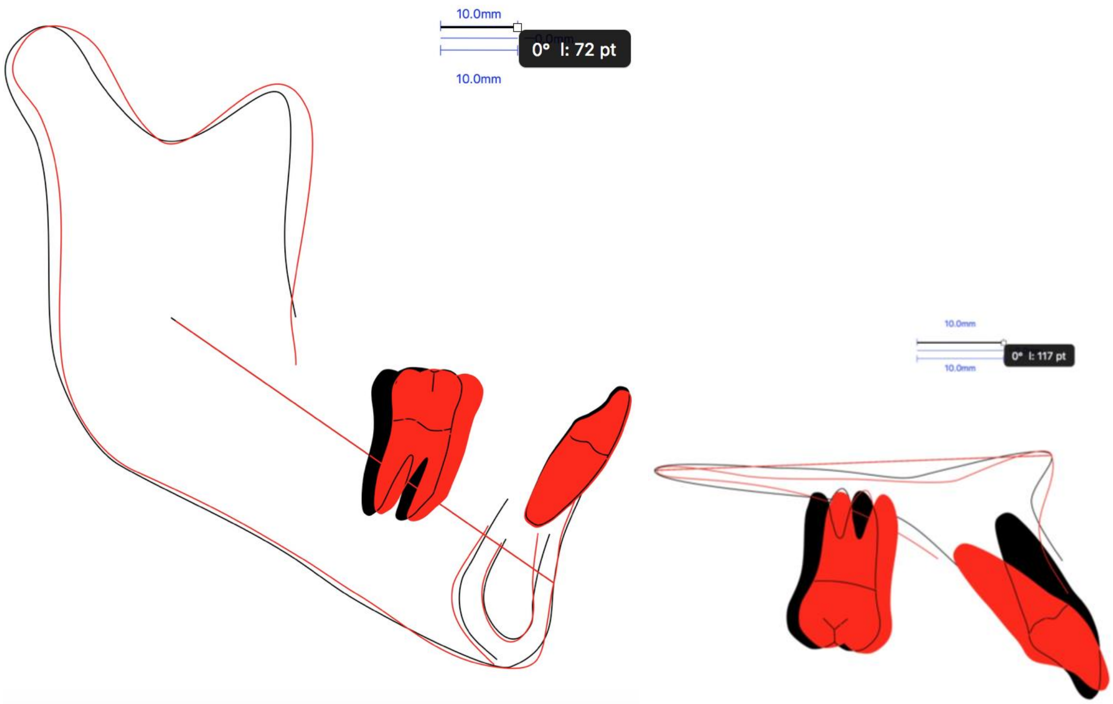


Figure 9. Corresponding measurement of the reference length for mandibular and maxillary superimpositions were recorded in pixel, which was represented as points in Keynote. Example shows mandible measuring 72 reference pixel and maxilla measuring 117 reference pixel for a 10 mm reference length.

On Keynote, for mandibular superimposition, the corpus axis (Xi to PM) was oriented parallel to the horizontal plane (Fig 10). For maxillary superimposition, the palatal plane (ANS to PNS) was oriented parallel to the horizontal plane (Fig 10). A line was drawn on maxillary and mandibular incisors from crown tip to root tip. The midpoint of the line is termed "center of tooth." A one by one pixel point was placed in the following measurement locations:

Maxillary and mandibular molars (Fig 11):

1) Crown groove
2) Root furcation

3) Root tip

Maxillary and mandibular incisors (Fig 12):

4) Crown tip

5) Center of tooth

6) Root tip

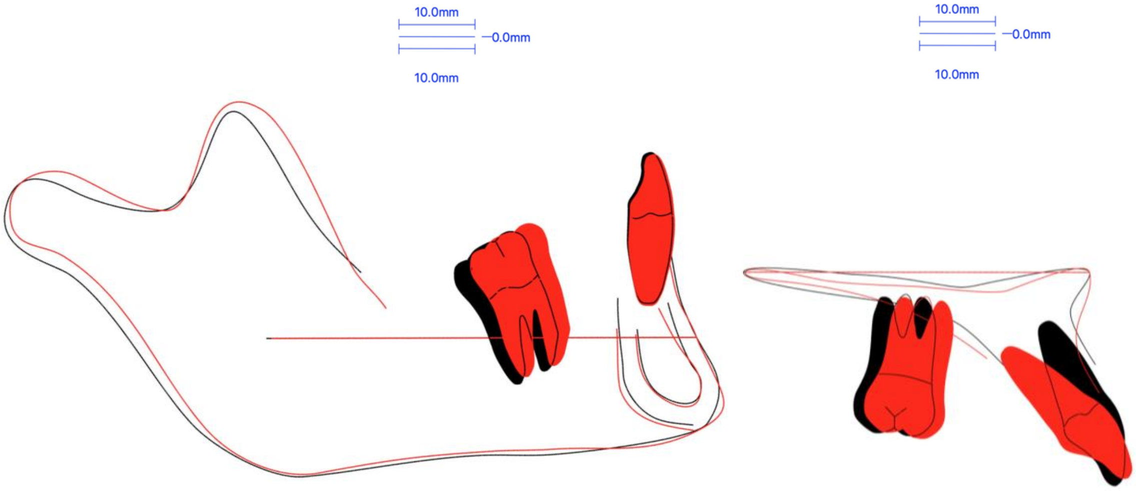


Figure 10. Corpus axis (Xi to PM) was oriented parallel to the horizontal plane for mandible. Palatal plane (ANS to PNS) was oriented parallel to the horizontal plane for maxillary.

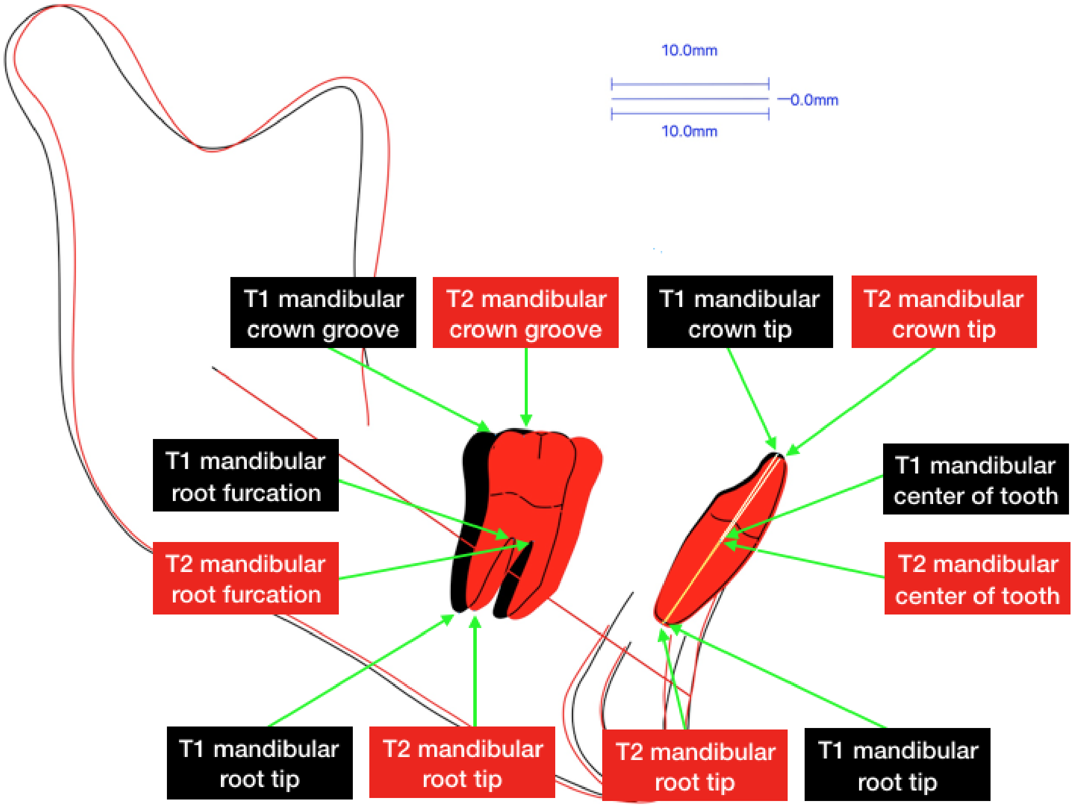


Figure 11. Mandibular superimposition of T1 to T2 displaying measurement locations.

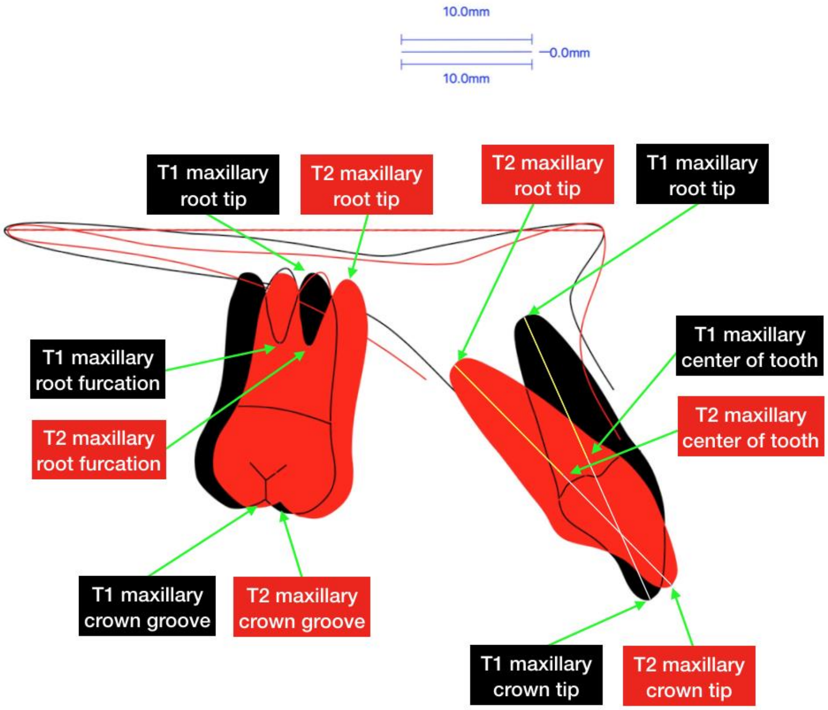


Figure 12. Maxillary superimposition of T1 to T2 displaying measurement locations.

Measurement locations were represented by an x (horizontal) and a y (vertical) value. Tooth movements were calculated from the pixel change in x and y coordinates. Change in pixel was then converted to mm as followed:

$$\mathit{\Delta}\,\text{mm} = \mathit{\Delta}\,\text{pixel x}\left(\frac{10\,mm}{reference\ pixel}\right)$$

For directional tooth movements (DTMs), negative values represented extrusion and protraction and positive values denoted intrusion and retraction.

Total tooth movements (TTMs) were calculated as:

$$TTM = \sqrt{(\mathit{\Delta}\,x)^2 + (\mathit{\Delta}\,y)^2}$$

Intraexaminer Reliability

Based on the sample size, five randomly selected CLCs and CBLCs were digitized twice, two weeks apart, by the same examiner (T.N.). Ricketts and ABO cephalometric analyses were measured , as well as measurements of tooth movements.

Statistical Analysis

Statistical analysis was performed using IBM SPSS 25.0 (IBM Corp., Armonk, NY, USA). The intraexaminer reliability was analyzed using intraclass correlation coefficient (ICC). A power analysis was conducted to determine that a sample size of 35 was justified at the power of 80% and α=0.05. Our proposed sample size of 38 met this requirement. The difference between the cephalometric measurements of CLCs and

CBLCs in the orthogonal perspective were assessed using one-sample Wilcoxon signed rank test and correlation was evaluated with ICC. The following levels were used to interpret intraclass correlation: > 0.90 = excellent correlation; 0.75-0.95 = good correlation, 0.5-0.75 = moderate correlation, <0.5 = poor correlation.[19]

DTMs and TTMs between the three groups were compared using Friedman's two-way analysis of variance by ranks and pairwise comparison. Nonparametric tests were used to adjust for measurements because the data did not follow a normal distribution.

Results

Thirty-eight patients fulfilled the study's criteria. A total of 10 males and 28 females participated in the study, with a mean age of 14 years and 11 months ± 4 years and 6 months, and mean treatment time of 2 years and 8 months ± 8 months. The intraexaminer reliability of repeated measurements were completed by a single operator (T.N.) (Appendix Tables A-D). For cephalometric measurements, intraexaminer reliability test showed that all measurements of CLCs and CBLCs were above 0.900, indicating excellent reliability (Appendix Tables A and B). For DTMs, the mandibular arch for CBCT ranged between 0.592 – 0.957 and LC was between 0.602 – 0.912 (Appendix Table C). For the maxillary arch, the range for CBCT was between 0.617 – 0.995, and LC was between 0.689 – 0.995 (Appendix Table D). Both mandibular and maxillary arch showed CBCT and LC to have moderate and excellent reliability.

When comparing angular measurements between CLCs T1 and CBLCs T1 using one-sample Wilcoxon signed rank test, the differences between the two modalities were

Table 6. The comparison of T1 angular measurements between CLCs and CBLCs using one-sample Wilcoxon signed rank test at $\alpha = 0.05$ with correlation expressed as ICC.

Angular Measurements	CLCs Mean ± SD (deg)	CBLCs Mean ± SD (deg)	Difference of Mean[a] (deg)	P-Value	ICC[b]
Ricketts Analysis					
Cranial Defl.	28.76 ± 2.63	29.19 ± 2.44	-0.43 ± 0.19	0.094	0.880
Facial Axis	88.10 ± 4.79	88.31 ± 5.07	-0.21 ± -0.28	0.400	0.982
Facial Depth	88.02 ± 3.11	88.12 ± 2.94	-0.10 ± 0.17	0.373	0.961
LFH	43.94 ± 4.37	43.87 ± 4.27	0.07 ± 0.10	0.591	0.970
Md Arc	32.46 ± 5.69	32.96 ± 5.47	-0.50 ± 0.22	0.184	0.955
MPA	22.76 ± 5.10	21.38 ± 5.40	1.38 ± -0.30	<0.001*	0.971
Mx Depth	91.71 ± 3.34	91.63 ± 2.99	0.08 ± 0.35	0.827	0.952
Ramus Position	73.77 ± 4.29	74.46 ± 3.99	-0.69 ± 0.30	0.164	0.905
TFH	57.89 ± 5.01	57.50 ± 5.44	0.39 ± -0.43	0.044*	0.981
ABO Analysis					
L1 to MP	91.88 ± 15.77	92.89 ± 16.43	-1.01 ± -0.66	0.026*	0.993
U1 to SN	100.94 ± 10.67	100.78 ± 11.12	0.16 ± -0.45	0.833	0.971
ANB	4.70 ± 1.74	4.57 ± 1.52	0.13 ± 0.22	0.286	0.947
FMA	24.59 ± 4.92	23.45 ± 3.32	1.14 ± 1.66	<0.001*	0.969
SNA	81.47 ± 3.01	80.77 ± 3.46	0.70 ± -0.45	0.017*	0.928
SNB	76.73 ± 2.99	76.21 ± 2.38	0.52 ± 0.61	0.016*	0.960
SN-MP	32.54 ± 10.76	32.50 ± 9.38	0.04 ± 1.38	0.163	0.981

Asymptotic significances are displayed, N=38.

a. Difference was found by subtracting CBLCs' measurements from CLCs.
b. Type A intraclass correlation coefficients using an absolute agreement definition. The estimator is the same, whether the interaction effect is present or not.

* Denotes statistical difference.

statistically significant at MPA, TFH, L1 to MP, FMA, SNA, and SNB. ($P<0.05$, Table 6). Good to excellent correlation for all angular measurements were seen using intraclass correlation test (0.880-0.993, Table 6). A total of 15 out of the 16 angular measurements T1 measurements had ICC above 0.900, which suggests excellent correlation (Table 6).

Using one-sample Wilcoxon signed rank test, linear measurements between CLCs T1 and CBLCs T1 had statistical significance at ACB, U6 to PTV, and PFH ($P<0.05$, Table 7). When assessing linear measurements using intraclass correlation test, good to excellent correlation were seen (0.868-0.992, Table 7). A total of 15 out of the 16 angular measurements had single measures ICC above 0.900, which suggests excellent correlation.

Table 7. The comparison of T1 linear measurements between CLCs and CBLCs using one-sample Wilcoxon signed rank test at $\alpha = 0.05$ with correlation expressed as ICC.

Linear Measurements	**CLCs Mean ± SD (mm)**	**CBLCs Mean ± SD (mm)**	**Difference of Mean[a] (mm)**	**P-Value**	**ICC[b]**
Ricketts Analysis					
ACB	53.18 ± 3.33	54.02 ± 3.45	-0.84 ± -0.12	<0.001*	0.966
Corpus Length	63.33 ± 3.86	63.02 ± 3.78	0.31 ± 0.08	0.241	0.940
Mx Convexity	3.49 ± 2.16	3.37 ± 2.12	0.12 ± 0.04	0.400	0.971
L1 to APo	0.93 ± 2.95	0.90 ± 2.89	0.03 ± 0.06	0.407	0.993
U6 to PTV	15.38 ± 4.44	15.96 ± 4.54	-0.58 ± -0.10	0.015*	0.973
U1 to APo	6.47 ± 3.71	6.75 ± 3.70	-0.28 ± 0.01	0.780	0.980
Porion Loc.	-39.16 ± 2.78	-39.68 ± 2.82	0.52 ± -0.04	0.119	0.868
PFH	58.91 ± 3.80	60.05 ± 4.25	-1.14 ± -0.45	<0.001*	0.938
ABO Analysis					
U1 to NA	4.56 ± 3.70	4.97 ± 3.55	-0.41± 0.15	0.088	0.962
L1 to NB	5.52 ± 2.58	5.45 ± 2.66	0.07 ± -0.08	0.528	0.992

Asymptotic significances are displayed, N= 38.

a. Difference was found by subtracting CBLCs' measurements from CLCs.
b. Type A intraclass correlation coefficients using an absolute agreement definition. The estimator is the same, whether the interaction effect is present or not.

* Denotes statistical difference.

When comparing DTMs of group 1, group 2, and group 3 using Friedman's test, all horizontal and vertical movements for the mandibular arch were found to have no statistical significance, except for mandibular incisor crown in the horizontal direction (*P*=0.048, Table 8). Pairwise test of the mandibular incisor crown, adjusted by the Bonferroni correction, had no statistical significance between group 1 and 2, 1 and 3, and 2 and 3 (*P*>0.05, Table 9). For the maxillary arch, all six locations had no statistical significance (*P*>0.05, Table 10).

TTMs showed statistical significance for maxillary molar furcation and maxillary molar root (*P*=0.005 and *P*=0.020, respectively, Table 11). Pairwise test, adjusted by the Bonferroni correction, showed statistical significance for maxillary molar furcation between group 1 and 2 and group 2 and 3 (*P*=0.048 and *P*=0.006, respectively), as well as maxillary molar root between group 2 and 3 (*P*=0.035) (Table 12).

Table 8. DTMs of the mandibular locations, analyzed using Friedman's Two-Way Analysis of Variance by Rank for group 1, 2, and 3, as well as *P*-value with significance level at α = 0.05.

DTMs of Mandibular Locations	Group 1 Mean ± SD (mm)	Group 2 Mean ± SD (mm)	Group 3 Mean ± SD (mm)	P-Value	Group 1 Mean ± SD (mm)	Group 2 Mean ± SD (mm)	Group 3 Mean ± SD (mm)	P-Value
	Horizontal				Vertical			
Incisor Crown	-1.2 ± 2.43	-1.05 ± 2.72	-0.97 ± 2.68	0.048*	0.37 ± 1.22	0.29 ± 1.09	0.51 ± 1.10	0.136
Incisor Center	-0.28 ± 1.21	-0.03 ± 1.33	-0.15 ± 1.44	0.265	0.36 ± 1.22	0.3 ± 1.03	0.52 ± 1.03	0.078
Incisor Root	0.71± 1.26	1.02 ± 1.18	0.64 ± 1.41	0.129	0.37 ± 1.24	0.22 ± 1.08	0.54 ± 1.04	0.228
Molar Crown	-1.26 ± 1.42	-1.28 ± 1.27	-1.12 ± 1.23	0.723	-1.62 ± 0.96	-1.56 ± 1.02	-1.44 ± 1.00	0.486
Molar Furcation	-1.58 ± 1.53	-1.63 ± 1.43	-1.48 ± 1.41	0.284	-1.85 ± 1.07	-1.81 ± 1.11	-1.73 ± 1.11	0.087
Molar Root	-1.94 ± 1.86	-2.00 ± 1.72	-1.92 ± 1.69	0.593	-1.67 ± 1.20	-1.73 ± 1.13	-1.64 ±1.08	0.186

N=38

Table 9. Pairwise test, adjusted by the Bonferroni correction, of mandibular incisor crown in the horizontal position for DTM with significance level at α = 0.05.

Pairwise Test

DTMs of Mandibular Locations	Group 1 and 2	Group 1 and 3	Group 2 and 3
Horizontal			
Incisor Crown	0.226	0.056	1.000

Asymptotic significances (2-sided tests) are displayed, N=38.

Significance values have been adjusted by the Bonferroni correction for multiple tests.

Table 10. DTMs of the maxillary locations, analyzed using Friedman’s Two-Way Analysis of Variance by Rank for group 1, 2, and 3, as well as *P*-value with significance level at α = 0.05.
N=3

DTMs of Maxillary Locations	**Group 1 Mean ± SD (mm)**	**Group 2 Mean ± SD (mm)**	**Group 3 Mean ± SD (mm)**	**P-Value**	**Group 1 Mean ± SD (mm)**	**Group 2 Mean ± SD (mm)**	**Group 3 Mean ± SD (mm)**	**P-Value**
	Horizontal				**Vertical**			
Incisor Crown	0.05 ± 3.33	0.32 ± 3.67	0.15 ± 3.44	0.068	-0.82 ± 1.25	-0.76 ± 1.42	-0.67 ± 1.36	0.368
Incisor Center	0.8 ± 1.54	1.04 ±1.85	0.93 ± 1.76	0.881	-0.97 ± 0.98	-0.92 ± 1.07	-0.92 ± 0.97	0.924
Incisor Root	1.44 ± 2.47	1.75 ± 2.28	1.73 ± 2.28	0.832	-1.23 ± 1.53	-1.17 ± 1.36	-1.09 ± 1.53	0.656
Molar Crown	-0.64 ±1.51	0.66 ± 1.48	-0.59 ± 1.44	0.993	-1.32 ±1.38	-1.41 ± 1.20	-1.34 ± 1.39	0.752
Molar Furcation	-0.03 ± 1.47	-0.01 ± 1.29	-0.09 ± 1.55	0.541	-1.22 ± 1.27	-1.21 ± 1.11	-1.27 ± 1.28	0.548
Molar Root	0.26 ±1.65	0.16 ± 1.35	0.19 ± 1.72	0.729	-1.09 ± 1.29	-1.11 ± 1.05	-1.16 ± 1.15	0.405

Table 11. TTMs of locations, analyzed using Friedman's Two-Way Analysis of Variance by Rank for group 1, 2, and 3, as well as *P*-value with significance level at α = 0.05.

TTMs of Locations	Group 1 Mean ± SD (mm)	Group 2 Mean ± SD (mm)	Group 3 Mean ± SD (mm)	P-Value	Group 1 Mean ± SD (mm)	Group 2 Mean ± SD (mm)	Group 3 Mean ± SD (mm)	P-Value
	Mandibular				**Maxillary**			
Incisor Crown	2.47 ± 1.66	2.55 ± 1.77	2.56 ± 1.71	0.710	2.96 ± 2.04	2.98 ± 2.36	2.94 ± 2.10	0.772
Incisor Center	1.45 ± 1.01	1.61 ± 1.69	1.59 ± 0.91	0.275	1.88 ± 1.13	2.14 ± 1.35	1.98 ± 1.32	0.729
Incisor Root	1.72 ± 0.86	1.71 ± 0.83	1.81 ± 0.66	0.172	2.89 ± 1.88	2.89 ± 1.74	2.86 ± 1.85	0.900
Molar Crown	2.33 ± 1.30	2.29 ± 1.19	2.20 ± 1.00	0.729	2.14 ± 1.36	2.12 ± 1.23	2.13 ± 1.25	0.924
Molar Furcation	2.45 ± 1.31	2.7 ± 1.36	2.57 ± 1.33	0.575	2.24 ± 1.46	1.78 ± 1.08	2.08 ± 1.12	0.005*
Molar Root	2.8 ± 1.69	2.94 ± 1.59	2.8 ± 1.59	0.518	2.08 ± 1.15	1.76 ± 1.02	2.09 ± 1.09	0.020*

N=38

Table 12. Pairwise test of TTMs of maxillary molar root with significance level at α = 0.05.

Pairwise Test			
TTMs of Locations	**Group 1 and 2**	**Group 1 and 3**	**Group 2 and 3**
Mx Molar Furcation	0.048*	1.000	0.006*
Mx Molar Root	0.065	1.000	0.035*

Asymptotic significances (2-sided tests) are displayed, N=38.

Significance values have been adjusted by the Bonferroni correction for multiple tests.

Discussion

Cephalometry is an important tool for diagnosing skeletal asymmetry and evaluating response to treatment, growth, and long-term stability of orthodontic treatment. Traditionally, cephalometric analysis of patients was performed using 2D conventional lateral cephalograms. Numerous of studies and databases have established standards of 2D computer radiography. CBCT has become an alternative and additive tool to orthodontic diagnosis and treatment planning. In many regards, CBCT is believed to be a superior radiographic technique compared to conventional radiography.[21] Unlike conventional cephalograms, CBCT has minimal distortion of anatomic structure. However, standard population norms have not been established for 3D CBCT volumes.

One of the goals of this study was to determine whether Ricketts and ABO cephalometric analyses used on CBLCs could provide similar measurements to those performed on CLCs. Furthermore, the current study was undertaken to determine whether tooth movements on CLCs and CBLCs were comparable. During this transition period, it is crucial to the field of orthodontics to assess the added benefits of CBCT in orthodontic cases and compare the features of conventional radiography to CBCT.

The decision to use CBCT left-side projection in this study was to be consistent in tracing and assessing the left molar movements for all radiographic modalities. In CLCs, the left side of a patient is closest to the film and is subject to less distortion and magnification than the right side. CBCT volume allows for the operator to eliminate the erroneous superimposition of bilateral dental and skeletal landmarks by synthesizing lateral cephalograms to only show one side of the face. Thus, CBLCs have notable advantages. This study supported literature articles that indicated CBLCs projected to show only the left side compared to CLCs, had some areas of statistical significance, but overall was comparable.[11, 22, 23] In a recent study by Hariharan *et al.*, comparison of cephalometric measurements was completed for CLCs, CBCT half-skull synthesized lateral cephalogram, and CBCT total-skull synthesized lateral cephalogram.[24] The results showed that CBCT total-skull had higher reliability for mid-sagittal linear measurements. However, CBCT half-skull produced consistent and higher overall ICC values than those from CBCT total-skull. Hariharan *et al.* revealed that CBCT half-skull cephalograms had comparable angular and linear measurements to those of CLCs, allowing for better representation of the left and right side of skull separately.[24] With this finding, we were comfortable in this study to compare CLCs to CBLCs left-side projection.

Cephalometric Measurements

This research first compared the two imaging modalities based on cephalometric angular and linear measurements at T1. When assessing the results of angular and linear cephalometric measurements, the difference of mean for statistically significant measurements ranged from -0.10 to -1.01 degrees for angular measurements and -0.58 to -1.14 mm for linear measurements. These differences are small enough that selecting one radiographic modality over the other would not significantly change the diagnosis or course of treatment. Thus, these cephalometric measurements do not appear to be clinically significant.

Many of the cephalometric measurements that reached statistical significance had landmark identification at Po, Or, Go, Gn and Me. In this study, double images of the inferior border of the mandible, angle, and ramus were often seen in CLCs. Because the left side of the face is closer to the film and has less magnification, the left side was chosen to be traced for all T1s. However, when comparing T1s to T2s, there were inconsistencies in landmark identification of Go and Gn. It appeared that there may have been variation in head positioning, as the yaw and roll may be incorrect, and/or minimal anatomical asymmetry that could not have been accounted for in the CLCs. Also, the construction of FMA and MPA require identification of Po and Or to form Frankfort horizontal. Po and Or are two of the most difficult landmarks to correctly identify because of the bilateral nature of the anatomical structures.[11, 25-28] It is believed that superimposition occurring at the bilateral middle ear and other temporal fossa structures cause difficulty in detecting anatomic porion.[27] As for Or, the outline is superimposed on bilateral key ridges and maxillary sinus, making it difficult to accurately identify.Furthermore, landmark identification of Go and Me influence the mandibular plane (Go to Gn for Ricketts and Go to Me for ABO) for a number of cephalometric measurements and are recognized to have highest clinical deviations (=/- 4 degrees). [25-26] Literature articles revealed that landmarks on a curved surface, specifically Go, Gn, and Me, are difficult to reproduce.[25-26, 29] This proved to be true in this study where FMA, L1 to MP, MPA, and PFH, which required identification of Frankfort Horizontal, Me, and/or Go, were statistically significant. Thus, statistical significances seen between CLCs and CBLCs for angular measurements in this study were consistent with current literature. [23, 30-32]

With SNA, SNB, and TFH reaching statistical significance, the discrepancy in three cephalometric measurements is speculated to be due to identification of nasion (Na). Literature has shown that Na can be a challenging landmark to identify consistently.[5, 33-35] Yet, Na is an important point, such that many cephalometric numbers are based on the line SN. Midsagittal measurements, such as sella and nasion, tend to be magnified uniformly on conventional lateral cephalograms.[34] Sekiguchi *et al.* found in their study that Na is often time difficult to identify if the nasofrontal suture is not correctly visualized.[35]

Statistical significance at ACB and U6 to PTV use PT point to determine the length measurements. PT point is the junction of pterygomaxillary fissure and foramen rotundum. It is indicated as the 11 o'clock position of the pterygomaxillary fissure on a lateral cephalogram.[36] However, this landmark often time poses a problem because it is a bilateral structure that more often than not, does not coincide perfectly in a 2D radiograph. Moreover, the 11 o'clock position can be variable due to the shape of pterygomaxillary fissure being different for each patient, as well as variation that occur from head position in cephalometer. Thus, ACB and U6 to PTV can vary depending on clarity of radiograph, the position of patient's head, and operator's skills and training.

Measurements of Tooth Movements

The second part of this study evaluated tooth movements from superimposition of T1 and T2 tracings and compared the different combinations of superimposition based on radiographic modalities.

For DTMs in the mandibular arch, no statistical significance was seen for the three groups with the exception for mandibular incisor crown movement in the horizontal direction (P=0.048). With the P-value barely reaching statistical significance, it was expected that pairwise test showed no statistical significance between group 1 and 2, group 1 and 3, and group 2 and group 3. The maxillary arch had no statistical significance for any category in both the horizontal and vertical direction. This demonstrates that superimposition to assess tooth movements using CLCs, CBLCs, or combination of both can provide similar results. Clinicians who choose to utilize CBCT scans for pre-treatment diagnosis can take progress CLCs to superimpose and assess tooth movements. This reduces unnecessary radiation to patients should CBCT scan is not deemed necessary for progress records. If CLCs are taken at T1, progress CBLCs taken for necessary reasons can also effectively be superimposed with CLCs T1. There would be no need in taking additional CLCs at progress purely for comparison to T1. Moreover, taking both CLCs and CBLCs at T1 may not be valuable, as these two radiographic modalities show to be comparable. Reducing further unneeded radiation would be beneficial for patients.

When TTMs were evaluated, similar results were seen amongst the three groups. Statistical significance was only detected for maxillary molar furcation and root tip. This can be explained by first assessing the software's limitations. Because of the restriction with a standardized tooth template, accuracy of positioning the maxillary molar root tip and subsequently the furcation were compromised. Quick Ceph Studio allowed for a point to be placed at the exact molar root tip, but the molar template itself has a maximum size the tooth will expand to. Thus, the variation in the size of the cephalometric teeth could not be accounted for with the set template. Moreover, detection of the maxillary molar furcation and root tip were prone to error due to the superimposition of radiopaque structures in the region, such as the maxillary palate, density of the buccal cortical bone, and three-rooted structure of the maxillary molar. The lack of contrast in this region hindered the precision in identifying key landmarks. In a study by Ohiomba *et al*., the results showed that interradicular buccal cortical bone was detected to be thickest (1 mm) and densest (1395 Hounsfield units) between the maxillary first and second molar on a computed tomography imaging.[37] This high density level caused the specified region to be more radiopaque. This explains the finding in this study, such that differences in landmark placement between radiographic modalities at maxillary first molar could be due to radiopacity of the maxillary bone and superimposition of various skeletal and dental structures in the area.

General Source of Variability

Landmark identification. Errors associated with landmark identification can be due to the inherent difficulty of the landmark, the quality of the radiograph, and the operator's experience. Systemic errors seen with identifying cephalometric landmarks affect CLCs and CBLCs.[5, 11, 17] Many studies have compared CLCs and CBLCs and saw that landmark identification is easier with CBCT. With 3D imaging, landmarks that often lack contrast with CLCs are more easily recognized with CBLCs.

Head orientation. Malkoc *et al.* found that cephalometric measurements on lateral cephalograms changed from 16.1% to 44.7% when the head rotated by 14 degrees.[39] The errors that contribute to head orientation can be from technician's improper positioning of the subject in the machine and/or patient's sudden movement after fixation in the cephalometer. Moreover, patient's anatomy can also affect head positioning. The ears are used as reference and are assumed to be symmetrical and at the same level. However, patient with severe asymmetry could create head positioning error.[40] With CLCs, once radiograph is taken and processed, no changes can be made to correct the roll and yaw if head positioning is detected be incorrect. However with CBLCs, the operator can manipulate the CBCT volume to orient the head properly before constructing the lateral cephalograms. However, if the patient is out of the beam detector, perhaps can be minimized by software realignment, distortion of the radiograph can still occur.

X-ray emitter. Another source of error is misalignment of x-ray emitter focal spot seen in conventional cephalogram machines. X-ray units are calibrated periodically. However, lateral cephalograms are taken many months apart, possibly years, apart and x-ray source may not be constant throughout the entire period. Lee *et al.* saw that misalignment of x-ray emitter affects the interpretation of facial asymmetry in PA cephalograms.[41] This can be an issue with conventional lateral cephalograms too, such as the mandibular plane that can be affected by incorrect positioning of the x-ray emitter.

Radiograph processing. If analog radiograph films are taken and transferred to digital format, the quality of the original film is an important criterion in understanding the validity of study results. According to Ongkosuwito *et al.,* digital images that originate from poor-quality analogue radiographs can add to the error seen in digital tracings.[42] Quality of film plays an important factor, allowing for better recognition of landmarks. Moreover, scanning analog radiographic film not only is a time-consuming step but introduces magnification errors.[43-44] Another error seen with digital technique is possible unknown formats and unknown grey shades.[43-44] Current studies have shown that image quality of cephalogram processed in high-resolution (600 dpi) does not lead to better results and greyscale less than 7-bit may result in landmark identification errors.[42]

Image manipulation. CBCT involves a single 360° scanner that rotates around the patient’s head to acquire 360 images at every degree of rotation.[46] Radiographs can be smoothened by increasing the slice intervals and consequently, sharpened by reducing the slice thickness. If slice thickness is increased at a considerable amount, visualization of small details and landmarks are compromised.[47] Moreover, slice intervals during x-ray acquisition can cause errors in radiographs. Slice intervals can be reduced to lower radiation exposure, as well as increase speed of processing. However, the risk of such reduction is potentially acquiring less information than adequate for accurate depiction of landmarks.[47]

Motion artifacts. CBCT acquires images in one single rotation. Acquisition time is rapid, ranging between 6 seconds and 20 seconds.[48] This is enough time for a patient to perform minor movements. If movement occurs during any portion of the scan, landmarks in specified segment is compromised, even if the whole volume is not.[46] Smaller voxel size, and thus higher spatial resolution, allows for smaller movement necessary to move the patient structure out of the correct voxel.[46] In other words, higher nominal resolution causes higher likelihood of motion artifacts to appear. Thus, it is crucial to fixate the patient's head during the scan process to help reduce potential movements.

Conclusions

1. Cephalometric measurements between CLCs and CBLCs were statistically significant at L1 to MP, FMA, SNA, SNB, ACB, U6 to PTV, and PFH, but appear to not be clinically significant. Cephalometric measurements with statistical significance may be due to identification of Po, Or, Go, Gn, Na, and PT point.

2. DTMs for superimpositions of CLCs and CBLCs were comparable. Clinicians who choose to utilize CBCT scans for pre-treatment diagnosis can take progress CLCs to superimpose and assess tooth movements. If CLCs are taken at T1, progress CBLCs taken for necessary reasons can also effectively be superimposed with CLCs T1. There would be no need in taking additional CLCs at progress purely for comparison to T. Taking both CLCs and CBLCs at T1 may not be valuable, as these two radiographic modalities show to be comparable.

3. TTM showed statistical significance at maxillary molar furcation and maxillary molar root. Difficulty in detecting this position may be due to software's limitations, superimposition of radiopaque structures, and the greater density in the region of the maxillary first molar.

CHAPTER THREE

EXTENDED DISCUSSION

Study Limitations and Future Studies

There were limitations in this study that should be recognized for better understanding of the results, as well as for future studies. The main limitation in this study was that landmark identification was based on only one operator. The proficiency of the observer played a heavy role in this research. The operator's skills and biases could introduce unwanted errors in the data. Future studies would benefit from having more operators identifying landmarks and superimposition and assessing the consistency with inter-rater reliability test. Moreover, landmark identification has been discussed extensively in this study, as well as many literature articles, as to being variable for certain landmarks. Thus, systematic difference in landmark position and identification error should be considered as potential limitations for future studies utilizing digital cephalograms.

This study also had a total of 38 patient cases. Although a power analysis was conducted to determine that a sample size of 35 was justified, increasing the power and sample size could have potentially increased the strength of the study.

Previous studies have recognized the advantage of 3D radiographs over 2D radiographs. One of which was that CBCT volume can be oriented to operator's preference, as well as selection of cut for construction of CBLCs. This study relied on CLCs that could no longer be manipulated, but CBCT volumes were able to be changed before construction of CBLCs. Moreover, it was assumed that all CLCs in this study was taken consistently by the different operators, in terms of correct positioning of placement's head and proper operation of the machine. Thus, there is a potential lack of consistency in the CLCs.

This research looked exclusively at measurements on cephalograms. To further enhance the study, evaluation of the accuracy of cephalometric measurements and tooth movements can be done using dry skulls. In recent studies, caliper measurements on human skulls have been compared to those made on radiographic measurements. Results showed that measurements on CBCT images were different than the ones made on dry skulls.[48-50] Lascala *et al.* discovered that CBCT measurements were systematically smaller than those directly made on skull.[50] This was supported by Baumgaertel *et al.*, who saw that CBCT measurements were underestimated in comparison to direct measurements.[49] However, no clinical significances were seen in these studies. [48-50] With recent studies demonstrating differences in actual skull measurements versus radiographic measurements, it begs the question on whether superimposition of radiographs differ from actual changes seen on dry skulls. Thus, valuable information would be gained from studies assessing validity of this current study in comparison to skull measurements.

The types of CBCT scan and cephalometric analysis software contribute to the variation in result, and therefore should not be generalized to all cephalometric machine and software. This study utilized one type of CBCT and lateral cephalogram machine, as well as one cephalometric analysis software. Future studies could potentially look at a various type of machines and compare cephalometric measurements and tooth movements among the different machines.

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APPENDIX A

INTRAEXAMINER RELIABILITY FOR CEPHALOMETRIC MEASUREMENTS OF 5 PATIENTS' CONVENTIONAL LATERAL CEPHALOGRAMS

LC Measurements		**ICC**^{b}	**95% Confidence Interval**	
			Lower Bound	**Upper Bound**
L1 to MP	Single Measures	0.996^a	0.984	0.999
	Avg. Measures	0.998	0.992	1.000
U1 to NA	Single Measures	0.976^a	0.785	0.995
	Avg. Measures	0.988	0.880	0.997
L1 to NB	Single Measures	0.993^a	0.973	0.998
	Avg. Measures	0.996	0.986	0.999
U1 to SN	Single Measures	0.988^a	0.954	0.997
	Avg. Measures	0.994	0.977	0.998
ANB	Single Measures	0.893^a	0.496	0.975
	Avg. Measures	0.943	0.663	0.987
ACB	Single Measures	0.963^a	0.860	0.991
	Avg. Measures	0.981	0.925	0.995
Convexity	Single Measures	0.966^a	0.861	0.99
	Avg. Measures	0.983	0.926	0.996
Corpus Length	Single Measures	0.900^a	0.646	0.974
	Avg. Measures	0.947	0.785	0.987
Cranial Deflection	Single Measures	0.923^a	0.731	0.980
	Avg. Measures	0.960	0.845	0.990
Facial Axis	Single Measures	0.993^a	0.971	0.998
	Avg. Measures	0.996	0.985	0.999
Facial Depth	Single Measures	0.942^a	0.796	0.985
	Avg. Measures	0.970	0.887	0.992

FMA	Single Measures	0.999[a]	0.996	1.000
	Avg. Measures	1.000	0.998	1.000
LFH	Single Measures	0.973[a]	0.890	0.993
	Avg. Measures	0.986	0.942	0.997
Md Arc	Single Measures	0.937[a]	0.779	0.984
	Avg. Measures	0.937	0.876	0.992
Md Plane	Single Measures	0.973[a]	0.901	0.993
	Single Measures	0.987	0.948	0.997
Mx Depth	Avg. Measures	0.856[a]	0.515	0.962
	Single Measures	0.922	0.680	0.981
L1 to APo	Avg. Measures	0.990[a]	0.911	0.998
	Single Measures	0.995	0.953	0.999
U6 to PTV	Avg. Measures	0.971[a]	0.889	0.993
	Single Measures	0.985	0.941	0.996
U1 to APo	Avg. Measures	0.991[a]	0.922	0.998
	Single Measures	0.995	0.959	0.999
Porion Location	Avg. Measures	0.893[a]	0.648	0.972
	Single Measures	0.944	0.787	0.986
PFH	Avg. Measures	0.865[a]	0.561	0.964
	Single Measures	0.928	0.719	0.982
Ramus Position	Single Measures	0.971[a]	0.891	0.993
	Avg. Measures	0.985	0.943	0.996
SN-MP	Single Measures	0.998[a]	0.992	1.000
	Avg. Measures	0.999	0.996	1.000
SNA	Single Measures	0.919[a]	0.714	0.979
	Avg. Measures	0.958	0.833	0.989
SNB	Single Measures	0.925[a]	0.472	0.984
	Avg. Measures	0.961	0.641	0.992
TFH	Single Measures	0.966[a]	0.868	0.991
	Avg. Measures	0.983	0.930	0.996

a. The estimator is the same, whether the interaction effect is present or not.

b. Type A intraclass correlation coefficients using an absolute agreement definition.

APPENDIX B

INTRAEXAMINER RELIABILITY FOR CEPHALOMETRIC MEASUREMENTS OF 5 PATIENTS' CBCT-GENERATED LATERAL CEPHALOGRAMS

CBCT Measurements		ICC[b]	95% Confidence Interval	
			Lower Bound	Upper Bound
L1 to MP	Single Measures	0.996[a]	0.983	0.999
	Avg. Measures	0.998	0.991	0.999
U1 to NA	Single Measures	0.963[a]	0.865	0.990
	Avg. Measures	0.981	0.928	0.995
L1 to NB	Single Measures	0.986[a]	0.944	0.996
	Avg. Measures	0.993	0.971	0.998
U1 to SN	Single Measures	0.988[a]	0.955	0.997
	Avg. Measures	0.994	0.977	0.999
ANB	Single Measures	0.903 [a]	0.693	0.975
	Avg. Measures	0.920	0.863	0.987
ACB	Single Measures	0.907[a]	0.552	0.978
	Avg. Measures	0.951	0.712	0.989
Convexity	Single Measures	0.970[a]	0.889	0.992
	Avg. Measures	0.985	0.941	0.996
Corpus Length	Single Measures	0.903[a]	0.679	0.975
	Avg. Measures	0.945	0.809	0.987
Cranial Deflection	Single Measures	0.913[a]	0.627	0.979
	Avg. Measures	0.955	0.771	0.989
Facial Axis	Single Measures	0.983[a]	0.620	0.997
	Avg. Measures	0.991	0.765	0.998
Facial Depth	Single Measures	0.991[a]	0.965	0.998
	Avg. Measures	0.996	0.982	0.999
FMA	Single Measures	1.000[a]	0.999	1.000

	Avg. Measures	1.000	0.999	1.000
LFH	Single Measures	0.953[a]	0.830	0.988
	Avg. Measures	0.976	0.907	0.994
Md Arc	Single Measures	0.949[a]	0.721	0.988
	Avg. Measures	0.974	0.838	0.994
Md Plane	Single Measures	0.964[a]	0.869	0.991
	Avg. Measures	0.982	0.930	0.995
Mx Depth	Single Measures	0.906[a]	0.625	0.962
	Avg. Measures	0.912	0.710	0.981
L1 to APo	Single Measures	0.972[a]	0.892	0.993
	Avg. Measures	0.986	0.943	0.996
U6 to PTV	Single Measures	0.908[a]	0.436	0.980
	Avg. Measures	0.952	0.607	0.990
U1 to APo	Single Measures	0.988[a]	0.955	0.997
	Avg. Measures	0.994	0.977	0.999
Porion Location	Single Measures	0.916[a]	0.706	0.978
	Avg. Measures	0.956	0.828	0.989
PFH	Single Measures	0.937[a]	0.776	0.984
	Avg. Measures	0.968	0.874	0.992
Ramus Position	Single Measures	0.934[a]	0.770	0.983
	Avg. Measures	0.966	0.870	0.991
SN-MP	Single Measures	0.999[a]	0.996	1.000
	Avg. Measures	0.999	0.998	1.000
SNA	Single Measures	0.900[a]	0.714	0.979
	Avg. Measures	0.942	0.833	0.989
SNB	Single Measures	0.907[a]	0.626	0.977
	Avg. Measures	0.951	0.770	0.988
TFH	Single Measures	0.966[a]	0.877	0.991
	Avg. Measures	0.983	0.935	0.996

a. The estimator is the same, whether the interaction effect is present or not.

b. Type A intraclass correlation coefficients using an absolute agreement definition.

APPENDIX C

INTRAEXAMINER RELIABILITY FOR CEPHALOMETRIC MEASUREMENTS OF 5 PATIENTS' MANDIBULAR LOCATION MEASUREMENTS

Mandibular Locations		CBCT			LC		
		ICC[b]	95% CI		ICC[b]	95% CI	
X-value							
Incisor Crown	Single Measures	0.957[a]	0.720	0.995	0.896[a]	0.304	0.989
	Avg. Measures	0.978	0.837	0.998	0.945	0.467	0.994
Incisor Center	Single Measures	0.592[a]	-0.480	0.949	0.811[a]	-0.033	0.979
	Avg. Measures	0.743	-1.844	0.974	0.896	-0.069	0.989
Incisor Root	Single Measures	0.629[a]	-0.505	0.955	0.912[a]	0.219	0.991
	Avg. Measures	0.772	-2.043	0.977	0.954	0.359	0.995
Molar Crown	Single Measures	0.897[a]	0.431	0.988	0.806[a]	0.034	0.978
	Avg. Measures	0.946	0.602	0.994	0.893	0.066	0.989
Molar Furcation	Single Measures	0.857[a]	0.287	0.984	0.841[a]	0.011	0.982
	Avg. Measures	0.923	0.446	0.992	0.914	0.021	0.991
Molar Root	Single Measures	0.806[a]	0.059	0.978	0.790[a]	-0.082	0.976
	Avg. Measures	0.892	0.112	0.989	0.882	-0.179	0.988
Y-value							
Incisor Crown	Single Measures	0.754[a]	-0.053	0.971	0.735[a]	-0.369	0.970
	Avg. Measures	0.860	-0.111	0.985	0.847	-1.169	0.985
Incisor Center	Single Measures	0.765[a]	-0.026	0.972	0.602[a]	-0.541	0.951
	Avg. Measures	0.867	-0.052	0.986	0.751	-2.361	0.975

Incisor Root	Single Measures	0.818[a]	0.079	0.979	0.801[a]	-0.105	0.978
	Avg. Measures	0.900	0.147	0.989	0.889	-0.234	0.989
Molar Crown	Single Measures	0.762[a]	0.042	0.971	0.855[a]	0.106	0.984
	Avg. Measures	0.865	0.080	0.985	0.922	0.192	0.992
Molar Furcation	Single Measures	0.810[a]	0.126	0.978	0.811[a]	-0.088	0.979
	Avg. Measures	0.895	0.224	0.989	0.896	-0.194	0.989
Molar Root	Single Measures	0.815[a]	0.101	0.979	0.807[a]	-0.141	0.979
	Avg. Measures	0.898	0.183	0.989	0.893	-0.328	0.980

APPENDIX D

INTRAEXAMINER RELIABILITY FOR CEPHALOMETRIC MEASUREMENTS OF 5 PATIENTS' MAXILLARY LOCATION MEASUREMENTS

Maxillary Locations		CBCT			LC		
		ICC[b]	95% CI		ICC[b]	95% CI	
X-value							
Incisor Crown	Single Measures	0.995[a]	0.960	0.999	0.995[a]	0.966	1.00
	Avg. Measures	0.997	0.980	1.000	0.998	0.983	1.00
Incisor Center	Single Measures	0.972[a]	0.784	0.997	0.816[a]	-0.100	0.980
	Avg. Measures	0.986	0.879	0.999	0.898	-0.221	0.990
Incisor Root	Single Measures	0.915[a]	0.420	0.991	0.911[a]	0.434	0.990
	Avg. Measures	0.955	0.592	0.995	0.954	0.606	0.995
Molar Crown	Single Measures	0.796[a]	-0.056	0.977	0.765[a]	0.030	0.972
	Avg. Measures	0.886	-0.118	0.988	0.867	0.058	0.986
Molar Furcation	Single Measures	0.990[a]	0.917	0.999	0.886[a]	0.203	0.988
	Avg. Measures	0.995	0.957	0.999	0.940	0.338	0.994
Molar Root	Single Measures	0.993[a]	0.936	0.999	0.867[a]	0.107	0.986
	Avg. Measures	0.997	0.967	1.000	0.929	0.193	0.993
Y-value							
Incisor Crown	Single Measures	0.959[a]	0.733	0.996	0.869[a]	0.167	0.986
	Avg. Measures	0.979	0.846	0.998	0.930	0.287	0.993
Incisor Center	Single Measures	0.896[a]	0.418	0.988	0.940[a]	0.604	0.993
	Avg. Measures	0.945	0.590	0.994	0.969	0.753	0.997

Incisor Root	Single Measures	0.896[a]	0.215	0.989	0.911[a]	0.341	0.990
	Avg. Measures	0.945	0.353	0.994	0.954	0.508	0.995
Molar Crown	Single Measures	0.617[a]	-0.140	0.948	0.805[a]	0.131	0.977
	Avg. Measures	0.763	-0.326	0.973	0.892	0.232	0.988
Molar Furcation	Single Measures	0.646[a]	-0.125	0.954	0.727[a]	-0.027	0.966
	Avg. Measures	0.785	-0.286	0.977	0.842	-0.056	0.983
Molar Root	Single Measures	0.809[a]	-0.060	0.980	0.689[a]	-0.108	0.961
	Avg. Measures	0.894	-0.128	0.990	0.816	-0.243	0.980