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Effect of Facial Asymmetry on Two-Dimensional and Three-Dimensional Cephalometric Measurements

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Two dimensional (2D) lateral cephalometric analyses are used to measure the shape, size, position and orientation of the different facial units. These analyses are done on lateral cephalometric radiographs. In these radiographs, all the facial structures are projected onto a single sagittal plane. However, the information which can be gathered from them is limited. In determining position, the information is limited to the anteroposterior and vertical dimensions. In determining orientation, the data is limited to pitch. In determining size, the parameters are limited to length and height, while in determining shape the analysis is restricted to projections on the sagittal plane. In spite of all these limitations, clinicians have found lateral cephalometric analyses useful and have utilized them to study facial growth, to appraise facial deformities, to plan treatment, and to evaluate outcomes. The usefulness of these analyses arises from the fact that most individuals have facial symmetry. In this group of patients most of clinically relevant measurements can be determined from a lateral analysis. Nevertheless, as many as one third of patients with dentofacial deformities have facial asymmetries.¹ Therefore, the effects of these types of deformities on 2D lateral cephalometric measurements needs to be established. Preliminary observations completed in our laboratory suggest that facial asymmetry can distort 2D cephalometric measurements and that these distortions cannot be prevented by the standard practice of averaging bilateral landmarks.

We are experiencing a paradigm shift in computer-aided surgical simulation for craniomaxillofacial surgery as we transit to three-dimensional (3D) cephalometry². This transition has been facilitated by the introduction of cone-beam computer tomography, which allows for the acquisition of 3D images in the office setting with a minimal amount of

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radiation. Theoretically, 3D cephalometry can eliminate the shortcomings of the 2D studies, especially in patients with facial asymmetries. However, observations completed in our Surgical Planning Laboratory suggest that asymmetry can also affect these measurements. Therefore, the purpose of this study was to test the hypothesis that facial asymmetry will affect 2D and 3D cephalometric measurements.

Methods

In first step of this study we constructed a *baseline model* of the face. A 3D imaging software (3D Studio Max, Autodesk Inc, San Rafael, CA) was utilized for this purpose. The *baseline model* consisted of a 3D cloud of points which included a list of commonly used cephalometric landmarks (Table 1). These landmarks were located in a 3D *Cartesian* coordinate system. The *x* axis of the coordinate system denoted right-left, the *y* axis front-back and the *z* axis top-bottom. Landmarks, that by definition exist on the midsagittal plane, were digitized on the *y-o-z* plane. Bilateral landmarks were digitized on each side of this plane at their average distance from the plane. Depending on their location, the landmarks were assigned to 1 of 3 groups: skull base, maxilla or mandible. These cephalometric landmarks were then utilized to construct a set of commonly used cephalometric lines and planes (Table 2). All the landmarks were moved in an iterative fashion until the common cephalometric measurements inscribed by them was averaged. The pitch of the entire computer model was then adjusted so that none of the cephalometric planes (e.g. Frankfort Horizontal) were parallel to the horizontal plane of the coordinate system. This was done to prevent lack of effect during testing, which occurs when the axis of rotation of an object is perpendicular to a reference plane. Finally, perfect mirror symmetry was created between the right and left points, and the origin of the coordinate system was set to coincide with Nasion.

In the second step of the study we modified the *baseline model* to create 10 different *asymmetric models*, 6 with maxillary asymmetries and 4 with mandibular asymmetries. In the 6 maxillary models, 2 had roll deformities of different severities (5° and 10°), 2 had yaw deformities of 5° and 10°, and the 2 had transverse-translational deformities of 5 mm and 10 mm. In the 4 mandibular models, 2 had roll deformities of 5° and 10°, and 2 had yaw deformities of the same magnitudes (Fig.1). The roll and yaw deformities were created by rotating the maxillary or mandibular landmarks around Nasion. After extensive testings, we finally selected the center of rotation around Nasion over other different possible centers. This was because it produced asymmetries that were similar to those commonly seen in clinical practice. In addition, this center was selected because this location prevented the lack of effect during testing that is often seen when a symmetrical object is rotated around its axis of symmetry. Roll deformities were simulated by rotating the maxillary or mandibular points around the anteroposterior (*y*) axis of Nasion, while yaw deformities were simulated by rotating the same landmarks around its vertical axis (*z*). The maxillary transverse-translation models were created by moving the maxillary points sideways (*x* axis).

The computer models described above were utilized to test the hypotheses that facial asymmetry will affect both 2D and 3D cephalometric measurements. Seven different cephalometric measurements were selected for testing (Table 3). These measurements were selected because each represented a different set of geometrical conditions related to the geometric parameters being measured (shape, size, position and orientation), the elements involved (i.e. points, lines, and planes), and the type of measurements (distances and angles) (Table 3).

The experiment was made up of 2 parts. In the first part, we examined the effect of asymmetry on 2D cephalometric measurements and in the second part its effect of 3D measurements. Each part required a separate experimental group. However, both shared the same control group. The control group was composed of the collection of cephalometric measurements made on the symmetric *baseline model*. In this group, all measurements were done in 3D with the exception of the Gonial angle which was calculated after the involved landmarks (Co-Go-Me) had been projected on the midsagittal plane of this model. In the experimental groups, ANS-PNS, U1-FH and OP-FH were measured in the maxillary-roll and maxillary-yaw models; SNA and Ricketts' Convexity of Point A were measured in the maxillary transverse-translation models; and the Gonial angle and the interincisal angle were measured in the mandibular asymmetry models. The need to test the different measurements in different models was due to the fact that each type of measurement (shape, size, position and orientation) was best tested using a unique set of conditions.

The effect of asymmetry on 2D cephalometric measurements was tested by calculating the difference between the 2D cephalometric measurements of the asymmetric models (2D experimental group) and those in the control group. In the experimental group, 2D cephalometry was simulated by projecting all cephalometric landmarks onto a virtual cephalometric film that was placed on the side of the facial models at a distance of 12 cm from their center. The landmarks were projected using parallel rays to prevent magnification errors. Bilateral landmarks were averaged after they had been projected on the virtual films. The 2D cephalometric angles between 2 lines were calculated using the equation

$$\theta = \arctan \left(\frac{m_2 - m_1}{1 + m_1 m_2} \right), \text{ where } m_1 \text{ and } m_2 \text{ represented the slopes of the 2 lines. Point to point}$$

distances were calculated using the equation $d = \sqrt{(X_2 - X_1)^2 + (Y_2 - Y_1)^2}$, where (X_1, Y_1) and (X_2, Y_2) represented the coordinates of the 2 landmarks. Finally, point to line distances using

$$d = \frac{|Am + Bn + C|}{\sqrt{A^2 + B^2}}, \text{ where the } Ax + By + C = 0 \text{ represented the line, and } (m, n) \text{ represented the point's coordinate.}$$

In the second part of the study, the effect of asymmetry on 3D cephalometric measurements was tested by calculating the difference between the 3D cephalometric measurements of the asymmetric models (3D experimental group) and those in the control group. Three-dimensional measurements were calculated using different methods depending on the geometric parameter being measured (shape, size, position and orientation) the elements involved (i.e. points, lines, and planes) and the type of measurement (distances and angles).

Three-dimensional shape (Gonial angle) was measured in reference to the *local* coordinate system of the involved unit (e.g., mandible). This *local* coordinate system was built on a surrounding box that encompassed the object. This box was constructed so its side walls were parallel to the intrinsic plane of symmetry of the mandible (*local* midsagittal plane) (Fig 2). The advantage of this type of Cartesian system is that its relationship to the object (mandible) remains constant even if the object changes position or orientation. After all the involved landmarks had been projected on the *local* midsagittal plane and the right and left landmarks had been averaged, the 3D Gonial angle was measured.

Three-dimensional size (ANS-PNS) was measured by calculating the distance between 2

points using the equation $d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}$ where d represented the distance between points P_1 and P_2 , (X_1, Y_1, Z_1) represented the 3D coordinates of P_1 and (X_2, Y_2, Z_2) the coordinates of P_2 .

Three-dimensional positions (SNA and Ricketts' Convexity to Point A) were calculated using different equations. The SNA was calculated as an angle between 2 lines using the

equation $\theta = \arccos \frac{a \cdot b}{|a| \cdot |b|}$, where a and b represented the vectors pointing in the direction of each line. The Ricketts' convexity was calculated by measuring the distance between point

A and the N-Pg line. The equation $= \frac{|(p - a) \times v|}{|v|}$, where p was the position vector for the point, a was the position vector for the line and v was the direction vector for the line, was utilized for this purpose.

Three-dimensional orientations (U1-L1, U1-FH, and OP-FH) were calculated using the following equations. Line-line angles (U1-L1) were calculated using the same equation

$\theta = \arccos \frac{a \cdot b}{|a| \cdot |b|}$. Line-plane angles (U1-FH) were determined by first calculating the plane's normal vector and then using the formula for 2 lines to calculate the angle between the normal vector and the line. A normal vector is a vector that is perpendicular to the plane. It can be calculated by the cross product ($a \times b$) of 2 vectors lying on the plane given 2 coplanar vectors a and b , $x = (Y_a * Z_b) - (Y_b * Z_a)$, $y = (Z_a * X_b) - (Z_b * X_a)$, and $z = (X_a * Y_b) - (X_b * Y_a)$. The angle between 2 planes (OP-FH) was determined by first calculating the normal vectors for each plane and then using the equation for the angle between two lines (i.e., 2 normal vectors).

Results

The results of the study are presented in Table 4. The 2D cephalometric measurement of shape (Gonial angle) was distorted by roll and yaw asymmetries, while the same measurement in 3D was not. The 2D measurement of size (ANS-PNS) was also distorted by yaw, but not by roll, while again this measurement in 3D was not distorted. For measurements of position (SNA and Ricketts' Convexity of Point A), the results were reversed. The 2D cephalometric measurements of position were not distorted, while all measurements in 3D were distorted. Of note, the magnitude of the distortion was much larger for the linear measurement (Ricketts' convexity) than angular measurement (SNA). Finally, both 2D and 3D measurements of orientation were distorted by asymmetry, although the magnitude of the distortion was larger for the 3D measurements.

Discussion

This study confirmed the hypothesis that facial asymmetry affects both 2D and 3D cephalometric measurements. It also demonstrated that the effects of asymmetry on cephalometric measurements depend on the geometric parameter being measured (i.e., shape, size, position or orientation).

Shape Measurement

In the presence of facial symmetry, the measurement of shape (Gonial angle) was distorted when it was measured using conventional 2D cephalometry. However, this distortion was not seen in the 3D measurements. Asymmetry distorted 2D cephalometric measurements of shape because in 2D cephalometrics, this parameter was measured on a projected 2D image. When an object was oriented orthogonal to the film, the projected image corresponded to the object. However, when an object was obliquely oriented to the film, as in most asymmetries, the projected image was no longer a facsimile of the object. Fig 3 illustrates this phenomenon. Conversely in 3D, the measurement of shape was not distorted because the method used to measure this parameter in 3D was unaffected by the asymmetries. In this

study, we measured shape in 3D by projecting the involved cephalometric landmarks on a *local* coordinate system built around a surrounding box of the object. This strategy prevented distortion of the shape measurements because the relationship between the *local* coordinate system (surrounding box) and the object (mandible) was unaffected even if the object changed position or orientation.

Size Measurement

In the presence of facial asymmetry, the measurement of size (ANS-PNS) was distorted when measured on the 2D films. However, this did not occur with the direct 3D measurements. The reason for the distortion in 2D cephalometry was the same as for the measurement of shape. The projected 2D image did not correspond to the object because the object was not orthogonal to the film. Another finding of the 2D arm of the study was that the 2D measurement of size (ANS-PNS) was only distorted in the yaw asymmetry models. Roll asymmetries did not distort the measurement. This occurred because ANS-PNS was a measurement of length (anteroposterior dimension) and the simulated roll asymmetries did not change the anteroposterior position of the 2 points that bound this line segment. If we had selected a measurement of height (vertical dimension) instead of a length measurement for testing, we would have seen the opposite effect. Because the 3D measurements are never distorted, it can be concluded that for size measurement, direct 3D measurements are superior.

Position Measurement

In the presence of facial asymmetry, the results for the position measurements were opposite to those seen for shape and size. While the measurements were not distorted on 2D, they were distorted on 3D. This phenomenon can be better explained by the basic principles of 3D geometry. To determine the position of any point requires a frame of reference. The frame of reference of the face consists of 3 perpendicular planes (axial, coronal and sagittal) oriented to 6 cardinal directions (anterior, posterior, cranial, caudal, right and left) (Fig 4). In this system, any measurement of anteroposterior position (e.g., SNA, Ricketts' convexity) must be done on a sagittal or parasagittal plane. In traditional 2D cephalometrics, all points are projected on a film that is parallel to the sagittal plane and only (y, z) coordinates are calculated (Fig 4). Therefore, the direction of the measurements in anteroposterior position is always correct, even in the presence of facial asymmetry. However, the same is not true in 3D measurements, in which all (x, y, z) coordinates are calculated (Fig 4). In subjects with facial asymmetry, when one of the cephalometric points is displaced away from the midsagittal plane, the plane on which the measurement is taken becomes oblique to the sagittal plane. In this scenario, the direction of the measurement is no longer truly anteroposterior because an irrelevant "third" dimension, x coordinate (in transverse dimension), is also taken into the computation. Therefore, in regards to position measurements, it can be concluded that the measurements of projected 2D points on the sagittal plane are superior to direct 3D measurements.

Orientation Measurement

In the presence of facial asymmetry, the results of the orientation measurements demonstrated that both 2D and 3D measurements were distorted. The 2D measurements of orientation were distorted because in 2D the orientation of an object has a marked effect on the landmark positions.^{3, 4} Fig 5 illustrates this phenomenon. When the object is orthogonal to the film, the projected landmarks reflect the object. However, when the object is tilted (roll or yaw), the position of the projected landmarks changes, thus distorts the value of the measured angle.

The 3D measurements of orientation were also distorted in the models with roll or yaw asymmetries. This phenomenon can also be explained by the basic principles of 3D geometry. The orientation of an object is a description of how it is aligned to the space that it inhabits. Orientation is given relative to a frame of reference usually specified by a *Cartesian* coordinate system. The orientation of an object is established by giving the rotation that would move the object from its base or starting orientation to its current orientation. It can be described using 3 angles (pitch, roll, and yaw). Pitch refers to the rotation of the object around transverse axis (x); roll refers to the rotation of the object around the anteroposterior axis (y); and yaw refers to the rotation of the object around the vertical (z) axis. To measure these angles it is necessary to have 2 separate coordinate systems, one for the object (*local* coordinate system) and one for the space surrounding it (*world* coordinate system). The pitch, roll and yaw are the angles between the corresponding axes of the *world* and *local* coordinate systems (Fig 6).

The cephalometric measurements of orientation evaluated in this study (U1-L1, U1-FH and OP-FH) were designed to measure the pitch of specific facial elements on 2D cephalograms. Although not originally intended for this purpose, these measurements can also be used to measure the pitch of the different facial elements in 3D space, if the measured elements have zero roll or yaw. However, as demonstrated in this study, roll and yaw rotations may change the value of the 3D cephalometric angles even if the pitch of the object remains constant. In this scenario, the measured 3D angle is a composite of pitch, roll and yaw and no longer represents only pitch as originally intended. Regarding the measurements of orientation, it can be concluded that in the presence of facial asymmetry (abnormal roll or yaw), both 2D and direct 3D measurements are distorted. Although 2D measurements in the presence of asymmetry will always be distorted, it is possible to correctly measure orientation in 3D if pitch, roll and yaw are measured separately. This can be accomplished by calculating the angles between the *local* and the *world* coordinates of each element (Fig 6). The technique is presented in detail in the accompanying article of “3D cephalometry” by the same authors.²

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Fig 1.
The study design

Fig 2.
The surrounding box of an object and its local coordinate system

Figure 3a

Figure 3b

Fig 3.

In this example, we measure the Gonial Angle (shape) of a mandible with intrinsic symmetry. The *local* coordinate system of the mandible is shown as a surrounding box. The *local* midsagittal plane is in middle of the surrounding box. Although the mandible should be projected to both *local* and *world* midsagittal planes, for the purpose of demonstration, the 2D projection on the *local* midsagittal plane is moved to the right side of the surrounding box, while the 2D projection on the *world* midsagittal plane is moved to the left side of the *world* coordinate system.

A) When both yaw and roll of the mandible are 0°, the *local* coordinate system of the mandible is completely parallel to the *world* coordinate system. Therefore, the 2D projection of the mandible on the *local* midsagittal plane (red) is the same as the one on the *world* midsagittal plane (blue). Both projected Gonial Angles are measured at 127°.

B) When we rotate the mandible to produce 20° of yaw while the roll remains at 0°, the *local* coordinate system is no longer parallel to the *world* coordinate system. The Gonial Angle projected on the *local* midsagittal plane remains the same at 127° (red) because its *local* coordinate system is rotated together with the mandible. However, the Gonial Angle projected on the *world* midsagittal plane is distorted and increased to 130° (blue).

Fig 4.
The model was oriented in the cardinal direction of the face (anterior, posterior, head, foot, right and left).

Fig 5.

The presence of facial asymmetry could affect both 2D and 3D measurements. In this example, when the upper and lower incisors were orthogonal to the film, the projected landmarks reflect the objects. The interincisal angle was measured at 137°. However, when both incisors were tilted 20° in roll without changing their relative position and orientation, the position of the projected landmarks still changed. The interincisor angle was measured at 133°.

Fig 6.
The pitch, roll and yaw are the angles between corresponding axes of the *world* and *local* coordinate systems.

Table 1

Selected cephalometric landmarks

Landmark	Abbreviation
Skull Base	
Sella	S
Nasion	N
Right Orbitale	Or-R
Left Orbitale	Or-L
Right Porion	Po-R
Left Porion	Po-L
Maxilla	
Anterior Nasal Spine	ANS
Posterior Nasal Spine	PNS
Point A	A
Apex of the maxillary right central incisor	U1A-R
Apex of the maxillary left central incisor	U1A-L
Incisal edge of the maxillary right central incisor	U1-R
Incisal edge of the maxillary left central incisor	U1-L
Mesiobuccal cusp of the right first molar	U6-R
Mesiobuccal cusp of the left first molar	U6-L
Mandible	
Apex of the mandibular right central incisor	L1A-R
Apex of the mandibular left central incisor	L1A-L
Incisal edge of the mandibular right central incisor	L1-R
Incisal edge of the mandibular left central incisor	L1-L
Mesiobuccal cusp of the mandibular right first molar	L6-R
Mesiobuccal cusp of the mandibular left first molar	L6-L
Pogonion	Pg
Menton	Me
Condylion, right	Co-R
Condylion, left	Co-L
Gonion, right	Go-R
Gonion, left	Go-L

Table 2

Selected cephalometric lines and planes

Measurements	Landmarks
Lines	
Sella-Nasion	S, N
Nasion-A	N, A
Facial line	N, Pg
Upper Incisor	Average(U1-R, U1-L), Average(U1A-R, U1A-L)
Lower Incisor	Average(L1-R, L1-L), Average(L1A-R, L1A-L)
Co-Go	Average (Co-R, Co-L), Average (Go-R, Go-L)
Go-Me	Average (Go-R, Go-L), Me
Planes	
Frankfort Horizontal	Po-R, Po-L, Average (Or-R, Or-L)
Maxillary Occlusal Plane	U6-R, U6-L, Average(U1-R, U1-L)
Mandibular Occlusal Plane	L6-R, L6-L, Average (L1-R, L1-L)
Mandibular Plane	Go-R, Go-L, Me

Table 3

Seven selected different cephalometric measurements for testing

Geometric Parameter	Cephalometric Measurement	Type of measurement
Shape	Gonial angle (Co-Go-Me)	Line-line angle
Size	ANS-PNS	Linear distance
Position	SNA	Line-line angle
	Ricketts' convexity	Linear distance
Orientation	Interincisal angle (U1-L1)	Line-line angle
	U1 to FH	Line-plane angle
	Occlusal plane to FH (OP-FH)	Plane-plane angle

Table 4

Results: Differences between the control and the experimental groups

SHAPE	Gonial angle	Control		Roll 10°	Roll 5°	Yaw 5°	Yaw 10°
		124°	2D	-0.5	-0.47	-0.46	-0.44
		3D	0	0	0	0

SIZE	ANS-PNS	Control		Roll 10°	Roll 5°	Yaw 5°	Yaw 10°
		50mm	2D	0	0	-0.18	-0.74
		3D	0	0	0	0	

			Transverse translation		
POSITION	SNA	Control		5 mm	10mm
		82°	2D	0	0
		3D	0.03	0.13	
	Ricketts' convexity	2mm	2D	0	0
		3D	3.39	8.2

ORIENTATION	U1-L1	Control		Roll 10°	Roll 5°	Yaw 5°	Yaw 10°
		130°	2D	-0.28	-0.07	0.07	0.29
	3D	-0.89	-0.27	0.04	0.17		
	U1-FH	114°	2D	0.23	0.06	-0.06	-0.23
		3D	1.96	0.5	-0.05	-0.08	
	OP-FH	7°	2D	-0.26	-0.07	0.22	0.5
3D		5.02	1.57	0.24	0.34		