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Nov 2022	Annual Session of the American College of Prosthodontists 52nd Annual Meeting in Austin, TX
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Abstract

Omar Alqabandei, Master of Science, 2024

Thesis Directed by: Dr. Radi Masri, BDS, MS, PhD

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Title of Thesis: Determining Intercondylar Distance Using Cone-beam Computed Tomography (CBCT)

Purpose: To measure the intercondylar distance (ICD) from cone-beam computed tomography (CBCT) scans of a large population of subjects to determine the average ICD in male and female subject and to correlate ICD measurement obtained with sex and ethnicity of the subjects.

Materials and Methods: This cross-sectional study analyzed consecutive patients who had received maxillofacial field of view CBCT radiographic examinations at the University of Maryland School of Dentistry (UMSOD) between January 20th, 2016, and July 5th, 2023. Inclusion criteria comprised individuals over 18 years old who had maxillofacial CBCT scans on file in the UMSOD INFINITT (INFINITT NA, Phillipsburg, NJ) PACS system. Exclusion criteria included patients with prosthetic condyles, bone growth-affecting diseases, incomplete scans, poor image quality, or missing sex and age information. Of the initially included 459 patients, 25 were excluded. Data collected from patient charts included age, sex, presence of bone growth-affecting diseases, and measurements of left and right condyles, as well as ICD. The primary investigator reviewed scans, conducted chart reviews, and made measurements on the 434 included files.

Results: Four hundred and thirty-four images of subjects were analyzed. The sample consisted of an even number of male and female subjects (217). The median ICD value was 102.9 mm (min 86.2 mm – max 118.2 mm) for male subjects and 98.4 mm (min 81.5 – max 117.2) mm for female subjects. The mean ICD value of male and female subjects combined (total 434 subjects) was 100.92 mm (min 81.5 mm – max 118.2 mm) and the median value was 100.5 mm. There was statistically significant difference between ICD values of male and female subjects ($P<0.0001$), but not between Caucasian and African American subjects ($P=0.69$). There was no significant difference in the interaction between sex and ethnicity ($P=0.84$).

Conclusions: The ICD influences the radius of movement and the arcs traveled by the cusps during lateral mandibular movements in the horizontal plane. Although canine disocclusion can mitigate inaccuracies arising from an average ICD, it may not fully compensate for individual variations in all patients. For patients restored with group function occlusion, ICD setting may be more critical. Articulators with an adjustable ICD would provide a more anatomically correct tooth form for the treatment of full mouth rehabilitation cases.

Determining Intercondylar Distance Using Cone-beam Computed Tomography

by
Omar Alqabandei

Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, Baltimore in partial fulfillment
of the requirements for the degree of
Master of Science
2024

Dedication: To my parents, Aisha, and Mohammad. I owe you everything.

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List of Abbreviations

2D	Two dimensions
3D	Three dimensions
ANS	Anterior Nasal Spine
CBCT	Cone-beam Computed Tomography
CADIAX	Computer Aided Diagnosis Axiograph
FH	Frankfort Horizontal
ICD	Intercondylar Distance
IMLT	Immediate Mandibular Lateral Translation
IRB	Institutional Review Board
MM	Millimeter
PACS	Picture Archiving and Communication System
PNS	Posterior Nasal Spine
SCI	Sagittal Condylar Inclination
TMJ	Temporomandibular Joint
UMSOD	University of Maryland Baltimore, School of Dentistry

Chapter 1 Introduction and Background

1.1 *Dental Facebow*

A facebow records the three-dimensional (3D) position of the maxilla using two or three cranial points. According to the Glossary of Prosthodontic Terms-9 (GPT-9): the face-bow is a “an instrument used to record the spatial relationship of the maxillary arch to some anatomic reference point or points and then transfer this relationship to an articulator; it orients the dental cast in the same relationship to the opening axis of the articulator; customarily the anatomic references are the mandibular transverse horizontal axis and one other selected anterior reference point” (GPT-9, 2017).

Dr. Francis H. Balkwill first demonstrated the apparatus to the Odontological Society of Great Britain in 1866 (Balkwill, 1866). The apparatus had an angle between 23-30 degrees and the mounted maxillary cast had a distance of 3.5 cm below the condylar plane. Dr. C. H. Luce in 1889 photographed mandibular movements using highly polished silver beads on a frame and found that the condylar paths were curved (Starcke, 2001). He called the facebow “articulating caliper” when he patented his articulator (Starcke, 2001; Prothero, 1916). Only the median incisal point was localized in relation to its distance from the two condyles (Starcke, 2001; Prothero, 1916). The articulator possessed lateral movements and inclined condylar paths but lacked control of the proper orientation of the occlusal plane (Starcke, 2001; Prothero, 1916). Dr. W.E. Walker in 1896 developed a complicated device called a “clinometer” and used it to measure the inclination of the condylar path (Walker, 1896). Dr. Gilmer, an oral surgeon from Chicago, described the principles of facebow at the meeting of the Illinois State Dental

Society in 1882 (Prothero, 1916). Dr. George B. Snow developed the facebow in 1899 (Starcke, 2002). Prothero and Hanau added additional improvements to Snow's face-bow. Prothero added additional attachments to stabilize the instrument and used additional reference points. Hanau constructed it of aluminum, added cushioning (dime-size cups) on the rods, and developed an improved locking system. Dr. John Parfitt in 1902 introduced the first mandibular facebow (Starcke, 2001). He was the first to imitate the anatomic curvatures of the condylar paths in an articulator (Starcke, 2001). He showed that there were three types of mandibular movements (Starcke, 2001; Prothero, 1916):

1- Rotation around a horizontal axis passing through the two condyles
2- Translation forward and downwards
3- Rotation about a vertical axis passing through one condyle

Gysi in 1910 introduced a facebow capable of adjustment to asymmetry on a patient's face, in both vertical and horizontal planes (Starcke et al., 2010; Prothero, 1916). Wadsworth additionally added a new dimension to face-bows by establishing the "third point of reference" (Prothero, 1916). The points of the naso-optic-condylar triangle were the lower border of the ala of the nose, the pupil of the eye, and the condylar rod (Prothero, 1916). Henry "Harry" Page advocated a third cranial reference point using the "Cranial Plane Relator" and located it approximately level with and parallel to the pupils of the eye (Prothero, 1916).

There are five commonly used anterior reference points: (Wilkie, 1979)

1. Orbitale - lowest point of the infraorbital rim, located by palpation (Wilkie, 1979).

2. Orbitale minus 7 mm (Gonzalez & Kingery, 1968)–Frankfort Horizontal plane (FH): The FH plane passes through the porion and orbitale (boney landmarks). Sicher recommends using the midpoint of external auditory meatus as the posterior cranial landmark (Sicher, 1956). Gonzalez found that this landmark lies 7mm superior to the axis, and recommended compensation by making the anterior point of reference 7mm below the orbitale or position the orbitale pointer 7mm above in the articulator to the orbitale indicator (Gonzalez & Kingery, 1968). Bergstrom's arcon articulator automatically compensates by placing the orbital index 7mm higher than the condylar horizontal axis (Beck & Morrison, 1956). The FH plane of the patient becomes the horizontal plane of reference in the articulator (Wilkie, 1979).
3. Nasion (Whipmix) relator is 23 mm above the articulator crossbar: The nasion guide or position of the quick mount facebow fits into the deepest part of the midline depression just below the level of the eyebrows (Sicher, 1952; Wilkie, 1979). The crossbar located 23 mm below the midpoint of the nasion positioner will be in the approximate region of orbitale (Wilkie, 1979). The crossbar not the nasion guide is the third point of reference (Wilkie, 1979).
4. 43 mm above the incisal edge of the right lateral incisor: locates plane of occlusion near mid-horizontal (Guichet, 1970).
5. Virtual facebow (VF): There are different techniques related to the VF that can be categorized as arbitrary VF (based on cutaneous landmarks and planes) or kinematic VF (based on cephalometric landmarks and planes) (Lepidi et al., 2021).

In a study of 10 subjects using a bubble level, Stade found that the 7 mm correction is inadequate, instead, 16.4 mm is needed to duplicate the esthetic reference position, and the axis orbitale plane may result in improper cants to the maxillary cast (Stade et al., 1982). Pitchford in 1991 found that using the orbitale as the anterior reference point frequently results in an overly steep anteroposterior angulation of the occlusal plane (Pitchford, 1991). Errors in the vertical relationship may result in esthetic failures and occlusal errors in both the balancing and non-working sides (Pitchford, 1991)

There are two main types of facebows: 1- kinematic facebow: adjustable ends used to locate the transverse horizontal axis of the mandible and 2-average axis (arbitrary) facebow, where the position of the transverse horizontal axis is estimated. In a kinematic facebow, the vertical dimension of occlusion can be altered on the articulator. According to Palik, 89% of ear bow points were within a 6 mm radius of the true hinge axis (Palik et al., 1985). True hinge axis was clinically located posterior to the ear-bow position in 92% of the subjects (Palik et al., 1985). Discrepancy was significant in the anteroposterior direction but not in the superior-inferior direction (Palik et al., 1985).

Average axis (arbitrary) face-bow employs an approximate location of the hinge axis based on an anatomic average. According to Weinberg, an error of 5.0 mm in the location of the transverse hinge axis location will produce a negligible anteroposterior mandibular displacement of approximately 0.2 mm posteriorly when a centric relation record is removed to close the articulator (Weinberg, 1961).

There are two types of Average axis facebows: 1-fascia type and 2-ear-piece type. Among the fascia points are Beyron and Bergstrom. Beyron's Point is found 13 mm anterior to the posterior marginal center of the tragus to outer canthus of the eye (Wilkie, 1979). Beyron's Point is the second best according to Beck, with 58.5% existing within 5 mm of condylar center (Beck, 1959). Up to 98 percent of Beyron's points were within 5 mm of the true axis of rotation (Schallhorn, 1957). Bergstrom's Point is found 10 mm anterior to the center of spherical inserts for the external auditory meatus and 7 mm below the FH plane (Wilkie, 1979). According to Beck, it is the closest to the terminal hinge axis, 83% lie within 5 mm (Beck, 1959; Wilkie, 1979).

1.2 *Terminal Hinge Axis*

There has been considerable debate about whether a hinge axis exists, if it can be accurately located, if there is only one hinge axis, if it is clinically useful to locate it, and whether an arbitrary point can be substitute for a kinematic axis. There are four schools of thoughts:

1- Absolute location of hinge axis there is a definitive transverse axis and it should be located

McCollum was a leading advocate of the hinge-axis theory (McCollum, 1939). He stated that rotation occurs during the first 0.5 in. at incisors for most people (McCollum, 1960). Stuart complemented the work of McCollum (Weinberg, 1959). Together Stuart and McCollum pioneered Gnathology Theory: they believed in a 3D location of rotational centers, border movements are to be recorded, and movements are reproduced on fully adjustable articulators (Weinberg, 1959).

2- Arbitrary location of hinge axis is reliable, even though accurate location is valuable (Schallhorn, 1957; Palik et al., 1985).

3- It is impossible to locate it with accuracy due to anatomy, physiology, and capabilities of the patient (Kurth & Feinstein, 1951).
4- Split axis rotation: the condyles rotate independent of each other (Gysi, 1910).

According to Gysi, the mandible opens/closes and rotates on another rotational center, and it has no influence in the setting up of the teeth nor should it be considered in the construction of an articulator (Gysi, 1910). Wadsworth in 1925 stated that the first movement is around transverse axis through condyles which remain seated in fossae the second movement is on the eminentia (Wadsworth, 1925). Harry L. Page, known for the transograph, believed in two axes, one for each condyle (Prothero, 1916). Weinberg and Aull believed that only one axis exists (Weinberg, 1959; Aull, 1963). Trappozano and Lazzari believed in multiple hinge axes (Trappozano & Lazzari, 1961). According to Kurth and Feinstein, it is doubtful that a hinge axis can be determined with accuracy due to anatomy, physiology, and capabilities of the patient (Kurth & Feinstein, 1951).

1.3 *Articulators*

Most articulators used today feature fixed condylar axis elements at 110 mm rather than adjustable ICD, such as Hanau 92H2, Panadent, Denar Mark II, and Whipmix (Celenza, 1979), and occlusal simulation with an ICD greater that 110 mm cannot be precisely replicated. Celenza Class IV articulators can have the ICD adjusted, such as the temporomandibular joint (TMJ) articulator, Stuart Gnathological Computer, Denar Model 5A, and Denar Model SE (Celenza, 1979).

Gysi was the first to provide variable width of the condylar posts to meet the width captured from the patient's face (Gysi, 1910; Mitchell & Wilkie, 1978). Hanau in 1923 popularized the idea with his Model M Kinoscope articulator and Wadsworth in 1924 developed an articulator with a variable ICD (Mitchell & Wilkie, 1978).

Currently, virtual articulation relies on the ARCON type Artex-CR articulator (Amann Girrbach, Koblach, Austria). This articulator allows adjustment of sagittal condylar inclination (SCI), immediate mandibular lateral translation (IMLT), protrusion, retrusion, and distraction, but not ICD.

1.4 *Intercondylar Distance*

ICD is the distance between the rotational centers of two temporomandibular joint condyles or their analogues (GPT-9., 2017). The ICD is a stable measurement that remains unchangeable throughout life once growth is complete (Keshvad et al., 2000). Researchers and investigators have used the ICD in many aspects of prosthetic rehabilitation of patients. For example, the ICD was used as a guide to set posterior denture teeth (Shaikh et al., 2012), others reported strong correlation between the ICD and the dental arch width in the canine and the molar region (Ranjan et al., 2012).

ICD was first measured by William Gibson A. Bonwill in 1885. He described the average ICD using 6000 skulls and 4000 living persons and reported an average value of 4 inches(Bonwill, 1889). He measured from this same center of the condylar processes to the median line between the mandibular central incisors to be also four inches(Bonwill, 1889). He reported that there is a slight variation among subjects that does not exceed "about one-fourth of an inch" (Bonwill, 1889).

However, in Bonwill’s paper, there is no report on how the measurements were performed, the exact points used, the error of the measurement and if there were sex and ethnicity differences in these measurements. He only reported an average of four inches and mentioned that in some cases, the measurements were five inches in Indian and Malay subjects (Bonwill, 1889).

Bosse measured 500 jaws by measuring from the middle of the mesial surface of one condyle to the lateral surface of the other, revealing significant variability in ICD, averaging 96 mm (Christensen, 1958). Choquet's study of 149 mandibles showed external distances between condyles ranging from 138 to 97 mm and internal distances from 96 to 65 mm, emphasizing asymmetry (Choquet, 1914). Welcher similarly observed condylar asymmetry, finding only two symmetric condyles in the 50 mandibles they studied (Welcher, 1902).

Amoedo reported condylar distances ranging from 7 to 13 cm (Amoedo, 1913). Wilson mentioned in his paper that another investigator named F. W. Frahm only found 6% conformity with Bonwill’s theory in the 300 jaws he studied, and cautioned against using Bonwill’s theory of equilateral triangle (Wilson, 1921). Welcher demonstrated mandibular shape changes when submerged in water, with ICDs fluctuating notably (Welcher, 1902).

Welcher illustrated the morphological alteration by immersing desiccated mandibles in water (Welcher, 1902). One mandible exhibited a surge of over 10 mm in ICD within an hour of immersion. Subsequently, after several weeks of drying, the distance diminished by approximately 13 mm (Welcher, 1902). The intercondylar dimension of the mandible was approximately 3 mm smaller than its initial measurement before the experiment commenced (Welcher, 1902).

A more recent study radiographically evaluated the ICD of 43 male and 58 female subjects with an age range of 20 to 80 years (Lazić et al., 2006). All the subjects were residents of Croatia (Lazić et al., 2006). The authors used two-dimensional posterior-anterior cranial radiographs traced on acetate paper to determine the rotational center of the condyles as their reference points (Lazić et al., 2006). Despite the tendency of these radiographs to slightly produce geometrical and positioning errors (Pirttiniemi et al., 1996), the ICD measured ranged from 110-145 mm with an average of 126 ±0.74 mm—values significantly different from Bonwill's measurements described above. They also found that ICD was significantly greater in men averaging 130.2 ±0.81mm compared to women who averaged 126.3 ±0.52mm (Lazić et al., 2006). In another study on nineteen human mandibles (10 male and 9 females), it was concluded that there were no significant differences of the dimensions of Bonwill's triangle (with ICD being part of this equilateral triangle) between male and female mandibles with male average measuring 102.4 ±1.21mm and female average measuring 101.38 ±1.94mm (Nikolopoulou et al., 2019). However, this study was done in a very small sample (nineteen subjects) and it was performed on dried mandibles which might affect the measurement (Choquet, 1909). The lack of details in Bonwill's study, and conflicting results from Lazić's, Wilson's, and Amoedo's studies, all point to a significant gap in the literature and understanding of basic human anatomy. It also suggests that results from Bonwill's study may not be representative of the actual value of the ICD especially when different ethnicities are considered. The construction of articulators is generally based on Bonwill's equilateral triangle theory, and Monson's pyramid is based also on Bonwill's triangle. In the Bonwill articulator, the median line between the lower incisors should be exactly four inches from the rotational points of the Bonwill articulator (1858). The maxillary cast is mounted midway between the upper and lower bows of the articulator.

Beyond the theoretical and academic interest of elucidating basic anatomical dimensions of the human jaw, the ICD influences the anteroposterior position of the cusps and also affects the groove pathway (Heartwell & Rahn, 1986). In a given arch width, increasing the ICD will produce more acute angles between the transverse path of maxillary teeth and the oblique path of a mandibular posterior cusp in its movements to the right and left. When the ICD is decreased, a more obtuse angle will be observed between the maxillary posterior teeth as they travel across the corresponding mandibular teeth (Aull., 1963). Thus, understanding the ICD measurement and applying it correctly to articulator design is a clinically relevant research question.

Numerous methods have been suggested to measure the ICD on patients, especially in devices that track jaw movements, for example: pantographic tracing and Computer Aided Diagnosis Axiograph (CADIAX). However, these measurement methods rely on estimates that arbitrarily factor in soft tissue overlying the condyles (Mandilaris et al., 1992). Thus, they are not exact measurements. Three dimensional (3D) radiographic images CBCT's are routinely used in dental offices (Dahlström & Lindvall, 1996; Krishnamoorthy et al., 2013; Miracle & Mukherji, 2009) and can be used to accurately measure ICD (Barreto et al., 2020).

To our knowledge, previous studies that assessed dimensions of the ICD revealed inconsistent results and exhibited significant limitations in the methodology used (e.g.: two dimension (2D) radiographs, dried skulls, lack of diversity) to measure ICD. This study is designed to address this knowledge gap and find a more systematic approach using modern methods to measure and accurately record ICD.

Chapter 2 Aim and Null Hypothesis

This study aims to provide an accurate, modern measurement of ICD in live patients using a standardized protocol.

Aim: The study aims to measure ICD from CBCT scans in a large, diverse population to determine average ICD values for male and female subjects.

Null Hypothesis:

1- There is no significant difference in ICD measurements between male and female subjects.

2- There is no significant relationship between ICD measurement and ethnicity.

3- There are no significant interactions between sex and ethnicity when ICD measurements are considered.

Chapter 3 Materials and Methods

3.1 *Patient Population*

This is a cross-sectional study that investigated consecutive patients that received maxillofacial field of view CBCT radiographic examinations at the University of Maryland School of Dentistry, from January 20th, 2016, to July 5th, 2023. Inclusion criteria included subjects older than 18 years of age with maxillofacial CBCT's for dental reasons unrelated to the purpose of this study. Exclusion criteria include subjects with prosthetic condyles, diseases altering bone growth (e.g.: growth hormone insufficiency, or excess), subjects with an incomplete scan, poor image quality, or missing chart information on sex and age. When multiple, duplicate CBCT scans were available, the most recent was used for measurement given that the quality was satisfactory and condyles were captured in the field of view.

Between the years 2016 and 2023, 459 patients were initially included. A total of 25 files were excluded for the following reasons: limited view CBCTs (15), poor quality and blurry image (6), no radiographic reports or available radiographs (2), prosthetic condyle (1), and bony growth of condyle (1). The following data were collected from the patients' charts: age, sex, presence of diseases altering bone growth, left condyle measurement, right condyle measurement, and ICD measurement.

The primary investigator (OA) was responsible for reviewing the scans, performing chart reviews, and making measurements on the 434 files that were included.

The following methods of blinding were implemented to prevent potential bias:

1. CBCT images were provided to the primary investigator (OA) by the interpreting radiologist (JP) without access to the patients' dental chart, thus preventing any bias in interpreting or studying the CBCT images.

2. Interpretations were labelled by serial numbers then the primary investigator was provided the dental record numbers for the scans and chart review was conducted by the primary investigator to obtain patient information. The studied scans included only maxillofacial field of view dental CBCT scans. Each subject's CBCT was analyzed, and a report was written by the radiologist. The primary investigator was trained and calibrated to review and document the temporomandibular joint (TMJ) and condyles anatomy by the radiologist (JP). Collected images were limited to two Carestream 9300 devices as described previously (Amarin et al., 2023).

Institutional Review Board (IRB) reviewed the study protocol and determined that it is exempt (University of Maryland, Baltimore, HP-00084560). Medical history was documented. Each patients' CBCT was imported from the INFINITT (INFINITT NA, Phillipsburg, NJ) PACS to Xelis 2.0 Dental for review of the CBCT and measurement of the ICD. After images extraction to Xelis 2.0, the CBCT was reoriented in the MPR – reconstruction view. The three different views (Axial, Coronal and Sagittal) were adjusted until both right and left condyles were centered and an accurate measurement using a digital ruler was obtained to determine the ICD.

3.2 *Image Reorientation.*

Due to different orientation of the images, a systematic approach for each patient CBCT was developed to standardize the measurements in all three views: Sagittal, Coronal, and Axial (Figs 1,2,3). After the CBCT was uploaded to Xelis 2.0 Dental from INFNITT PACS, the MPR reconstruction tool was selected and the image was reoriented. Starting with the sagittal view, the horizontal plane was adjusted to be parallel with a line that goes through the anterior nasal spine (ANS) and the posterior nasal spine (PNS) (Fig 1).

Figure 1: Calibrated CBCT image in the sagittal view with the blue line of the calibration tool being parallel and intersecting through ANS and PNS.

Then, from axial view, the image was reoriented again using the (ANS) and (PNS) landmarks until the condyles were centered (Fig 2).

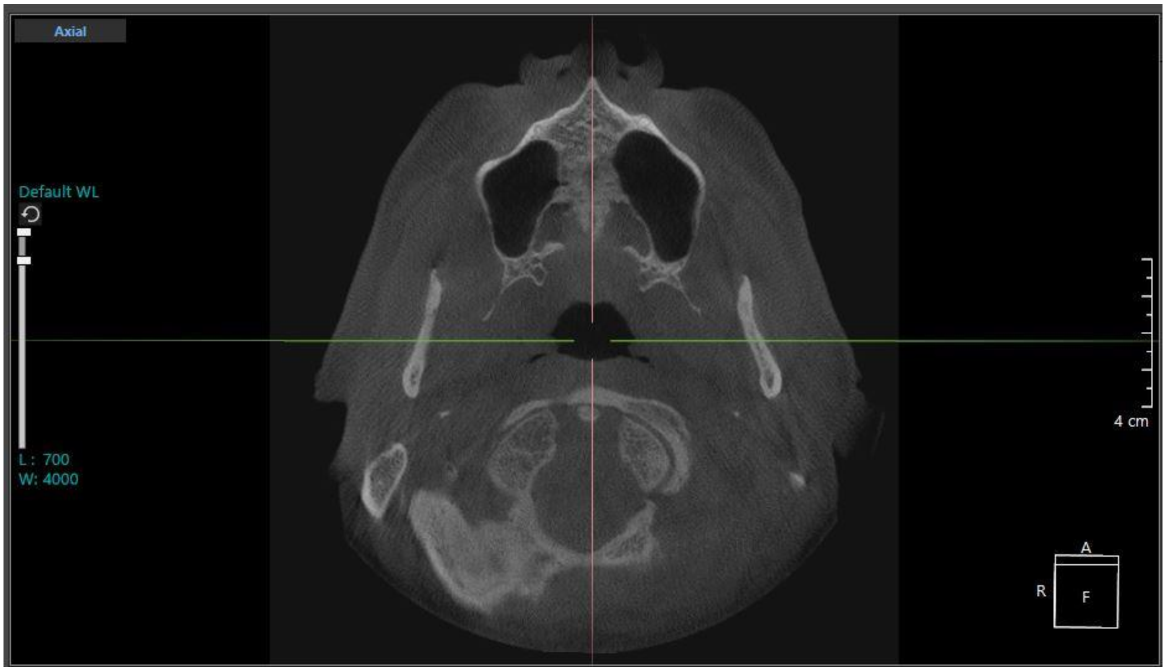

Figure 2: Calibrated CBCT image in the axial view with the red line of the calibration tool being parallel and intersecting through ANS and PNS.

Finally, from the coronal view, the image was reoriented until both the right and left condyles were centered (Fig 3).

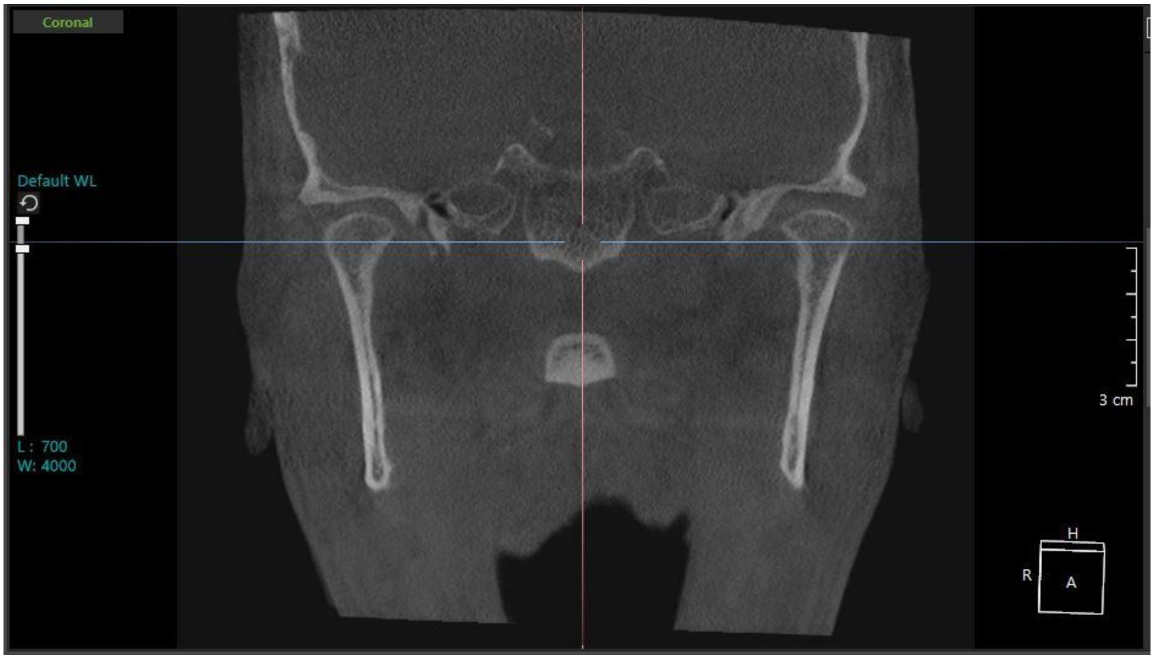

Figure 3: Calibrated CBCT image in the coronal view with the blue line of the calibration tool intersecting both left and right condyles in the middle of the center of rotation.

3.3 *Image Orientation and Finding the Centers of Rotation of the Condyles.*

Once the image was reoriented and the changes were applied and saved the TMJ toll in the Xiles software was selected. The TMJ view shows the axial view of the TMJs which was scrolled superiorly and inferiorly until both the right and left condyles were centered and broadest view of the condyles was obtained (Fig 4). Images of all subjects were consistent in that the centers of rotation were level with the C1 vertebra (Fig 4).

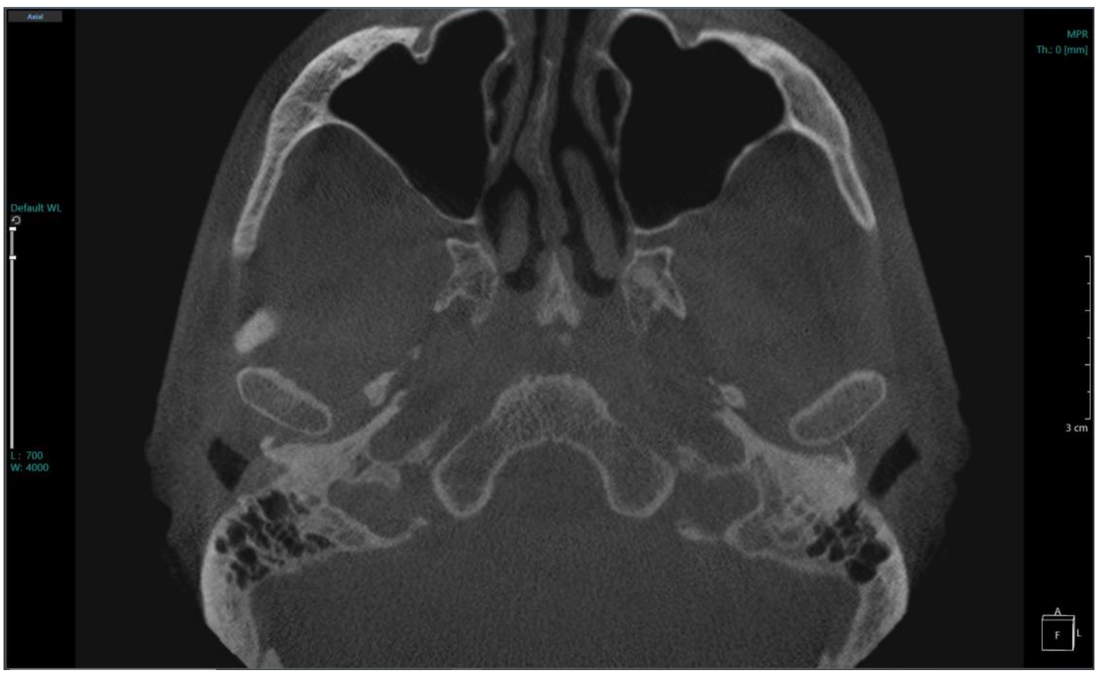

Figure 4: Axial CBCT view showing condyles in their broadest medio-lateral dimension. The image is selected under the TMJ bar icon in Xelis software. Within this view the ICD was measured.

For better visualization of the condyles, the slice selected was zoomed in to achieve clear view of the medial borders of the condyles (Fig 5). The digital ruler was selected and two points in each condyle were selected from the medial corticated border at their widest measurement in their medial to lateral aspect (Fig 5). The center of this measurement was automatically calculated by the Xelis software and was considered to be the center of rotation for each condyle respectively (Fig 5).

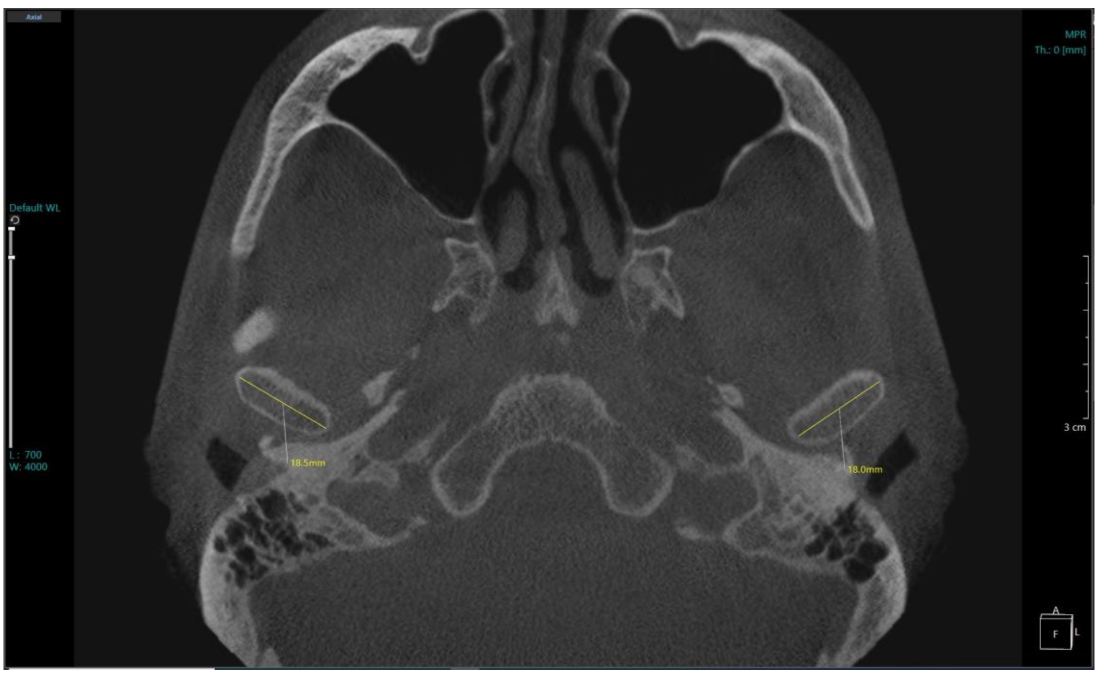

Figure 5: Axial CBCT view showing condylar dimension from medial cortical margins. Yellow lines showing the measurements of each condyle. The digital ruler tool provided by the Xelix software was selected and the medial cortical border of each condyle were measured from their broadest medio-lateral aspect.

3.4 *ICD Measurement*

After obtaining each condyle center of rotation, the digital ruler was used again to measure the ICD from the middle point in each condyle that was determined previously (Fig 6).

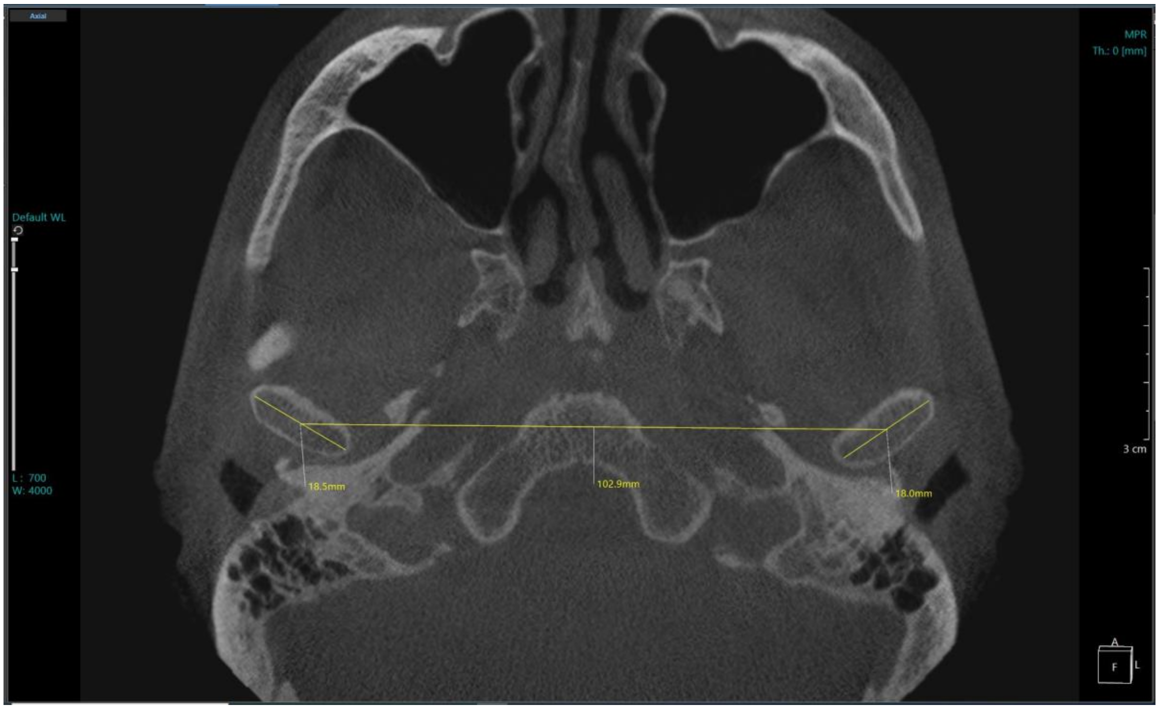

Figure 6: Axial CBCT view showing ICD from center of rotation of condyles. Xelis software automatically determines the midpoint of each condyle measurements. From the same midpoint of the right and left condyle, the digital ruler was selected once again and the ICD measurement was determined.

Data of each condyle width and ICD was then collated in an Excel file and housed for statistical analysis by the primary investigator.

3.5 *Statistical Analysis*

A normal probability plot (a quantile-quantile or Q-Q plot) was plotted to visualize data normalcy. First, the data was ordered from least to greatest. The expected quantile z-scores were found. A scatterplot was created with the empirical distribution (Y-axis) and the theoretical distribution (X-axis).

A t-test was performed to assess differences in ICD between male and female subjects. Two-way ANOVA test was used to analyze sex and ethnicity as main factors and the interaction of both. Multiple comparisons were done using the Tukey test. A $p<0.05$ was considered significant.

Chapter 4 Results

The data consisted of a final cohort of 434 subjects, with an equal number of male (217) and female (217) subjects. The data values fall along a roughly straight line at a 45-degree angle for both male and female subjects (Figs 7,8). This indicates that the data is normally distributed.

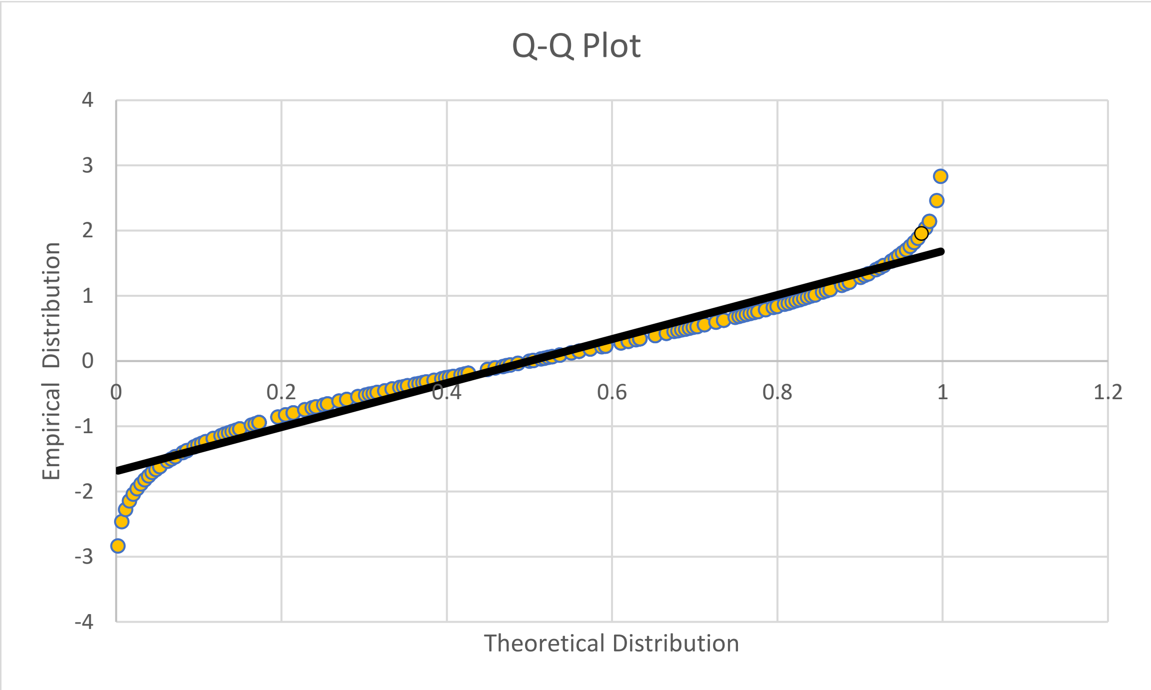

Figure 7: Test for data normality: Q-Q Plot for ICD (male) values.

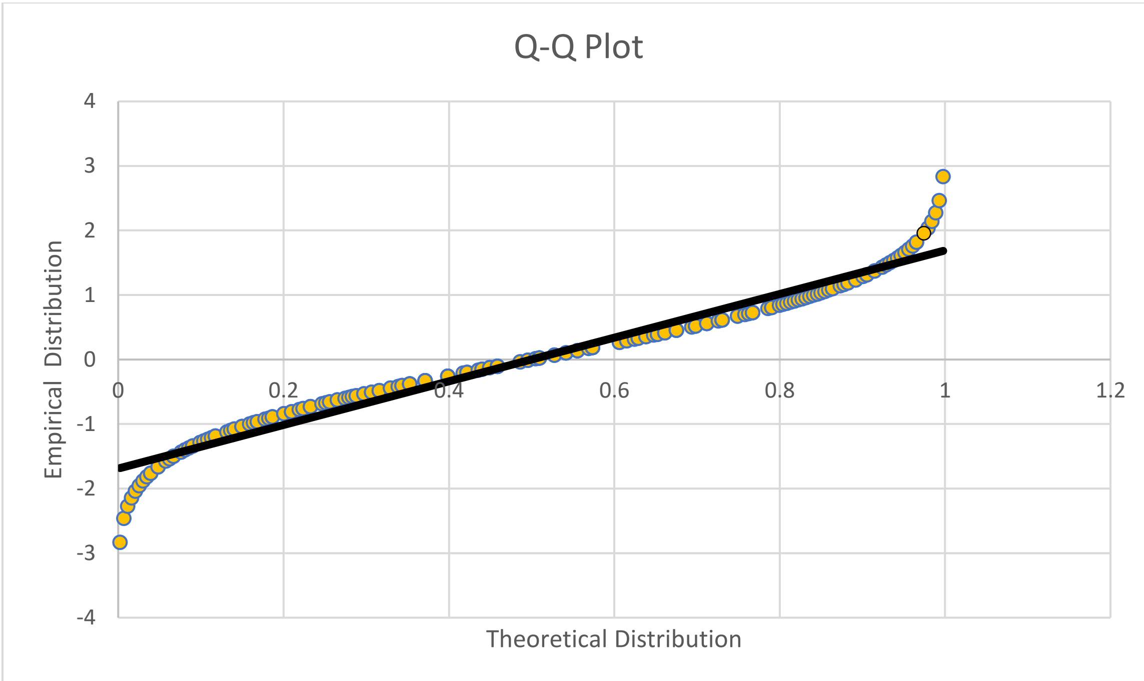

Figure 8: Test for data normality: Q-Q Plot for ICD (female) values.

There were 104 subjects with unknown ethnicities. There were 76 Caucasian male and 41 Caucasian female subjects (Table 1). There were 36 male African American subjects and 35 female African American subjects (Table 1). There were 7 male Asian subjects and 13 female Asian subjects (Table 1). There were 3 male Hispanic subjects and 8 female Hispanic subjects (Table 1).

Table 1: Demographic data of subjects included in the study.

Ethnicity	Male	Female
Caucasian	76	41
Hispanic	3	8
African American	36	35
Asian	7	13
Pacific Islander	-	1
Total	217	217
Unknown	104	119

The mean ICD value was 103.01 ±5.31 mm and 98.82 ±5.23 mm for male and female subjects respectively (Table 2). The median ICD value was 102.9 mm and 98.4 mm for male and female subjects respectively (Table 2). The mean ICD value for both male and female subjects combined was 100.92 mm (Table 3). The median ICD value for both male and female subjects combined was 100.5 mm (Table 3). The range was 32 mm for male subjects (min 86.2 mm – max 118.2 mm) (Table 2). The range was 35.7 mm for female subjects (min 81.5 mm– max 117.2 mm) (Table 2).

Table 2: Mean, range, standard deviation, and median values for ICD in male and female subjects

	ICD (male) (mm)	**ICD (female) (mm)**
Mean	103.01	98.82
Range	min 86.2 max 118.2	min 81.5 max 117.2
Standard deviation	5.31	5.23
Median	102.9	98.4

Table 3: Mean and median values for ICD (male and female subjects combined) compared to Bonwill's values.

	ICD (male + female) (mm)	**ICD (Bonwill's value) (mm)**
Mean	100.92	101.5
Median	100.5	101.5

A t-test was performed to test ICD differences between male and female subjects. The sample analyzed consisted of 217 male and 217 female subjects. The difference between the two groups was statistically significant (4.191 ± 0.5061, P <0.0001), demonstrating that male ICD was significantly larger than females. F-test was done to test for heterogeneity of the data demonstrating equal variance between the two groups (Table 5 - Appendix).

Two-way ANOVA test was used to assess relationship between sex and ethnicity (as main factors) as well as their interactions (Fig 9). The difference between male and female subjects was statistically significant (Table 6 - Appendix).

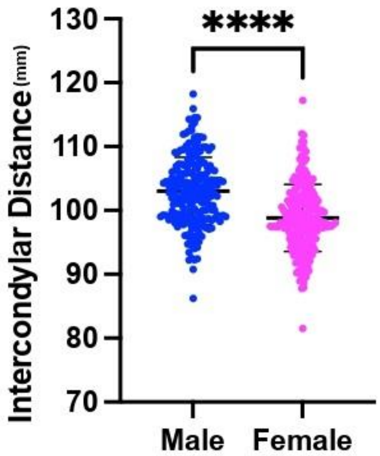

Figure 9: Two-way ANOVA of male and female ICD values. Male subjects represented with the blue dots and female subjects represented with the pink dots. The black bold line in the center of each is the mean value (close to 100 mm) and the two black lines in between showing the standard deviation. **** representing $P < 0.0001$.

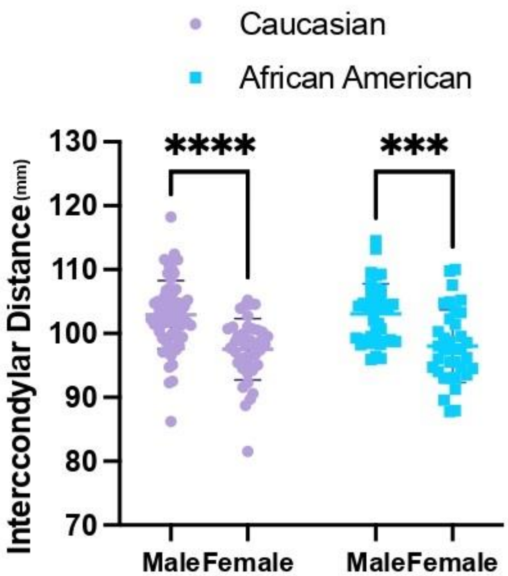

Figure 10: The effect of sex and ethnicity on ICD. Purple points representing Caucasian subjects and blue points representing African American subjects. The black lines in between showing standard deviation. ****, $P < 0.0001$ and ***, $P = 0.0003$.

The mean ICD value for Caucasian subjects was 102.91 ±5.35 mm for male subjects and 97.51 ±4.80 mm for female subjects (Fig 10). The mean ICD value for African American subjects was 103.06 ±4.73 mm for male subjects and 97.0 ±5.69mm for female subjects (Fig 10).

There was a significant difference in sex (F (1,175)=42, P <0.0001) (Table 6 - Appendix).

There was no significant difference in ethnicity F (1,175) = 0.1 P =0.69 (Table 6 - Appendix). The percentage of total variation was 0.07247% (Table 6 - Appendix).

There was no significant difference in the interaction between sex and ethnicity F (1,175)=42 P=0.84 (Table 6 - Appendix). The percentage of total variation was 0.01890% (Table 6 - Appendix).

Multiple comparisons using the Tukey test revealed that there was no statistically significant difference between Caucasian males and African American males P=0.9989 (Table 4).

There was statistically significant difference between Caucasian males and Caucasian females P<0.0001 (Table 4). There was statistically significant difference between Caucasian males and African American females P<0.0001 (Table 4). There was statistically significant difference between Caucasian females and African American males P<0.0001 (Table 4).

There was statistically significant difference between African American females and African American males P=0.0003 (Table 4).

There was no statistically significant difference between Caucasian females and African American females P=0.9775 (Table 4).

Table 4: Tukey's multiple comparison test (ANOVA Post Hoc)

Tukey's multiple comparison test	**Predicted (LS) mean diff.**	**95.00% CI of diff**	**Below threshold?**	**Summary**	**Adjusted P Value**
Male Caucasian vs Male African American	-0.1564	-2.934 to 2.621	No	Ns	0.9989
Male Caucasian vs Female Caucasian	5.390	2.725 to 8.055	Yes	****	<0.0001
Male Caucasian vs Female African American	4.907	2.104 to 7.711	Yes	****	<0.0001
Male African American vs Female Caucasian	5.547	2.477 to 8.617	Yes	****	<0.0001
Male African American vs Female African American	5.064	1.873 to 8.254	Yes	***	0.0003
Female Caucasian vs Female African American	-0.4829	-3.576 to 2.610	No	ns	0.9775

Chapter 5 Discussion

The study aimed to measure ICD from CBCT scans in a population of 434 subjects to determine average ICD values for male and female subjects. The results reveal that there is a statistically significant difference between ICD values in male and female subjects, with a larger ICD in male subjects. There was no significant relationship between ICD measurement and ethnicity. There were no significant interactions between sex and ethnicity when ICD measurements are considered. Therefore, two of the null hypotheses were rejected, and one was accepted.

The mean ICD for male and female subjects was 100.92 mm, the median value was 100.5 mm, which was very close to Bonwill's ICD value of 101.5 mm (Bonwill, 1889). Bonwill measured from the center of the condylar processes as done in this study (Bonwill, 1889). Bonwill reported that ICD measurement varies no more than one fourth of an inch, or 6.35 mm (Bonwill, 1889). The current study used a systematic radiographic approach that was repeatable for all the subjects. The standard deviation in this study was 5.31 mm for male subjects and 5.23 mm for female subjects which is also consistent with earlier reports from Bonwill.

The reported statistical significance of ICD values between male and female subjects has been corroborated by the literature (Lazić et al., 2006; Arat & Sen, 1997; Zakaria et al., 2012). Zakaria measured ICD on 25 male subjects and 25 female subjects using kinematic facebow, followed by transfer to a TMJ fully adjustable articulator and subtracting 12.5 mm from the measured reading on the articulator's graduated scale (12.5 mm represents the distance between the center of condyle ball and tip of condyle pin).

Lazić measured ICD using two-dimensional posterior-anterior cranial radiographs traced on acetate papers 101 Croatian subjects (Lazić et al., 2006). The mean ICD of male subjects was 130.2 mm and mean ICD value of female subjects was 123.5 mm (Lazić et al., 2006). The difference between male and female subjects was statistically significant (Lazić et al., 2006). However, measurements in two-dimensional radiographs that have tendency to produce geometrical and positioning errors (Pirttiniemi et al., 1996). Moreover, another investigator (Zarch et al., 2011), found that panoramic 2D radiographs has tendency to underestimate or overestimate linear measurements compared to the actual measurements with a difference up to 3.3 millimeter (mm) depending on the head position while the panoramic radiograph was taken.

Arat et al measured ICD of 600 Turkish subjects with equal male and female sample size using a facebow device with arbitrary facia points. The mean ICD for male subjects was 115.2 mm and for female subjects was 105.4 mm (Arat & Sen, 1997). The differences were statistically significant.

Other studies found no statistical difference in ICD measurements between male and female subjects. Nikolopoulou measured nineteen Greek skulls using digital calipers and found the mean ICD to be 102.4 mm in ten male subjects and 101.38 mm in nine females subjects (Nikolopoulou et al., 2019). Ganesh measured forty dry skulls from a south Indian population using a digital caliper and found the mean ICD to be 97.39 mm (Ganesh & Mohanraj, 2022). Ganesh did not distinguish male and female subjects and only made a comparison to Bonwill’s triangle, The sample was found to not correlate with an equilateral triangle. Common to both studies is the small sample size which may have contributed to the lack of significant differences and the use of measurement techniques that were difficult to standardize and target the centers of the condyles.

The classical studies of Amoedo, Wilson, Welcher, Bosse, and Choquet were not consistent in their points of measurements, failed to report it, or used skulls that were subject to shape changes by drying or submerging in water, with ICDs fluctuating notably (Welcher, 1902; Amoedo, 1913; Wilson, 1921; Christensen, 1958; Choquet, 1914). Additionally, anthropologists, unlike prosthodontist, measured ICD from the exterior condylar poles, in order to determine more precisely the border of a radiographic image (Saller et al., 1957).

The current study found there is no differences in ICD with regards to ethnicity (Caucasian and African American subjects). Zakaria obtained ICD values that were higher than Bonwill's (Zakaria at al., 2012). Mean male ICD values were 120.67 ± 5.917 mm, mean female ICD values were 110.58 mm ± 9.294 mm. This could be attributed to their measurement method of using manual finger operation and kinematic facebow on soft tissue to determine the center of rotation. Arat reported high ICD values using the facebow method as well (Arat & Sen, 1997).

The mean ICD measured in the Croatian sample (reported above) is also significantly larger than the results reported in this study and other studies referenced herein (Lazić et al., 2006). This may be due to their measurement method on acetate paper of radiographs made using posterior-anterior plane projection with the subjects' head towards their chest (Lazić et al., 2006). In fact, Pirttiniemi and his group cautioned against linear measurements and point identification using posterior-anterior plane projections as they have tendency to overestimate the actual measurement by about twenty percent

(Pirttiniemi et al., 1996). Another researchers Flores-Mir and his group compared CBCT scan linear measurements accuracy of teeth to conventional panoramic radiographs. They found 29 % overestimation of conventional panoramic radiographs while CBCT Scans had only 1 % difference to the actual teeth measurements giving only 0.2 to 0.4 mm difference (Flores-Mir et al., 2014). Even though there is a very minimal difference in CBCT scans, they are very high in resolution giving sharp images that are easy to interpret and measure while panoramic radiographs has tendency to be blurry (Flores-Mir et al., 2014). The static image of the temporomandibular joint was made in the maximum opening position (Lazić et al., 2006). The line between the angles of the eye and the tragus were perpendicular to the film (Lazić et al., 2006). Other studies using radiographs taken with different set ups could introduce geometrical and positioning differences (Pirttiniemi et al., 1996).

The south Indian sample by Ganesh and Mohanraj did not report the sex of the subjects, and their ICD values were close to the female ICD values reported in this study. Therefore, it is not clear how ethnicity could have been the main factor at play in determining ICD without knowing the sex of the subjects (Ganesh & Mohanraj, 2022). Nikolopoulou measured nineteen Greek skulls with values that closely approximate Bonwill's (Nikolopoulou et al., 2019).

The limitation in this study is the analysis only looked at two ethnicities with a relatively small sample size. Additionally, the unknown ethnicities sample size in this study was large (male = 104, female = 119). The sample size of Hispanic, Asian, and pacific islander was very small and was not included in the analysis of the relationship between ethnicity and ICD.

When the ICD and tooth-hinge axis distance are accurately reproduced on the articulator, the nonworking (buccal) and working (lingual) paths on the mounted casts will more closely coincide with those of the patient's (Hobo et al., 1976). If the location of the axis of rotation in relation to the cusp tip differs from the articulator to the patient, the radius of the arc of movement of the cusp tip may be different or the center of rotation may be displaced, and an error will exist (Hobo et al., 1976). The articulator paths of movement are slightly mesial to the paths in the patient's mouth when the ICD of the articulator is less than that of the mandible (when the casts are placed farther from the condyles) (Hobo et al., 1976). When the ICD of the articulator exceeds that of the mandible, the movement paths on the articulator will be slightly distal to those traced in the mouth (Hobo et al., 1976). The cusp paths on the articulator will also be distal to those in the mouth when the casts are positioned near the condyles on the articulator (Hobo et al., 1976). On a small hinge articulator, there is a significant discrepancy between the nonworking cusp path and the corresponding path in the mouth (Hobo et al., 1976).

Chapter 6 Conclusion

ICD is an important determinant for maxillary cusp pathways in lateral mandibular movements for prosthodontic rehabilitation (Aull, 1963). The results of this study were consistent with Bonwill's work regarding average ICD in male and female subjects, approximately 101 mm. Determining an accurate ICD measurement is important for setting articulators with more accurate representations of the patient anatomy resulting in more accurate restorations. If group function occlusion is desired for full mouth rehabilitation, recording accurate ICD and implementing the values in fully adjustable articulators will lead to less adjustments and save clinical chair time.

Appendix

Table 5: F-Test to compare variances

F, DFn, Dfd	1.030, 216, 216
P value	0.8282
P value summary	Ns
Significantly different (P<0.05)?	No

Table 6: Two-way ANOVA table

Source of variation	% of total variation	P value	P value summary	Significant
Sex	19.38	<0.0001	****	Yes
Ethnicity	0.07247	0.6904	Ns	No
Interaction	0.01890	0.8388	Ns	No

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