THE CUTTING EDGE

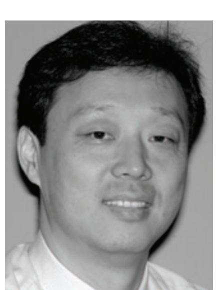
Around the middle of the 20th century, the profession of orthodontics made a giant leap forward. The standard records used for diagnosis and treatment planning were supplemented with cephalometric x-rays, various cephalometric analyses were developed, and, for the first time, growth could be documented through serial cephalograms and superimposition. By the time I completed my orthodontic residency in 1970, it would have been hard to imagine that orthodontic diagnosis could ever have been done without cephalometrics.

This month's Cutting Edge article, I believe, will become the "tipping point" for our next leap forward in understanding the growth and development of the craniofacial complex. Cone-beam computed tomography, relatively new in the orthodontic arena, has been awaiting a true three-dimensional analysis. Dr. Cho's 3D system is a first step in that direction. The aspect of his analysis that may truly revolutionize treatment is the ability to pinpoint minor asymmetries that have sometimes gone undiagnosed in the past.

Dr. Cho's analysis is probably best understood through video, which allows the reference planes, points, and measurements to be visualized through a volume in motion. I wish I were just beginning my orthodontic career, so that I could practice for the next 30-40 years and experience the knowledge and understanding that will come from these cutting-edge tools.

W. RONALD REDMOND, DDS, MS

Dr. Redmond



Dr. Cho

A Three-Dimensional Cephalometric Analysis

For the past few decades, orthodontists and researchers have used two-dimensional lateral cephalometric analysis to study the growth and development of craniofacial structures, to diagnose orthodontic problems, to plan orthodontic treatment, and to evaluate treatment outcomes.[1-15] Because the craniofacial structure is actually a three-dimensional object, however, the traditional lateral cephalometric radiograph provides limited information. The advent of cone-beam computed tomography (CBCT) technology and 3D software has now made it possible for us to visualize, study, and evaluate all three dimensions of the craniofacial structure.

The third dimension missing from the lateral cephalometric radiograph is the transverse plane (the x-axis in the 3D coordinate system). Three-dimensional radiographs provide information about not only the transverse plane, but also the intricate interrelationship among the sagittal, frontal, and transverse dimensions. These images are now being used in orthodontic research and treatment. Terajima and colleagues,[16,17] Suri and colleagues,[18] and Kau and Richmond[19] have performed 3D analysis of the craniofacial structures. Garrett and colleagues,[20] Phatouros and Goonewardene,[21] and Ballanti and colleagues[22] have evaluated orthodontic treatment outcomes using 3D images. Still, the task remains of developing a comprehensive, well-organized 3D analysis for the diagnosis of malocclusions and evaluation of orthodontic treatment outcomes.

The present article describes such a system. Measurements were made from a pretreatment 3D radiograph of an adult female patient who presented with normal Class I skeletal and dental relationships and mild incisor crowding. A 3D volumetric image of this patient was obtained using the iCAT cone-beam dental-imaging sys-

Fig. 1 Three landmarks, nasion (N) and the two frontozygomatic (FZ) points, are connected to construct naso-frontozygomatic (NFZ) plane, which is used to reorient axial and coronal axes of images.

tem.* The measurements were performed with InVivoDental software.**

Standardized Reorientation of 3D Images

Proper diagnostic use of a volumetric image for this 3D analysis requires a basic understanding of the Cartesian coordinate system and its three axes (*x, y,* and *z*), as well as of the definitions of lines and planes used in the analysis. This 3D system uses the naso-frontozygomatic (NFZ) plane as its cranial base reference plane (Fig. 1). The NFZ plane is constructed from nasion (N) and the right and left frontozygomatic (FZ) points. The coordinate system consists of three axes (*x, y,* and *z*) with their origin (0,0,0) registered at N. The *x*-axis, the transverse axis, is parallel to the FZ line. The *y*-axis is the anteroposterior axis perpendicular to the FZ line and parallel to the right Frankfort horizontal (R FH) line. The *z*-axis, the vertical axis, is perpendicular to both the FZ line and the R FH line. Assuming the subject is in an anatomical position, positive values are to the left, posterior, and superior (LPS) to the N point of the subject. Negative values are to the right, anterior, and inferior (RAI) to the N point. The 3D coordinates (*x,y,z*) of any landmark represent its 3D position relative to N (0,0,0).

To minimize measurement errors from nonstandard head postures, the 3D image is reoriented according to two reference planes, NFZ and FH. This protocol is equivalent to Broadbent's reorientation, using the cephalostat, in his Bolton Study.[23] Using the NFZ plane as the cranial base reference, the coordinates of the N point are set to (0,0,0). Then, *y*- and *z*-coordinate values of the right and left FZ points are matched symmetrically by reorienting the coronal and axial axes of the 3D image (Fig. 2). The FH plane is used to reorient the head in the sagittal plane (Fig. 3).

Direct vs. Projected Measurements

This 3D analysis requires many angular or linear measurements to be made on a projected plane, rather than being measured directly in three-dimensional space. For example, the facial line angle is best evaluated when it is projected on the sagittal plane, since the purpose of this angular measurement is to assess the anteroposterior position of the mandible relative to the cranial base. When the facial line angle for a patient with a severe mandibular asymmetry is evaluated, the direct angular measurement will actually show a smaller value than the projected measurement. This is because the direct measurement is affected by the transverse position of the asymmetrical chin, whereas the facial line angle should actually measure the anteroposterior mandibular position irrespective of transverse mandibular asymmetry.

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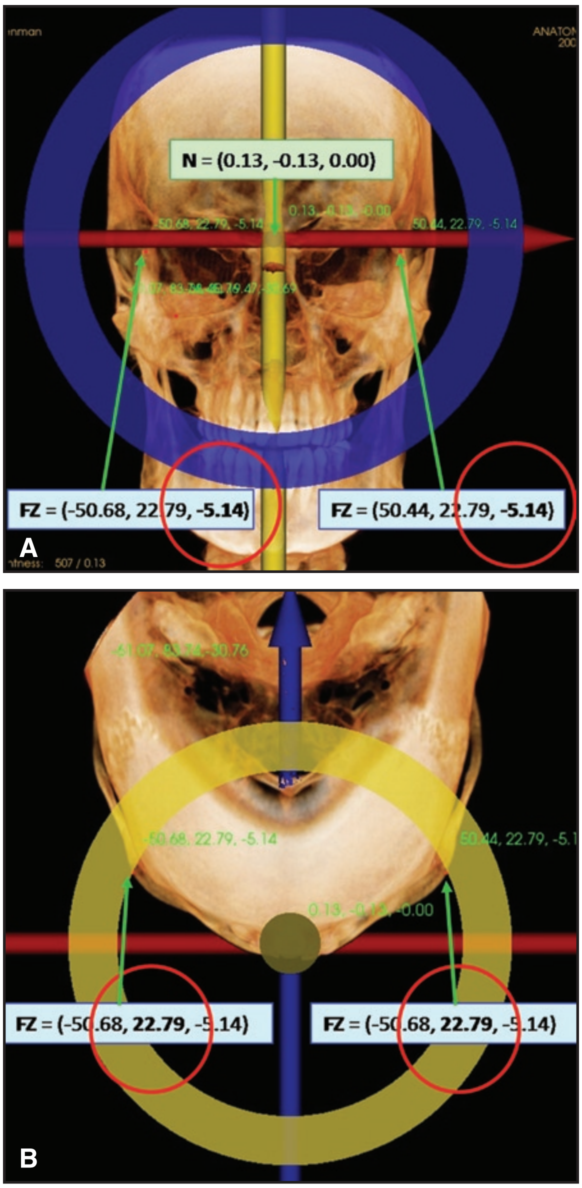

Fig. 2 A. Reorientation of three-dimensional image in frontal plane. Nasion is set as close to (0,0,0) as possible, and *z*-coordinates of right and left FZ points are matched symmetrically. B. Reorientation of 3D image in axial plane, with *y*-coordinates of FZ points matched symmetrically.

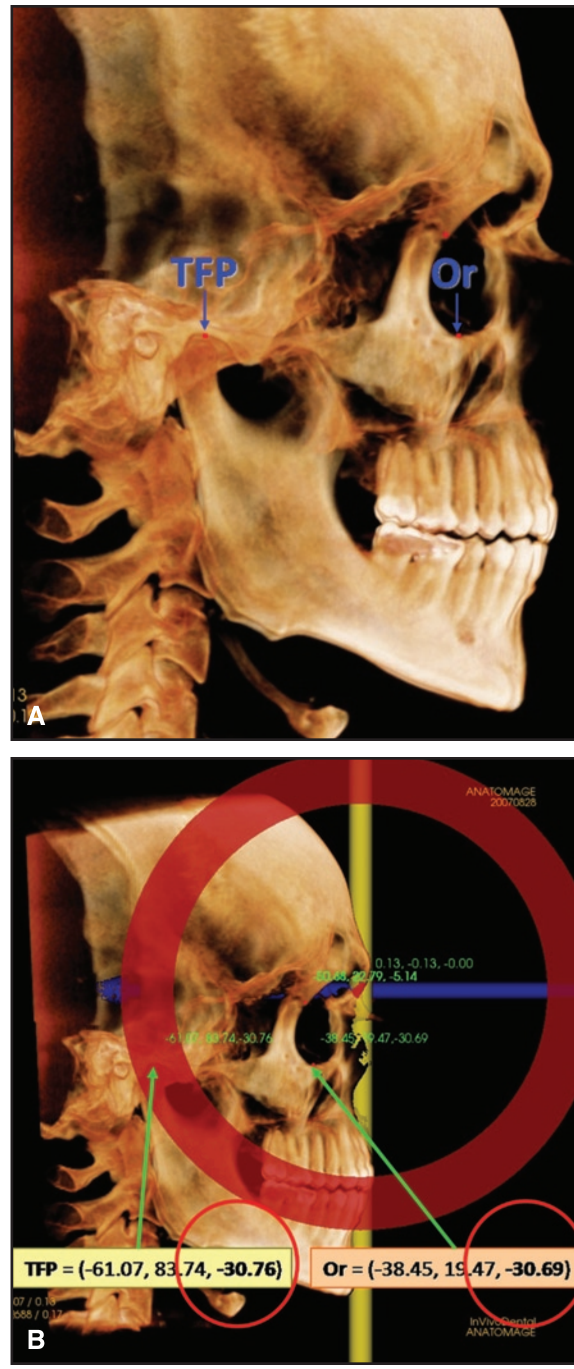

Fig. 3 A. Frankfort horizontal (FH) plane constructed using right and left temporal-fossa points (TFP) and orbitale (Or). B. Skull reoriented in sagittal plane using FH plane, with *z*-coordinates of two landmarks set as close as possible.

Skeletal Landmarks

Cranial Base Landmarks (RL = right and left)

N (nasion): the middle point of the frontonasal suture in the frontal plane

RL FZP (frontozygomatic point): the intersection of the frontozygomatic suture and the inner rim of the orbit in the frontal plane

Sella: the midpoint of the pituitary fossa in the sagittal plane; the midline point in the axial plane

RL Or (orbitale): the most inferior point of the orbital rim in the frontal plane

RL Po (porion): the most superior point of the external auditory meatus

RL TFP (temporal-fossa point): the most superior point of the inferior zygomatic arch border, above the condylar head as seen from the sagittal perspective; the most lateral landmark in the submental-vertex view

Maxillary Landmarks

ANS (anterior nasal spine): the most anterior point of the premaxillary bone in the sagittal plane

PNS (posterior nasal spine): the most posterior point of the palatine bone in the sagittal plane

A point: the deepest point in the anterior outline of the maxilla between supradentale and ANS in the sagittal plane

RL KRP (key ridge point): the most inferior point of the key ridge in the sagittal plane

RL MxBP (maxillary basal point): the point in the lateral outline of the maxilla at which the lateral surfaces of the maxilla turn into the inferior surfaces of the maxillary zygomatic processes in the frontal plane

Mandibular Landmarks

B point: the deepest point in the anterior outline of the mandible between infradentale and pogonion in the sagittal plane

Pog (pogonion): the most anterior point in the mandibular chin area in the sagittal plane

Me (menton): the most inferior point in the middle of the mandibular chin in the frontal plane; the deepest point in the mental depression in the submental-vertex view

RL Go (gonion): the point in the inferoposterior outline of the mandible at which the surface turns from the inferior border into the posterior border in the sagittal plane

RL condylar point: the tip of the mandibular condyle

RL CP (coronoid process) point: the tip of the coronoid process in the sagittal plane

(continued on next page)

Landmark Identification

Although this 3D analysis includes many skeletal and dental landmarks established in previous 2D analyses,[1-15,24,25] some new landmarks are proposed. Landmark location can vary on 2D images, raising the issue of reliability.[26-28] Muramatsu and colleagues evaluated the reproducibility of 19 landmarks on 3D computed tomographic (CT) images.[29] Basion had the smallest confidence ellipse area in all planes, indicating high reproducibility. In general, the size of the ellipse of a specific landmark increased with the slice thickness, but additional studies may be needed to evaluate more landmarks on 3D CT images.

Periago and colleagues compared linear measurements of cephalometric landmarks made on CBCT-derived 3D volumetric surface renderings obtained from direct measurements of a human skull, using Dolphin 3D*** software.[30] Although they found statistically significant differences for many of the measurements, they stated that the 3D image measurements were sufficiently accurate for craniofacial analysis. Lagravère and colleagues compared measurements from CBCT images with those taken from a coordinate measuring machine, which they considered the "gold standard".[31] They reported that the coordinate intraclass correlation coefficient between the two measurement methods was almost perfect, and that the CBCT machine produced a 1:1 image-to-reality ratio. Habersack and colleagues noted that multislice CT images can be valuable in visualizing skeletal effects on the midpalatal sutures and adjacent sutures.[32] They also found that precise 3D location of tooth positions was feasible.

The landmarks listed on these two pages are used to make the measurements required for the 3D cephalometric analysis.

***Dolphin Imaging & Management Solutions, 9200 Eton Ave., Chatsworth, CA 91311; www.dolphinimaging.com.

Dental Landmarks

Maxillary Dental Landmarks

RL U1CP (maxillary central incisor crown point): the midpoint of the incisal edge of the maxillary central incisor

RL U1RP (maxillary central incisor root point): the tip of the root of the maxillary central incisor

RL U3CP (maxillary canine crown point): the tip of the crown of the maxillary canine

RL U3RP (maxillary canine root point): the tip of the root of the maxillary canine

RL U6CP (maxillary first molar crown point): the tip of the mesiobuccal cusp of the maxillary first molar crown

RL U6RP (maxillary first molar root point): the tip of the mesiobuccal root of the maxillary first molar

Mandibular Dental Landmarks

RL L1CP (mandibular central incisor crown point): the midpoint of the incisal edge of the mandibular central incisor

RL L1RP (mandibular central incisor root point): the tip of the root of the mandibular central incisor

RL L3CP (mandibular canine crown point): the tip of the crown of the mandibular canine

RL L3RP (mandibular canine root point): the tip of the root of the mandibular canine

RL L6CP (mandibular first molar crown point): the tip of the mesiobuccal cusp of the mandibular first molar crown

RL L6RP (mandibular first molar root point): the tip of the mesiobuccal root of the mandibular first molar

Reference Lines

FZ line: formed by RL FZP

RL NFZ line: formed by connecting N and RL FZP, projected onto the sagittal plane

R FH line: formed by connecting R Po or R TFP and R Or

Facial line: formed by N and Pog

MxS (maxillary sagittal) line: formed by ANS and PNS

MxF (maxillary frontal) line: formed by RL MxBP

R MdS (mandibular sagittal) line: formed by R Go and Me

L MdS line: formed by L Go and Me

MdF (mandibular frontal) line: formed by RL Go

MxFO (maxillary frontal occlusal) line: formed by connecting RL U6CP in the frontal plane

MdFO (mandibular frontal occlusal) line: formed by connecting RL L6CP in the frontal plane

MxSO (maxillary sagittal occlusal) line: the line at the intersection of the MxO (maxillary occlusal) and MxS planes

MdSO (mandibular sagittal occlusal) line: the line at the intersection of the MdO (mandibular occlusal) and MdS planes

Reference Planes

NFZ plane: anterior cranial base, established by three skeletal landmarks, RL FZP and N

R FH plane: established by RL Po (or RL TFP) and R Or

Midsagittal plane: perpendicular to both the NFZ plane and the frontal plane passing through N

Frontal plane: perpendicular to the NFZ plane passing through RL FZP

Maxillary plane: includes ANS and PNS, parallel to the MxF line (inter-MxBP line)

Mandibular plane: formed by Me and RL Go

MxS plane: perpendicular to the maxillary plane passing through ANS and PNS

MdS plane: perpendicular to the mandibular plane passing through Pog and mid-Go

MxF plane: perpendicular to the maxillary plane passing through RL MxBP

MdF plane: perpendicular to the mandibular plane passing through RL Go

RL maxillary oblique planes: obtained by a 45° rotation of the MxS plane in the horizontal plane

RL mandibular oblique planes: obtained by a 45° rotation of the MdS plane in the horizontal plane

MxO plane: established by three maxillary dental points, R U1CP and RL U6CP

MdO plane: established by three mandibular dental points, R L1CP and RL L6CP

Occlusal plane: formed by bisecting the MxO and MdO planes

TABLE 1
SKELETAL ANTEROPOSTERIOR ANALYSIS

Measurement	Value	Type of Measurement
A(*y*)	1.0mm	Projected (sagittal plane)
B(*y*)	6.0mm	Projected (sagittal plane)
B(*y*)–A(*y*)	7.5mm	Projected (sagittal plane)
SNA	81.5°	Projected (sagittal plane)
SNB	76.5°	Projected (sagittal plane)
ANB	5.0°	Projected (sagittal plane)
Wits appraisal	–2.0mm	Projected (sagittal plane)
Pog(*y*)	2.5mm	Projected (sagittal plane)
Facial line angle (FH-NPog)	92.0°	Projected (sagittal plane)
MxL (ANS-PNS)	47.0mm	Direct
R MdL (R condylar point-Pog)	118.5mm	Direct
L MdL (L condylar point-Pog)	118.0mm	Direct
R MdBL (R Go-Pog)	82.0mm	Direct
L MdBL (L Go-Pog)	81.5mm	Direct

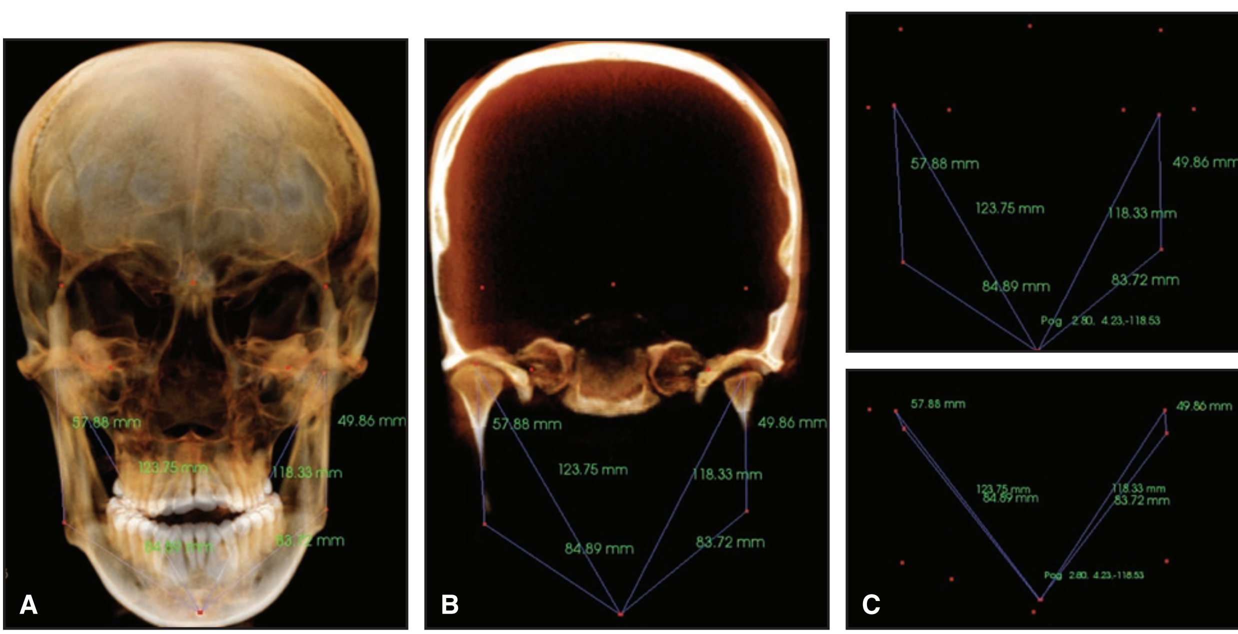

Fig. 4 A. Mandibular lengths—right and left ramal height (RH) and right and left body length (BL)—used to demonstrate mandibular asymmetry. B. Ramal height measured from middle of superior surface of condylar head. C. Mandibular asymmetry demonstrated after cropping of skull surface.

Skeletal Analysis

Most lateral cephalometric analyses use sella-nasion as the anterior cranial base reference line. Sella is defined as the midpoint of the concavity of the sella turcica. On a standard lateral cephalometric radiograph, it can be located fairly reliably from a 2D perspective of a point within a 3D structure. On a volumetric image, however, it can be a problem to locate a landmark that represents the midpoint of a concavity, rather than a physical structure, in three planes of space. Therefore, the NFZ plane is a more reliable reference structure in 3D analysis, since the FZ points are visible

TABLE 2
SKELETAL VERTICAL ANALYSIS

Measurement	Value	Type of Measurement
R TFP(*z*)	27.0mm	Projected (frontal plane)
L TFP(*z*)	26.0mm	Projected (frontal plane)
R Or(*z*)	29.5mm	Projected (frontal plane)
L Or(*z*)	28.5mm	Projected (frontal plane)
ANS(*z*)	52.0mm	Projected (sagittal plane)
PNS(*z*)	49.0mm	Projected (sagittal plane)
R MxBP(*z*)	53.0mm	Projected (frontal plane)
L MxBP(*z*)	53.0mm	Projected (frontal plane)
MxS line angle	3.5°	Projected (sagittal plane)
Me(*z*)	116.5mm	Projected (frontal plane)
R Go(*z*)	87.0mm	Projected (frontal plane)
L Go(*z*)	88.0mm	Projected (frontal plane)
R MdS line angle	26.5°	Projected (sagittal plane)
L MdS line angle	26.0°	Projected (sagittal plane)
R MdRH	62.0mm	Direct
L MdRH	62.0mm	Direct
R GA	116.0°	Direct
L GA	116.0°	Direct
LFH (ANS-Me)	66.5mm	Direct

surface landmarks on the 3D image and components of the anterior cranial base.

Skeletal Anteroposterior Analysis (Table 1)

Three-dimensional analysis is similar to 2D analysis in terms of landmark location and anteroposterior evaluation of the maxillomandibular structures.

Maxilla and Mandible: A(*y*), B(*y*), Pog(*y*). The maxilla is related to the NFZ plane by the value of the *y*-coordinate at A point A(*y*), whereas the mandible is assessed at B(*y*) and Pog(*y*).

Maxilla and Mandible: SNA, SNB, Facial Line Angle. The SNA and SNB angles are projected onto the sagittal plane.[6] Historically, A and B points have been used to assess the sagittal position of the jaws, but the usefulness of these two structural points is limited by their dentoalveolar position and origin. ANS and Pog are preferable because they are structural landmarks representing the basal bones of the maxilla and mandible, respectively. The facial line angle, an angle formed by the FH line and the facial line (NPog) projected onto the sagittal plane, represents the anteroposterior position of the mandible relative to the cranial base.[5]

Intermaxillary Relationship: B(*y*)–A(*y*), ANB. The interrelationship of the maxilla and the mandible is the difference between the *y*-coordinate values of B point and A point, B(*y*)–A(*y*). A larger positive value indicates a more anterior position of the maxilla in relation to the mandible, or a Class II skeleton, whereas a negative value suggests a Class III skeleton. The ANB angle is another measurement of the intermaxillary relationship.[6]

Wits Appraisal. This is the linear distance between AO and BO projected onto the sagittal plane. AO and BO are the perpendicular projections from A point and B point, respectively, to the occlusal plane.[11-12]

Maxillary Length: MxL. Maxillary length (MxL) is the distance between ANS and PNS.

Mandibular Lengths: RL MdL. Right and left mandibular lengths (RL MdL) are linear distances obtained by direct measurements from RL condylar point to Pog (Fig. 4).[9]

Mandibular Body Lengths: RL MdBL. Right and left mandibular body lengths (RL MdBL) are determined by the linear distance from RL Go to Pog (Fig. 4). Any differences in the values between RL MdBL indicate an intramandibular component of the mandibular asymmetry. Determining the underlying etiology is essential for proper diagnosis and treatment planning.

Skeletal Vertical Analysis (Table 2)

FH Lines: RL TFP(*z*), RL Or(*z*). TFP can be used instead of Po to orient the FH lines (Fig. 3A). Locating Po is challenging in 3D images because of the limited volume that 3D CBCT hardware can include in its field of view. The external auditory meatus is a fan-shaped funnel, and even a slight change in vertical position may result in a significant difference in its transverse position. When fully intact in the volumetric image, however, Po can be used as a posterior reference point for the FH plane. The RL TFP represent the base of the cranium on the temporal bone, where the condylar heads articulate. The vertical position of the RL TFP with respect to the NFZ plane in the vertical axis is evaluated using the *z*-coordinate values of RL TFP. These values can be compared to identify a vertical asymmetry between the bilateral cranial base structures (the temporomandibular fossae). The *z*-coordinate values of RL Or are compared to assess any asymmetry in their vertical positions. For convenience, unless a major discrepancy exists between RL FH lines, R FH can be used as a reference line.

Maxilla: ANS(*z*), PNS(*z*). The *z*-coordinates of ANS and PNS indicate the maxillary vertical dimension from the anterior and posterior aspects of the maxilla, respectively.

Maxilla: RL MxBP(*z*). Any difference between the two *z*-coordinates of RL MxBP will show a bilateral vertical asymmetry in the maxilla. The degree of vertical deficiency or excess can thus be accurately determined in both the frontal and sagittal planes.

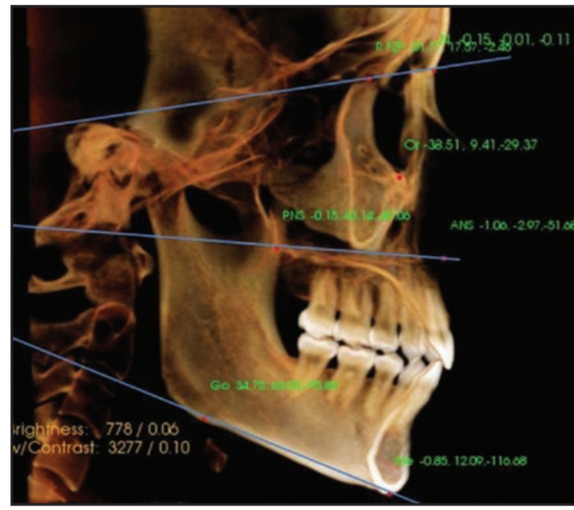

Fig. 5 Maxillary sagittal (MxS) line and mandibular sagittal (MdS) line angles.

Maxilla: MxS Line Angle. In the sagittal plane, the angle formed by the NFZ line and the MxS line determines the degree of divergence of the maxilla relative to the NFZ plane (Fig. 5). This MxS line angle,[7] is projected onto the sagittal plane.

Mandible: Me(*z*), RL Go(*z*). The vertical position of the mandible relative to the NFZ plane is evaluated by the absolute values of the *z*-coordinates of three skeletal points: RL Go and Me. A difference between the *z*-coordinate values of RL Go is a good indication of a vertical asymmetry in the mandible. On the other hand, the cranial base and the maxilla may also contribute to, or be the underlying cause of, the observed mandibular asymmetry. The true etiology of the asymmetry can be determined by evaluating the position of the cranial base by means of RL TFP, the maxilla, and the mandible. Thus, determining the values of the *x*-, *y*-, and *z*-coordinates of RL TFP and RL MxBP enables the clinician to assess any contribution of the cranial base or maxilla to the mandibular asymmetry.

Mandible: RL MdS Line Angles. Recall that RL Go and Me form the RL MdS lines. Using these structural lines, the divergence of the mandible relative to the NFZ plane is determined from the

TABLE 3
SKELETAL TRANSVERSE ANALYSIS

Measurement	Value	Type of Measurement
R FZP(*x*)	51.0mm	Projected (frontal plane)
L FZP(*x*)	50.5mm	Projected (frontal plane)
CBW (R FZP–L FZP)	101.5mm	Projected (frontal plane)
R TFP(*x*)	–62.0mm	Projected (frontal plane)
L TFP(*x*)	60.5mm	Projected (frontal plane)
ITFPW	122.0mm	Projected (frontal plane)
ANS(*x*)	–1.0mm	Projected (frontal plane)
PNS(*x*)	0.0mm	Projected (frontal plane)
R MxBP(*x*)	–32.5mm	Projected (frontal plane)
L MxBP(*x*)	30.0mm	Projected (frontal plane)
MxBW (R MxBP–L MxBP)	63.0mm	Projected (Mx frontal)
MxF line angle	0.0°	Projected (frontal plane)
Pog(*x*)	–0.5mm	Projected (frontal plane)
R Go(*x*)	–43.0mm	Projected (frontal plane)
L Go(*x*)	41.0mm	Projected (frontal plane)
MdBW (R Go–L Go)	84.0mm	Projected (Md frontal)
MdF line angle	0.5°	Projected (frontal plane)
MxMdF line angle	0.5°	Projected (frontal plane)
Mx/CB WR	0.62	Direct
Md/CB WR	0.83	Direct
Mx/Md WR	0.75	Direct

intersection of the NFZ line with the corresponding RL MdS lines in the sagittal plane (Fig. 5). The RL MdS line angles[5-7,15] are projected onto the sagittal plane. A difference between these angles indicates a combination of extramandibular and intramandibular components.

Mandible: RL MdRH, RL GA. The right and left mandibular ramal heights (RL MdRH) are measurements of the linear distance from R Go to R condylar point and L Go to L condylar point, respectively (Fig. 4A,B). Any difference between RL MdRH may indicate an intramandibular component of the mandibular asymmetry. The right and left gonial angles (RL GA) are direct measurements of the inside angles formed by the ramus lines and the MdS lines.[10]

Lower Facial Height. Lower facial height (LFH) is the linear distance between ANS and Me.[9,13]

Skeletal Transverse Analysis (Table 3)

The skeletal transverse analysis compares the right and left absolute values along the *x*-axis to assess symmetry, as well as the actual body width between the right and left points.

Cranial Base: RL FZP(*x*), RL TFP(*x*). The *x*-coordinates of FZP and TFP indicate the transverse dimension of the cranial base in both the frontal and axial planes. Any difference between the *x*-coordinate values of RL FZP indicates a transverse asymmetry in the cranial base. The values of the *x*-, *y*-, and *z*- coordinates of RL TFP provide information for appraisal of any asymmetry between the bilateral condylar housings. This is useful in determining whether a mandibular asymmetry is due to an extramandibular factor, such as differences in the RL TFP positions, or to intramandibular anatomical factors.

Fig. 6 Cranial base widths: inter-FZP or cranial base width (CBW) and inter-TFP width (ITFPW).

Cranial Base Width: CBW, ITFPW. The inter-FZP or cranial base width (CBW) is the linear distance between the RL FZP projected onto the frontal plane (Fig. 6). The inter-TFP width (ITFPW) is the linear distance between RL TFP projected onto the frontal plane.

Maxilla: ANS(*x*), PNS(*x*). The *x*-coordinate values of ANS and PNS provide information about the transverse position of the maxilla.

Maxilla: RL MxBP(*x*). The *x*-coordinate values of the RL MxBP provide information about the transverse position of the posterior maxilla on both sides.

Maxillary Base Width: MxBW. The maxillary base width (MxBW) is the linear distance between the RL MxBP projected onto the MxF plane.

Maxilla: MxF Line Angle. An asymmetry of the maxilla can also be evaluated using this angle. Any angle formed between the FZ line (not the NFZ plane) and the MxF line projected onto the frontal plane determines the degree of canting of the maxillary basal bone relative to the FZ line (Fig. 7). This is known as the MxF line angle. An absolute value greater than 0° indicates a cant of the maxillary basal bone relative to the FZ line. The value is positive when the base of the angle is to the subject's right and diverges to the left, and negative in the opposite situation.

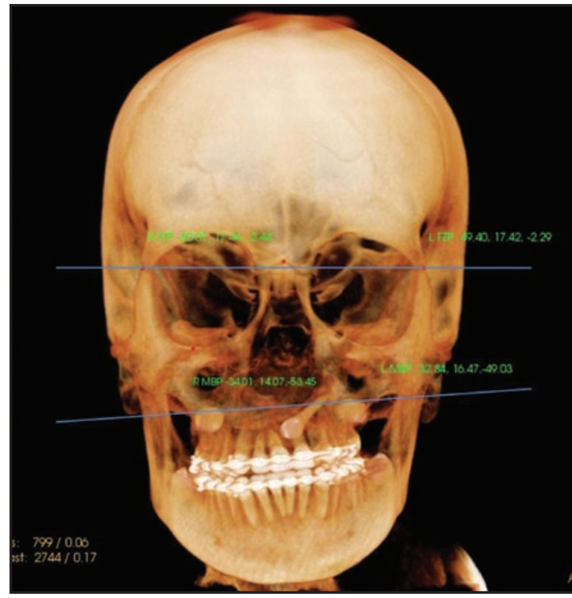

Fig. 7 Maxillary frontal (MxF) line angle.

Mandible: Pog(*x*). The *x*-coordinate value of Pog provides information about the transverse position of the anterior mandible.

Mandible: RL Go(*x*). The *x*-coordinate values of RL Go provide information about the transverse position of the posterior mandible. Any difference between these two values is a good indication of a transverse asymmetry in the mandible.

Mandibular Base Width: RL MdBW. The mandibular base width (MdBW) is measured by the linear distance between RL Go projected onto the MdF plane.

Mandible: MdF Line Angle. Any angle formed between the FZ line and the MdF line in the frontal plane determines the degree of canting of the mandibular basal bone relative to the FZ line. This is known as the MdF line angle. An absolute value greater than 0° indicates a cant of the mandibular basal bone relative to the FZ line. The value is positive when the base of the angle is to the subject's right and diverges to the left, and negative in the opposite situation. A difference between RL MdF line angles indicates a combination of extramandibular and intramandibular components.

TABLE 4
DENTAL ANTEROPOSTERIOR ANALYSIS

Measurement	Value	Type of Measurement
R U1SI	114.0°	Projected (Mx sagittal)
L U1SI	106.5°	Projected (Mx sagittal)
R U1SP	2.5mm	Projected (Mx sagittal)
L U1SP	2.5mm	Projected (Mx sagittal)
R L1SI	97.0°	Projected (Md sagittal)
L L1SI	96.5°	Projected (Md sagittal)
R L1SP	6.5mm	Projected (Md sagittal)
L L1SP	6.0mm	Projected (Md sagittal)
R U3SI	98.5°	Projected (R Mx oblique)
L U3SI	94.5°	Projected (L Mx oblique)
R U3SP	16.0mm	Projected (Mx sagittal)
L U3SP	16.5mm	Projected (Mx sagittal)
R L3SI	90.0°	Projected (R Md oblique)
L L3SI	85.0°	Projected (L Md oblique)
R L3SP	7.0mm	Projected (Md sagittal)
L L3SP	7.5mm	Projected (Md sagittal)
R U6SI	95.0°	Projected (Mx sagittal)
L U6SI	89.5°	Projected (Mx sagittal)
R U6SP	3.5mm	Projected (Mx sagittal)
L U6SP	3.0mm	Projected (Mx sagittal)
R L6SI	87.0°	Projected (Md sagittal)
L L6SI	89.0°	Projected (Md sagittal)
R L6SP	21.5mm	Projected (Md sagittal)
L L6SP	22.5mm	Projected (Md sagittal)
L1:Pog	6.5	Projected (sagittal plane)

Intermaxillary Relationship: MxMdF Line Angle. Any angle formed between the MxF line and the MdF line in the frontal plane determines the degree of canting of the mandibular basal bone relative to the maxillary basal bone. This is known as the maxillomandibular frontal (MxMdF) line angle. The value is positive when the base of the angle is to the subject's right and diverges to the left, and negative in the opposite situation.

Maxillary/Mandibular Base to Cranial Base Width Ratios: Mx/CB WR, Md/CB WR. The ratios between MxBW/MdBW and CBW (Mx/CB WR and Md/CB WR) in normal skeletons will serve as good references for the management of patients with significant transverse discrepancies.

Maxillary Base to Mandibular Base Width Ratio: Mx/Md WR. The ratio between MxBW and MdBW (Mx/Md WR) is used to analyze the intermaxillary transverse relationship. Within each jaw, the ratio between the basal bone width and the intermolar width, as defined in the dental transverse analysis, provides valuable information about the transverse development of the dentition.

Dental Analysis

Dental Anteroposterior Analysis (Table 4)

Like the 3D skeletal anteroposterior analysis, the 3D dental anteroposterior analysis is similar to that of any 2D cephalometric system. The major difference is that in a lateral cephalometric radiograph, superimposition of the images makes it impossible to evaluate the teeth individually.

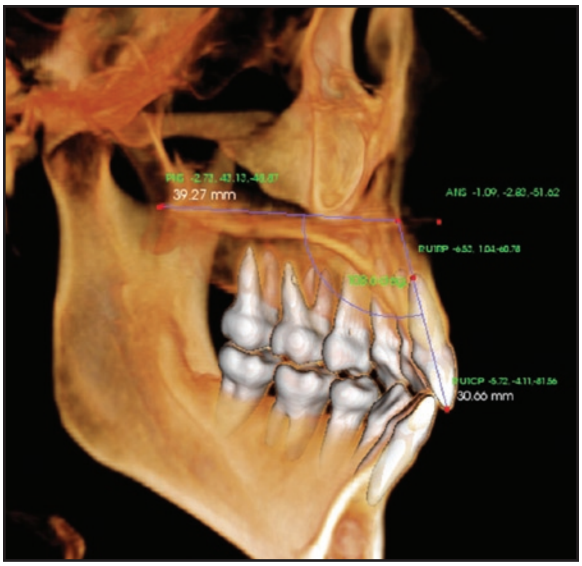

Fig. 8 Maxillary central incisor sagittal inclination (U1SI).

Because a unilateral evaluation of the dentition is usually sufficient for both the right and left dental structures, the analysis described below is taken from the right dental points for convenience. Bilateral evaluation is recommended in cases where significant asymmetries are suspected.

Maxillary Incisor: RL U1SI, RL U1SP. Both angular and linear measurements are used to evaluate incisor position. The maxillary central incisor sagittal inclination (U1SI) is the lingual angle between the long axis of the maxillary central incisor and the MxS line, projected onto the MxS plane (Fig. 8). The maxillary central incisor sagittal position (U1SP) is the perpendicular linear distance from U1CP to the NA line, projected onto the MxS plane.[6]

Mandibular Incisor: RL L1SI, RL L1SP. The mandibular central incisor sagittal inclination (L1SI, or IMPA) is the lingual angle formed by the intersection of the long axis of the mandibular central incisor and the R or L MdS line, projected onto the MdS plane.[5,8] The mandibular central incisor sagittal position (L1SP) is the perpendicular linear distance from the L1CP to the NB line, projected onto the MdS plane.[6]

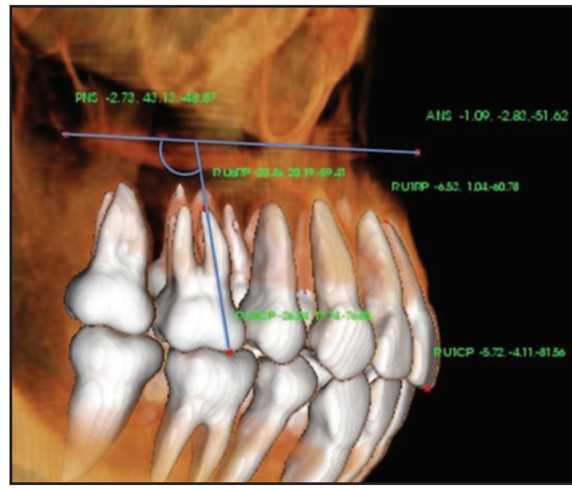

Fig. 9 Maxillary molar sagittal inclination (U6SI).

Maxillary Canine: RL U3SI, RL U3SP. The maxillary canine sagittal inclination (U3SI) is the distal angle between the long axis of the maxillary canine and the maxillary plane, projected onto the ipsilateral maxillary oblique plane. The canine root inclination is best evaluated in the oblique plane, because changes in inclination tend to be underestimated in the sagittal plane. The maxillary canine sagittal position (U3SP) is the difference between the *y*-coordinate values of U3CP and MxBP, projected onto the MxS plane.

Mandibular Canine: RL L3SI, RL L3SP. The mandibular canine sagittal inclination (L3SI) is the distal angle between the long axis of the mandibular canine and the R or L MdS line, projected onto the ipsilateral mandibular oblique plane. The mandibular canine sagittal position (L3SP) is the difference between the *y*-coordinate values of L3CP and Pog, projected onto the MdS plane.

Maxillary Molar: RL U6SI, RL U6SP. The maxillary molar sagittal inclination (U6SI) is the distal angle formed by the long axis of the maxillary first molar (the axis connecting the mesiobuccal cusp and root tips) and the R or L MxS line, projected onto the MxS plane (Fig. 9). The differ-

TABLE 5
DENTAL VERTICAL ANALYSIS

Measurement	Value	Type of Measurement
R U1VD	30.0mm	Direct
L U1VD	30.5mm	Direct
R U6VD	23.5mm	Direct
L U6VD	23.0mm	Direct
R L1VD	26.0mm	Direct
L L1VD	26.5mm	Direct
R L6VD	35.5mm	Direct
L L6VD	35.5mm	Direct
MxFO line angle	0.0°	Projected (Mx frontal)
MdFO line angle	0.5°	Projected (Md frontal)
MxSO line angle	12.5°	Projected (Mx sagittal)
MdSO line angle	15.0°	Projected (Md sagittal)

ence between the *y*-coordinate values of MxBP and the ipsilateral U6CP is the maxillary molar sagittal position (U6SP), which indicates the anteroposterior position of the maxillary first molar crown within the maxilla.

Mandibular Molar: RL L6SI, RL L6SP. The mandibular molar sagittal inclination (L6SI) is the distal angle formed by the long axis of the mandibular first molar (the axis connecting the mesiobuccal cusp tip and mesial root tip) and the R or L MdS line, projected onto the MdS plane. The difference between the *y*-coordinate values of Pog and L6CP is the mandibular molar sagittal position (L6SP), which indicates the anteroposterior position of the mandibular first molar crown within the mandible.

Lower Incisor to Pogonion Ratio: L1:Pog. The L1:Pog ratio compares the linear measurements of R L1CP and Pog from the NB line, projected onto the sagittal plane. This measurement is useful because the position of the mandibular incisor relative to Pog is important for facial balance and esthetics.

Dental Vertical Analysis (Table 5)

The relationship of the vertical position of the dentition to the apical base is readily seen in a 3D volumetric image. Vertical linear measurements reflect the amount of vertical development of the dentoaveolar process. Like the dental anteroposterior analysis, the dental vertical analysis can be performed bilaterally if necessary.

Maxillary Dentition: RL U1VD, RL U6VD. The maxillary incisor vertical development (U1VD) is the perpendicular distance from U1CP to the maxillary plane. The maxillary molar vertical development (U6VD) is the perpendicular distance from U6CP to the maxillary plane (Fig. 10).

Mandibular Dentition: RL L1VD, RL L6VD. The mandibular plane is used to measure the vertical development of the mandibular central incisors and first molars. Similar to U1VD, the mandibular incisor vertical development (L1VD) is the perpendicular distance from L1CP to the mandibular plane. The mandibular molar vertical development (L6VD) is the perpendicular distance from L6CP to the mandibular plane.

Occlusal Plane Canting: MxFO Line Angle, MdFO Line Angle. The MxFO line angle is the intersection, if any, of the MxFO line with the MxF line, projected onto the MxF plane. The MdFO line angle is the intersection of the MdFO line with the MdF line, projected onto the MdF plane. The value is positive when the base of the

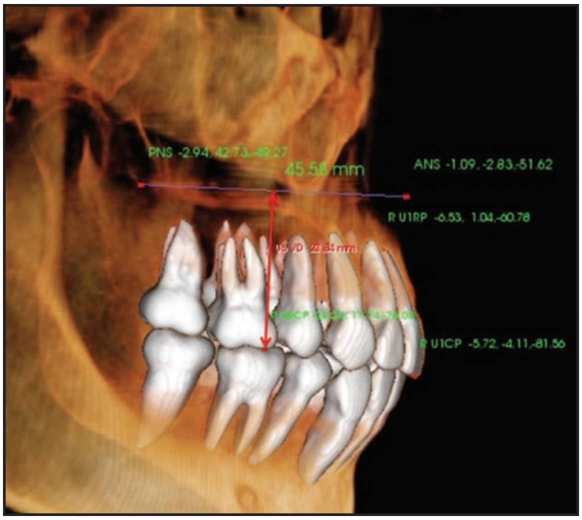

Fig. 10 Maxillary molar vertical development (U6VD).

angle is to the subject's right and diverges to the left, and negative in the opposite situation. Using these measurements, an occlusal cant can be readily determined as having a dental or skeletal origin, or a combination of the two. Skeletal asymmetries seen in the frontal plane have been previously described. Dental asymmetries are determined by measuring the distance from the RL U6CP to the maxillary plane. Differences between these two values indicate asymmetrical vertical development and positioning of the teeth. Likewise, the linear measurements from RL L6CP to the mandibular plane are used to detect abnormalities in the mandibular vertical dimension. This information may facilitate an assessment of asymmetrical vertical development of the dentition and thus improve diagnosis and treatment planning.

Occlusal Plane Inclination: MxSO Line Angle, MdSO Line Angle. The MxSO line angle is the intersection, if any, of the MxSO line with the maxillary plane, projected onto the MxS plane. The MdSO line angle is the intersection of the MdSO line with the mandibular plane, projected onto the MdS plane. The value is positive when the base of the angle is to the subject's posterior and diverges to the subject's anterior, and negative in the opposite situation.

Dental Transverse Analysis (Table 6)

Interdental width measurements are commonly used, especially in the mixed dentition, to evaluate the effectiveness of expansion or retention, and even to guide orthognathic surgery. These transverse measurements can readily be obtained from dental casts; while 2D lateral and frontal cephalograms can provide important estimates of tooth inclinations, they are often difficult to interpret because of the superimposition of structures. In contrast, 3D imaging allows accurate calculations to be made in any plane.

Transverse analysis of the dentition involves an evaluation of the tooth positions over the basal bone. This consists of linear measurements of the intercanine and intermolar widths, as well as an assessment of the molar inclinations relative to the apical base. Evaluation of molar position, which was seldom possible with 2D imaging, is essential for proper case diagnosis and outcome assessment. The linear distances between both the cusp tips and the apices are important indicators of crown positions over the root and the basal bone, and thus can help detect bodily or tipping movements during treatment. Information about the transverse dimension will aid in diagnosis of the skeletal and dental components of posterior crossbite.

Maxillary Incisor: RL U1FI, RL U1FP. Both angular and linear measurements are used to evaluate incisor positions in the frontal plane. The maxillary central incisor frontal inclination (U1FI) is the distal angle between the long axis of the maxillary central incisor and the MxF line, projected onto the MxF plane. The maxillary central incisor frontal position (U1FP) is the difference between the *x*-coordinate values of U1CP and ANS projected onto the MxF plane, indicating the transverse position of the maxillary central incisor crown within the maxilla.

Mandibular Incisor: RL L1FI, RL L1FP. The mandibular central incisor frontal inclination (L1FI) is the distal angle formed by the intersection of the MdF line and the long axis of the mandibular central incisor, projected onto the MdF plane. The mandibular central incisor frontal posi-

TABLE 6
DENTAL TRANSVERSE ANALYSIS

Measurement	Value	Type of Measurement
R U1FI	90.5°	Projected (Mx frontal)
L U1FI	87.0°	Projected (Mx frontal)
R U1FP	–3.5mm	Projected (Mx frontal)
L U1FP	5.0mm	Projected (Mx frontal)
R L1FI	86.0°	Projected (Md frontal)
L L1FI	87.0°	Projected (Md frontal)
R L1FP	–3.5mm	Projected (Md frontal)
L L1FP	2.0mm	Projected (Md frontal)
R U3FI	98.0°	Projected (L Mx oblique)
L U3FI	97.5°	Projected (R Mx oblique)
R U3FP	16.5mm	Projected (Mx frontal)
L U3FP	17.0mm	Projected (Mx frontal)
R L3FI	90.0°	Projected (L Md oblique)
L L3FI	93.0°	Projected (R Md oblique)
R L3FP	13.5mm	Projected (Md frontal)
L L3FP	12.0mm	Projected (Md frontal)
U3CW	34.0mm	Projected (Mx frontal)
U3RW	32.5mm	Projected (Mx frontal)
U3WR	1.04	Direct
L3CW	25.5mm	Projected (Md frontal)
L3RW	24.0mm	Projected (Md frontal)
L3WR	1.07	Direct
R U6FI	84.5°	Projected (Mx frontal)
L U6FI	83.5°	Projected (Mx frontal)
R U6FP	25.0mm	Projected (Mx frontal)
L U6FP	23.5mm	Projected (Mx frontal)
U6CW	48.5mm	Projected (Mx frontal)
U6RW	51.5mm	Projected (Mx frontal)
U6WR	0.94	Direct
U6MxWR	0.77	Direct
R L6FI	82.5°	Projected (Md frontal)
L L6FI	83.0°	Projected (Md frontal)
R L6FP	20.0mm	Projected (Md frontal)
L L6FP	17.5mm	Projected (Md frontal)
L6CW	37.5mm	Projected (Md frontal)
L6RW	43.5mm	Projected (Md frontal)
L6WR	0.87	Direct
L6MdWR	0.45	Direct

tion (L1FP) is the difference between the *x*-coordinate values of L1CP and Pog projected onto the MdF plane, indicating the transverse position of the mandibular central incisor crown within the mandible.

Maxillary Canine: RL U3FI, RL U3FP. The maxillary canine frontal inclination (U3FI) is the lingual angle formed by the long axis of the maxillary canine and the maxillary plane, projected onto the contralateral maxillary oblique plane. Using the MxF plane instead of the contralateral maxillary oblique plane will result in an underestimation of any changes in canine torque. The maxillary canine frontal position (U3FP) is the difference between the *x*-coordinate values of U3CP and ANS projected onto the MxF plane, indicating the transverse position of the maxillary canine crown within the maxilla.

Mandibular Canine: RL L3FI, RL L3FP. The mandibular canine frontal inclination (L3FI) is the lingual angle formed by the intersection of the R or L MdS line and the long axis of the mandibular canine, projected onto the contralateral mandibular oblique plane. The mandibular canine frontal position (L3FP) is the difference between the *x*-coordinate values of L3CP and Pog projected onto the MdF plane, indicating the transverse position of the mandibular canine crown within the mandible.

Maxillary Canine Widths: U3CW, U3RW, U3WR. The maxillary intercanine crown width (U3CW) is the distance between RL U3CP projected onto the MxF plane. The maxillary intercanine root width (U3RW) is the distance between RL U3RP projected onto the MxF plane. The maxillary canine width ratio (U3WR) is the ratio between U3CW and U3RW.

Mandibular Canine Widths: L3CW, L3RW, L3WR. The mandibular intercanine crown width (L3CW) is the distance between RL L3CP projected onto the MdF plane. The mandibular intercanine root width (L3RW) is the distance between RL L3RP projected onto the MdF plane. The mandibular canine width ratio (L3WR) is the ratio between L3CW and L3RW.

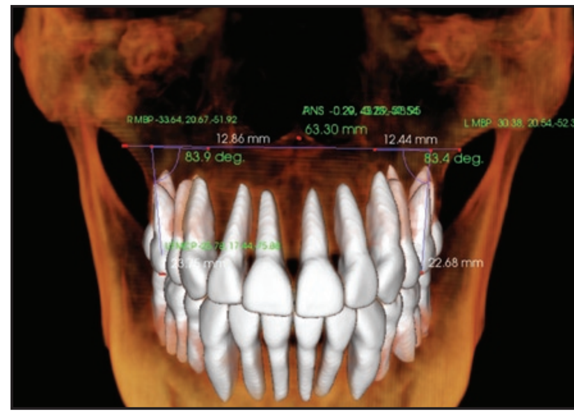

Fig. 11 Maxillary molar frontal inclination (U6FI).

Maxillary Molar: RL U6FI, RL U6FP. The maxillary molar frontal inclination (U6FI) is the palatal angle formed by the MxF line and the long axis of the maxillary first molar from U6CP through U6RP, projected onto the MxF plane (Fig. 11). The difference between the *x*-coordinate values of ANS and U6CP is the maxillary molar frontal position (U6FP), which indicates the transverse position of the maxillary first molar crown within the maxilla.

Maxillary Molar Widths: U6CW, U6RW, U6WR. The maxillary intermolar crown width (U6CW) is the distance between RL U6CP projected onto the MxF plane. The maxillary intermolar root width (U6RW) is the distance between RL U6RP projected onto the MxF plane. The maxillary molar width ratio (U6WR) is the ratio between U6CW and U6RW.

Maxillary Bone to Maxillary Molar Width Ratio: U6MxWR. As a comparison of the linear width of the dentition to that of the basal bones, the maxillary bone to maxillary molar width ratio (U6MxWR) provides useful information about the transverse development of the dentition relative to its skeletal base. The U6MxWR is the ratio between U6CW, the linear distance between RL U6CP projected onto the MxF plane, and MxBW, the linear distance between RL MxBP projected onto the MxF plane (Fig. 12).

Mandibular Molar: RL L6FI, RL L6FP. The

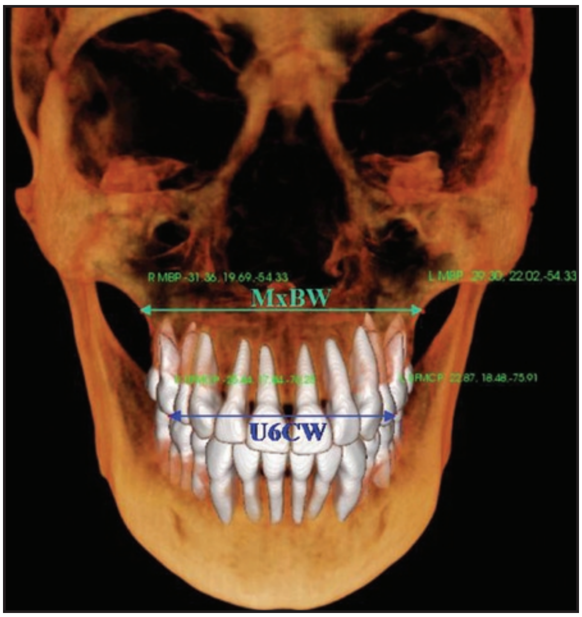

Fig. 12 Maxillary bone to maxillary molar width ratio (U6MxWR). (MxBW = maxillary bone width; U6CW = maxillary intermolar crown width.).

mandibular molar frontal inclination (L6FI) is the lingual angle formed by the MdF line and the long axis of the mandibular first molar from L6CP through L6RP, projected onto the MdF plane. The difference between the *x*-coordinate values of Pog and L6CP is the mandibular molar frontal position (L6FP), which indicates the transverse position of the mandibular first molar crown within the mandible.

Mandibular Molar Widths: L6CW, L6RW, L6WR. The mandibular intermolar crown width (L6CW) is the distance between RL L6CP projected onto the MdF plane. The mandibular intermolar root width (L6RW) is the distance between RL L6RP projected onto the MdF plane. The mandibular molar width ratio (L6WR) is the ratio between L6CW and L6RW.

Mandibular Bone to Mandibular Molar Width Ratio: L6MdWR. The mandibular bone to mandibular molar width ratio (L6MdWR) is the ratio between L6CW, the linear distance between RL L6CP projected onto the MdF plane, and MdBW, the linear distance between RL Go projected onto the MdF plane.

Discussion

Because the adult female patient analyzed here (Tables 1-6) was considered a good example of Class I malocclusion, her volumetric image was used to produce an initial set of measurements for this new 3D cephalometric analysis. Ongoing data collection from a wider sample of patients will provide useful means and normal ranges.

The 3D cephalometric analysis is based on many earlier 2D analyses and studies.[1-15] Limitations of 2D imaging include the superimposition of bilateral structural points, the magnification factor on a conventional cephalogram, and poor patient positioning. These limitations can make it difficult to determine whether a perceived asymmetry truly exists. In contrast, in the 3D analysis, the Cartesian coordinate system allows full visualization of any differences between bilateral structures. For example, differences between the right and left absolute values of the *x*-coordinates may suggest an asymmetrical position in the transverse dimension. Differences between the right and left absolute values of the *y*- and *z*-coordinates will indicate asymmetries in the anteroposterior and vertical dimensions, respectively.

The 3D analysis presented in this article has significant potential in the areas of diagnosis, treatment planning, and outcome evaluation. Because another important application of 3D imaging is the diagnosis of potentially serious sleep disorders, future studies are needed to develop a volumetric airway analysis. In any event, every 3D image should be reviewed by an oromaxillofacial radiologist.[33]

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ACKNOWLEDGMENTS: The author expresses his sincere gratitude to Dr. Stefan Alexandroni and Mr. Scott Frey for their help with the development of calculation formulas for the 3D cephalometric analysis. These are described in the Appendix, which appears in the online version of the article at www.jco-online.com. Drs. Joorok Park and Thao Nguyen provided outstanding contributions to the figures presented in this article, as well as editorial assistance. Thanks are also due to Dr. Jack Choi for his generous donation of the InVivoDental software and Dr. Ronald Redmond for his ongoing support of our school, including the donation of an iCAT machine, without which this research would have been impossible. Finally, the author thanks Dr. Robert Boyd for his administrative support for this project.

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