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Relationship of maxillary 3-dimensional posterior occlusal plane to mandibular spatial position and morphology

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Introduction: The purpose of this study was to examine the relationship of the 3-dimensional (3D) posterior occlusal plane (POP) and the mandibular 3D spatial position. The relationship of the POP to mandibular morphology was also investigated. **Methods:** Retrospective data from a convenience sample of pretreatment diagnostic cone-beam computed tomography scans were rendered using InVivo software (Anatomage, San Jose, Calif). The sample consisted of 111 subjects (51 male, 60 female) and included growing and nongrowing subjects of different races and ethnicities. The 3D maxillary POP was defined by selecting the cusp tips of the second premolars and the second molars on the rendered images of the subjects. The angles made by this plane, in reference to the Frankfort horizontal plane, were measured against variables that described the mandibular position in the coronal, sagittal, and axial views. The POP was also compared with bilateral variables that described mandibular morphology. **Results:** There were significant differences of the POP among the different skeletal malocclusions ($P < 0.0001$). The POP showed significant correlations with mandibular position in the sagittal ($P < 0.0001$), coronal ($P < 0.05$), and axial ($P < 0.05$) planes. The POP also showed a significant correlation with mandibular morphology ($P < 0.0001$). **Conclusions:** These findings suggest that there is a distinct and significant relationship between the 3D POP and the mandibular spatial position and its morphology. (Am J Orthod Dentofacial Orthop 2016;150:140-52)

Early in the history of our specialty, both clinicians and researchers were aware of the relevance of the occlusal plane in the diagnosis and treatment of malocclusions. References to the occlusal plane can be found throughout the orthodontic literature. In 1947, Björk[1] mentioned in his textbook that the steepness of the occlusal plane diminishes with prognathism. Bushra[2] stated that the flatter the occlusal plane, "the more forward the face." Downs,[3] in 1948, noted that Class II malocclusions tend to have steeper occlusal planes, and Class III malocclusions have flatter occlusal planes. Riedel[4] observed an apparent perpendicular relationship between the occlusal plane and the A-B plane in normal occlusions. Schudy,[5] in 1963, mentioned the relationship of the occlusal plane to function and its significance in treatment. Several authors stated that Tweed obtained more favorable profiles because of his control of the occlusal plane by minimizing the untoward effects of Class II mechanics with his anchorage preparation.[6-8]

The relationship of the occlusal plane to mandibular position continued to be observed as numerous studies, starting in the 1970s, began to show that during normal dentofacial development, both the occlusal plane and the mandibular plane flattened as the mandible rotated forward with growth.[9-11] Sato et al[12] demonstrated that the occlusal plane flattened excessively in growing patients with skeletal Class III malocclusions.

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Traditionally, the occlusal plane was defined as a line from the incisors to the first molars. In a 1996 study, the authors proposed an alternative way to describe the curvature of the occlusal plane.[13] They divided it into anterior and posterior components, with the anterior occlusal plane defined as a line drawn from the incisal edge of the maxillary central incisor to the cusp tip of the mandibular second premolar, and the posterior occlusal plane (POP) as a line from the cusp tip of the mandibular second premolar to the midpoint of the mandibular second molar at the occlusal surface.

These investigations have shown that the 2-dimensional (2D) POP correlates with anteroposterior mandibular position and predicts both Class II and Class III malocclusions.[12,13] More recently, Tanaka and Sato[14] conducted a longitudinal study using data from the Burlington Growth Center on white subjects and concluded that during normal Class I growth, the 2D POP flattens with age along with a concomitant decrease in the mandibular plane angle, as well as an increase in forward mandibular position. These findings are similar to previous studies with Japanese and African American samples.[9-11] The occlusal plane has also been implicated in the different mandibular morphologies of high-angle Class II malocclusions compared with normal Class I and low-angle Class II malocclusions.[15] A recent study with 3-dimensional (3D) cone-beam computed tomography (CBCT) data also found significant differences in the POP between Class II and Class III subjects.[16]

From the coronal perspective, the cant of the POP has shown a distinct and significant relationship with a deviation of the chin from the midline and the mandibular lateral deviation.[17-19] Researchers have found that the most common trait in facial asymmetries is a mandibular midline deviation.[20,21] Most studies on mandibular lateral deviation have been conducted using posteroanterior cephalograms, which are reliable in evaluating asymmetries but have inherent inaccuracies because of difficulties in identifying anatomic structures, projection errors, and lack of reproducibility.[22] There are also limitations to conventional 2D lateral cephalograms such as superimposition of bilateral structures and the inherent distortion of the radiograph.[23] To improve on these limitations, CBCT can be used to more accurately analyze and study the 3D relationships of the various craniofacial structures.[24,25] CBCT scans are on a 1:1 scale; therefore, there are no distortions associated with the data, and anatomic landmarks can more accurately be identified 3 dimensionally; this then provides the ability to select and measure bilateral structures with greater precision.[26]

The purpose of this study was to examine the relationship of the 3D POP to mandibular spatial positioning as well as its morphology using CBCT data.

Table I. Criteria for each class type

Class type	*APDI*	*FMA (°)*
Class I	78-82	
Class II, high angle	<78	>25
Class II, low angle	<78	<25
Class III, high angle	>83	>25
Class III, low angle	>83	<25

APDI, Anteroposterior dysplasia indicator; *FMA*, Frankfort-mandibular plane angle.

MATERIAL AND METHODS

Three-dimensional data were obtained from CBCT scans taken of patients at the principal investigator's private orthodontic practice (J.C.C.) as part of their pretreatment diagnostic records. The retrospective convenience sample consisted of 111 subjects (51 male, 60 female) and included growing and nongrowing subjects of different ethnicities. The selection criteria for the sample were patients (1) who signed the consent to use records section in the Informed Consent Form provided by the American Association of Orthodontists, (2) with fully erupted permanent dentition including maxillary second molars, (3) without syndromes or craniofacial anomalies, and (4) with no previous orthodontic treatment.

The sample was divided into Class I, Class II, and Class III based on the anteroposterior dysplasia indicator developed by Kim.[27] The anteroposterior dysplasia indicator was selected over the more commonly used ANB angle because it considers both dentoalveolar and skeletal relationships that cannot be described by 1 measurement. The anteroposterior dysplasia indicator has been shown to have more diagnostic significance when comparing anteroposterior discrepancies.[28] To take the vertical dimension into consideration, the Class II and Class III samples were further divided into high-angle and low-angle classifications based on the Frankfort horizontal plane to mandibular plane angle (Table I). Age and sex characteristics of the 5 groups were as follows: Class I (13 female, 10 male; mean age, 16.6 years; range, 11-41 years), high-angle Class II (14 female, 0 male; mean age, 17.2 years; range, 11-45 years), low-angle Class II (12 female, 14 male; mean age, 14.8 years; range, 11-39 years), high-angle Class III (11 female, 13 male; mean age, 20.5 years; range, 9-39 years), and low-angle Class III (10 female, 14 male; mean age, 20.7 years; range, 11-53 years).

The DICOM data were obtained using a Kodak 9500 Cone Beam 3D System (90 kW, full field of view: 200 × 184 mm, 0.3-mm voxel resolution, and 2-15 mA; Kodak, Rochester, NY) and was imported

Table II. Landmarks

Landmark	*Abbreviation*	*Definition*
Nasion	N	Midpoint of the frontonasal suture
Right orbitale	Or R	Most inferior point on the right infraorbital rim of the maxilla
Left orbitale	Or L	Lowest point on the left infraorbital rim of the maxilla
Medial orbitale	Med Or	Computer-generated medial (mean) point between the right and left orbitales
Right porion	Po R	Highest point on the upper margin of the right external auditory meatus
Left porion	Po L	Highest point on the upper margin of the left external auditory meatus
Sella turcica	S	Midpoint of the pituitary fossa
Basion	Ba	Midpoint of the anterior-inferior border of foramen magnum
Anterior nasal spine	ANS	Most anterior midpoint of the anterior nasal spine
Posterior nasal spine	PNS	Most posterior midpoint of the posterior nasal spine
A-point	A	Midpoint of the anterior limits of the apical base of the maxilla
Right condylion	Co R	Uppermost midpoint of the right condyle
Left condylion	Co L	Uppermost midpoint of the left condyle
Right gonion	Go R	Most lateral point on the right mandibular angle close to the bony gonion
Left gonion	Go L	Most lateral point on the left mandibular angle close to the bony gonion
Medial gonion	Med Go	Computer-generated medial (mean) point between the right and left gonions
Menton	Me	Midpoint of the lowest point on the mandibular symphysis
B-point	B	Midpoint of the anterior limits of the apical base of the mandible
Suprapogonion	PM	Midpoint of protuberance menti
Pogonion	Pog	Midpoint of the most anterior point of the mandibular symphysis
Right Xi point	Xi R	Point located on the geometric center of the right mandibular ramus
Left Xi point	Xi L	Point located on the geometric center of the left mandibular ramus
Medial Xi point	Med Xi	Computer-generated medial (mean) point between the right and left Xi points
U1 root tip	U1 root R	Maxillary right central incisor root tip
U1 incisal edge	U1 crown R	Midpoint on the incisal edge of the maxillary right central incisor
L1 root tip	L1 root R	Mandibular right central incisor root tip
L1 incisal edge	L1 crown R	Midpoint on the incisal edge of the mandibular right central incisor
Upper incisor point	U1	Most mesial and incisal point of the maxillary left central incisor
U5 cusp tip	U5 R	Buccal cusp tip of the maxillary right second premolar
U7 cusp tip	U7 R	Distobuccal cusp tip of the maxillary right second molar
U5 cusp tip	U5 L	Buccal cusp tip of the maxillary left second premolar
U7 cusp tip	U7 L	Distobuccal cusp tip of the maxillary left second molar
Medial U5	Med U5	Computer-generated medial (mean) point between the right and left maxillary second premolar buccal cusp tips

into and rendered with InVivo software (version 5.3.1; Anatomage, San Jose, Calif) to create a 3D image of the patient. The CBCT scans were taken with the patients standing up, with their heads positioned in Frankfort horizontal plane. The use of a custom-made cephalostat ensured that the interporion line was oriented parallel to the floor. This provided a standardized method for stabilizing the patient and diminished the need to reorient the scans in the software later.

All subjects were anonymized, and all patient identifiers were deleted. New InVivo files were created for each subject and assigned an identification number. The corresponding chronologic age and sex were recorded. Therefore, the retrospective research data did not contain any identifiable protected health information. The institutional review board of the University of Florida Health Center approved the research protocol.

Using the InVivo software, a 3D denture frame cephalometric analysis was developed with 33 landmarks (Table II).[29] These landmarks were selected on the reconstructed 3D volume and then refined in the axial, coronal, and sagittal slices using the slice locator feature in the software. Landmarks were selected using an optical mouse on a 27-in iMac computer (Apple, Cupertino, Calif). Since the InVivo program was not yet available for Macintosh software, Boot Camp, a multiboot utility included in the Apple Operating System, version OS X 10.9, assisted in installing a 64-bit version of the Windows 7 operating system (Microsoft, Redmond, Wash). An operator (J.C.C.), who was previously calibrated, selected the anatomic landmarks and performed the cephalometric analysis.

A coordinate system was defined using a plane parallel to the Frankfort horizontal but going through sella as the horizontal reference plane. Since 3 points define 3D planes, a computer-generated medial point (mean) between the right and left orbitales was created. The right and left porions completed the definition of the Frankfort horizontal plane. Authors of a recent study found that there tends to be less variation in natural head

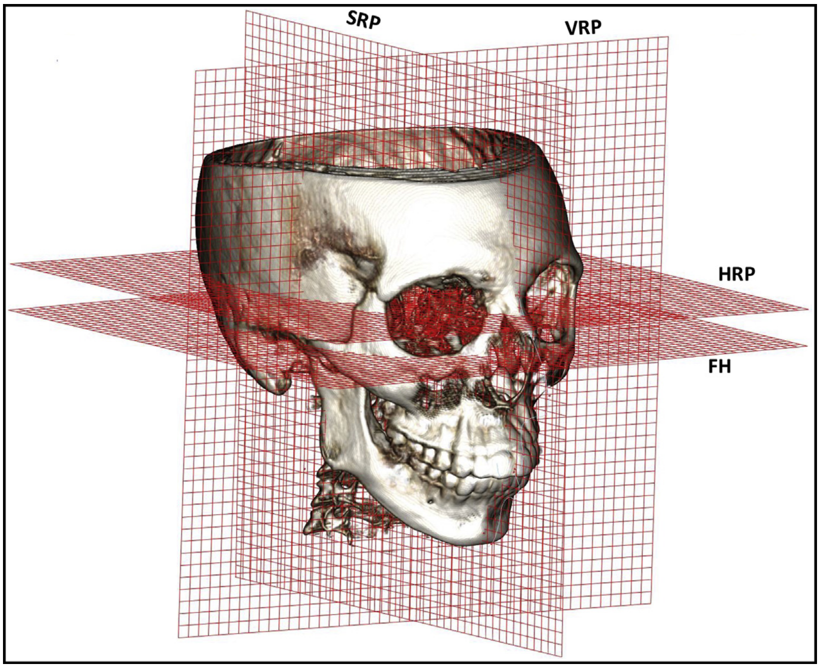

Fig 1. Three points define the Frankfort horizontal (*FH*) plane, the right and left porions and a computer-generated medial (mean) point between the right and left orbitales. The horizontal reference plane (*HRP*) is parallel to the Frankfort horizontal plane but goes through sella. The sagittal reference plane (*SRP*) is perpendicular to the horizontal reference plane passing through sella and nasion. The vertical reference plane (*VRP*) is perpendicular to both the horizontal reference plane and the sagittal reference plane passing through sella.

posture in the coronal axis,[30] possibly because the temporal bones house the organs of equilibrium, which impart the sensory input for the spatial orientation of the head.[31] This makes the Frankfort horizontal plane a logical starting reference plane on the coronal axis. The sagittal reference plane is defined as a plane perpendicular to the horizontal reference plane passing through sella and nasion. The vertical reference plane is perpendicular to both the horizontal reference plane and the sagittal reference plane passing through sella (Fig 1). The analysis consisted of 20 angular and 6 linear measurements (Tables III and IV, respectively).

To define the 3D curved surface orientation of the maxillary occlusal plane, it was divided into anterior and posterior occlusal planes as described by Okuhashi et al.[16] Occlusal landmarks were selected on the maxillary arch of the rendered 3D image as shown in Figure 2. The POP was defined by 3 points. The first point was a computer-generated medial (mean) point between the right and left second premolar buccal cusp tips. The other 2 points were the distobuccal cusp tips of the second molars. To measure its effect on the right and left sagittal views, 2 lines were created from the medial point between the right and left second premolar buccal cusp tips to the distobuccal cusp tips of the second molars. These were defined as POP right and POP left. To measure this plane's effect in the coronal and axial views, a third line was constructed from the distobuccal cusp tips of the second molars and named the POP cant (Figs 2 and 3). This 3D definition of the POP measured against the Frankfort horizontal plane was then used to analyze its relationship to mandibular position and morphology (Figs 2 and 3).

To determine the spatial position of the mandible in the coordinate system, several variables were selected or created. The variables describing the mandibular anteroposterior, vertical, and transverse dimensions are listed in Table V. The anteroposterior and vertical variables were borrowed from conventional 2D analyses and projected onto the sagittal and vertical reference planes accordingly.

The mandibular lateral deviation was defined as the angle made by a line from anterior nasal spine to menton and the midsagittal plane projected onto the vertical reference plane (Table III). The midsagittal plane was defined by basion, nasion, and anterior nasal spine. A

Table III. Angular measurements

Angular measurement	*Abbreviation*	*Definition*
Facial plane	FP	Na-Pog line and Frankfort horizontal (FH) plane
Line from A-point to B-point to mandibular plane	AB-MP	A-B line and Me-Med Go line
Sella to nasion to A-point angle	SNA	S-N line and Na-A point line
Sella to nasion to B-point angle	SNB	S-N line and N-B point line
A-point to nasion to B-point angle	ANB	N-A line and Na-B-point line
Anteroposterior dysplasia indicator	APDI	FP angle ± AB plane angle ± FH-PP
Mandibular lateral deviation	MLD	ANS-Me line and Ba-N-ANS plane
Frankfort horizontal to the mandibular plane angle	FMA	Me-Med Go line and FH plane
Gonial angle right	Go R	3D angle made by the right Co-right Go line and right Go-Me line*
Gonial angle left	Go L	3D angle made by the left Co-left Go line and left Go-Me line*
Condylar axis right	Co axis R	3D angle made by the right Co-Xi point line and right Xi point- Me line*
Condylar axis left	Co axis L	3D angle made by the left Co-Xi point line and left Xi point-Me line*
Palatal plane to Frankfort horizontal	PP-FH	ANS-PNS line and FH plane
Lower facial height	LFHt	ANS-Med Xi point and Med Xi point-PM line
Palatal plane to mandibular plane	PP-MP	ANS-PNS line and FMA line
Right posterior occlusal plane to Frankfort horizontal	POP_R	3D angle made by the line formed by the points Med U5 point-U7 cusp tip _R line and FH plane*
Left posterior occlusal plane to Frankfort horizontal	POP_L	3D angle made by the line formed by the points Med U5 point-U7 cusp tip_L line and FH plane*
Posterior occlusal plane cant	POP cant	3D angle made by the line formed by the points U7 cusp tip _R –U7 cusp tip _L line and FH plane†
Condylar cant	Co cant	3D angle made by the Co_R-Co_L line and FH plane†
Gonial cant	Go cant	3D angle made by the Go_R-Go_L line and FH plane†

*Projected onto the sagittal reference plane; †projected onto the vertical reference plane.

positive mandibular lateral deviation value indicated that menton was to the right of the midsagittal plane, and a negative value meant that it was to the left.

"Cant" is used to describe the lines or planes that are measured on the coronal view. To describe the angular position of the mandible from this perspective, gonial and condylar cants were defined as the intercondylar and intergonial lines in reference to the Frankfort horizontal plane. A negative value indicated that these lines were angled down on the patient's right side, and a positive value indicated that the lines were angled down on the patient's left side.

From the axial perspective, the condylar deviation measures the anteroposterior position of the right vs the left condylions in relation to the vertical reference plane. A negative value indicated that the right condylion was in front of the left condylion. Conversely, a positive value indicated that the left condylion was in front of the right condylion. The gonial deviation measures the anteroposterior position of the right vs the left gonions. A negative value indicated that the right condylion was in front of the left condylion, and a positive value indicated that the left condylion was in front of the right condylion.

Mandibular morphology was defined by 8 measurements: right and left ramal heights, right and left mandibular lengths, right and left condylar axes, and right and left gonial angles.

Statistical analysis

For this analysis, adequate power was required to detect correlations (overall and within malocclusion groups) and also to assess differences between malocclusion groups. Overall, by using a 2-sided test, with a significance level of 0.05, our sample size of 111 allowed sufficient power (0.80 or greater) to detect correlations of 0.27 or greater. With a more stringent level of significance of 0.001, correlations of 0.38 or greater can be detected with 0.80 or greater power. This magnitude of correlation would be of clinical interest. As expected, subgroup analysis has reduced power, with the ability to detect correlations in the range of 0.53 to 0.68 (level of significance, 0.05; power, 0.80; sample size, 14-26). Using a general framework for a 5-group analysis of variance, with the level of significance at 0.05, if the means are evenly spaced, we have greater than 0.80 power to detect a difference of 1 SD between the largest and smallest means. If the means are not evenly spaced, the power would be increased.

The operator (J.C.C.) was calibrated as follows. Two reliability assessments were conducted, each with

Table IV. Linear measurements

Linear measurement	Abbreviation	Definition
Mandibular length right	MdL_R	Distance between Go_R and Me*
Mandibular length left	MdL_L	Distance between Go_L and Me*
Ramus height right	RamHt_R	Distance between Co_R and Go_R*
Ramus height left	RamHt_L	Distance between Co_L and Go_L*
Condylar deviation	Co dev	Distance between the anteroposterior position of the right (−) vs the left (+) condylions, measured perpendicular to the vertical reference plane†
Gonial deviation	Go dev	Distance between the anteroposterior position of the right (−) vs the left (+) gonions, measured perpendicular to the vertical reference plane†

*Projected onto the sagittal reference plane; †projected onto the horizontal reference plane.

measurements of 10 subjects taken 2 weeks apart. After the first assessment, discrepancies were examined to refine the measurements. The second reliability assessment was then conducted. Mean differences between the paired measurements and absolute differences were used to assess bias and precision. Reliability coefficients based on the variability between subjects and the variability within subjects were calculated, and variables with a reliability coefficient less than 0.85 at the second calibration were discarded.[32]

Summary statistics and graphic methods were used to characterize the data. One-way analysis of variance was used to test for differences in mean values between occlusal plane groups. Correlations between POP characteristics and other variables were estimated with Pearson correlation coefficients. A P value less than 0.05 was considered statistically significant; however, emphasis was placed on P values less than 0.001 because of the number of comparisons performed. Analyses were performed using 2 statistical packages (version 9.4; SAS Institute, Cary, NC; and R version 2.15; R Foundation for Statistical Computing, Vienna, Austria).

RESULTS

Forty-seven variables were considered for inclusion in this analysis. Because of low intrarater reliability (0.62), 1 variable was discarded. Three variables with reliability estimates between 0.85 and 0.94 were reviewed to assess discrepancies. Of the remaining 43 variables with reliability estimates of greater than 0.94, 81% had reliability estimates greater than 0.98, indicating excellent reproducibility.

The inferential statistics showed significant differences in all parameters that were used to define the anteroposterior and vertical mandibular positions in the different class types (Table V). The right and left POPs differed among the groups (P <0.0001). Pearson correlation coefficients between occlusal plane variables and other craniofacial parameters of the total sample are shown in Tables VI through IX.

On the sagittal plane, anteroposterior dysplasia indicator, facial plane, and SNB, all measurement variables that define mandibular anteroposterior position, were negatively correlated (range, −0.4 to −0.6) to the POP, whereas ANB showed a positive correlation (0.5) to the POP (Table VI). The SNA angle did not show any correlation with the POP variables and was not significantly different among the different classifications of the 5 groups in the sample. The parameters that described the vertical dimension (FMA, PP-MP, and LFHt) all had positive correlations (range, 0.2-0.5) with steepness of the POP (Table VII).

On the coronal plane, the measurements that describe the mandibular lateral deviation showed no significant differences among the different classifications. The direction of the mandibular lateral deviation and gonial cant showed consistent positive (0.3) and negative (−0.2) correlations with the right and left POPs. The condylar cant did not show any correlation with either mandibular lateral deviation or POP (Table VIII). On the axial plane, neither the condylar deviation nor the gonial deviation correlated with the mandibular lateral deviation.

The variables used to describe bilateral mandibular morphology, mandibular corpus lengths, ramal heights, and corpus axes all showed negative correlations with POP (−0.3 to −0.5) (Table IX). The gonial angle did not show a sufficient correlation (0.1 to 0.2) (Table IX).

DISCUSSION

The results of this study suggest that the steeper the right and left POPs, the more retrognathic and hyperdivergent the mandibular posture on the corresponding side, and the flatter the POP, the more prognathic and hypodivergent (Tables VI and VII; Figs 4 and 5 see Video 1, available at www.ajodo.org).

From the coronal view, the direction of mandibular lateral deviation was consistent with the steepness of

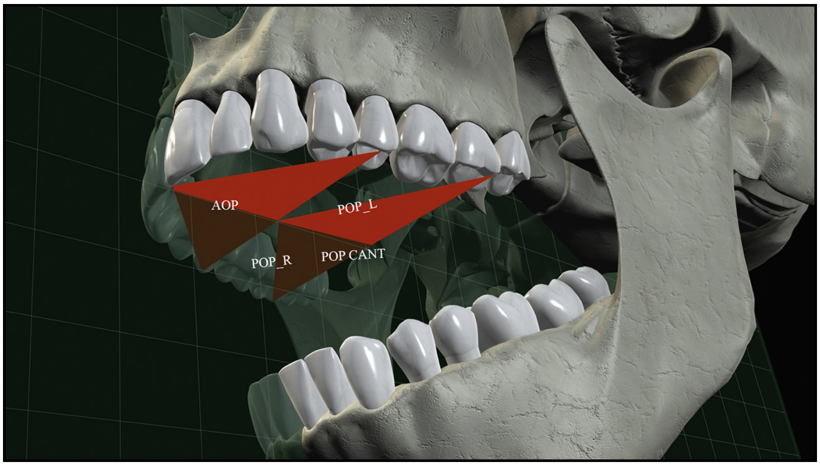

Fig 2. The POP is defined by 3 lines. The right and left POPs were created from a computer-generated medial (mean) point between the right and left second premolar buccal cusp tip to the distobuccal cusp tips of the right and left maxillary second molars. The third line of this plane was made from distobuccal cusp tips of the right and left second molars and named the *POP cant*. *AOP*, Anterior occlusal plane.

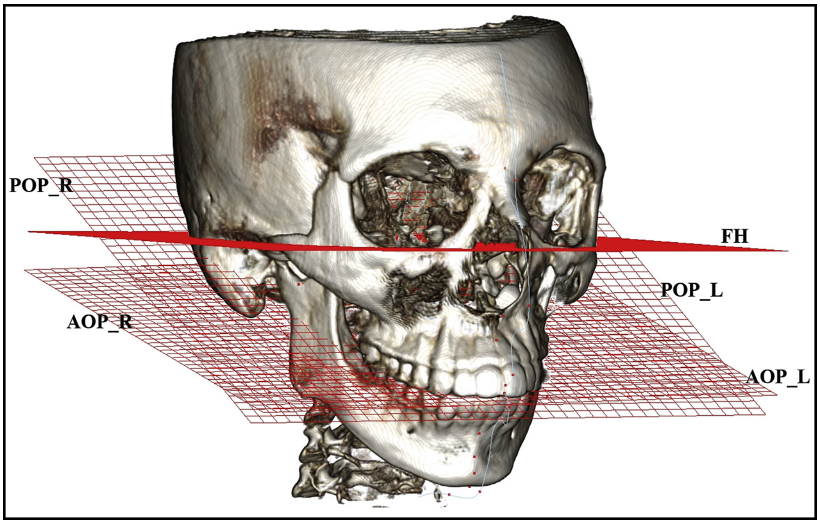

Fig 3. Depiction of the right and left POPs. Note the steep POP of the Class II skeletal morphology. *AOP_R*, Right anterior occlusal plane; *AOP_L*, left anterior occlusal plane.

the POP on the same side, suggesting that the mandible may adapt to the side with a smaller vertical dimension (Fig 6; see Video 2, available at www.ajodo.org).

The right and left POPs also relate to mandibular morphology. On the side of the steeper POP, both ramal height and corpus length were smaller, with a more hyperdivergent contour. In contrast, the side with the flatter occlusal plane exhibited larger ramal heights and corpus lengths and a more hypodivergent contour.

The 3D cephalometric analysis used in this study was developed to take advantage of the ability to accurately select the anatomic landmarks on the rendered 3D models of the subjects. This provides spatial position without superimposition of other structures and the inherent distortion seen with 2D films.[26,33] Although most of the measurements were similar to those used in conventional analyses and were projected onto their respective reference planes as 2D measurements, they served to describe the bilateral aspects of craniofacial morphology.

Rendered images from CBCT scans allowed us to visualize and quantify the occlusal planes in 3 dimensions. With this ability to measure and compare

Table V. Descriptive and inferential statistics (°)

Variable	*Class I Mean ± SD (n = 23)*	*HA Class II Mean ± SD (n = 14)*	*LA Class II Mean ± SD (n = 26)*	*HA Class III Mean ± SD (n = 24)*	*LA Class III Mean ± SD (n = 24)*	*Shapiro-Wilk P value*	*ANOVA P value*
Age (y)	16.5 ± 6.9	17.2 ± 9.3	14.8 ± 5.1	20.5 ± 11.3	20.7 ± 7.0	0.7	0.053
Anteroposterior							
Facial plane	89.9 ± 2.0	85.3 ± 2.3	87.1 ± 2.5	92.6 ± 3.2	96.5 ± 3.2	0.1	<0.0001
APDI	80.6 ± 1.6	74.3 ± 2.7	74.0 ± 2.4	93.9 ± 7.5	99.2 ± 5.9	0.1	<0.0001
SNA	82.9 ± 2.0	82.6 ± 2.9	81.9 ± 3.5	81.6 ± 3.9	82.9 ± 3.1	0.9	0.481
SNB	79.3 ± 1.9	76.2 ± 2.1	76.5 ± 2.8	82.7 ± 4.0	85.7 ± 3.8	0.9	<0.0001
ANB*	3.6 ± 1.1	6.4 ± 1.1	5.4 ± 1.5	−1.2 ± 2.5	−2.7 ± 2.2	0.9	<0.0001
Vertical							
FMA	22.4 ± 5.3	31.9 ± 4.9	20.1 ± 4.0	29.7 ± 5.0	19.8 ± 3.1	0.1	<0.0001
PP-MP	24.3 ± 5.3	32.0 ± 4.9	22.5 ± 3.6	29.3 ± 4.9	20.6 ± 4.1	1.0	<0.0001
AB-MP	74.5 ± 5.2	73.3 ± 4.5	82.5 ± 2.9	56.5 ± 6.9	59.9 ± 5.3	0.1	<0.0001
LFHt	42.9 ± 4.5	47.2 ± 4.3	40.8 ± 3.8	48.5 ± 4.6	40.8 ± 3.9	0.1	<0.0001
Transverse							
MLD	−0.1 ± 3.6	−0.5 ± 2.1	−0.8 ± 3.1	−0.1 ± 2.9	−0.4 ± 3.8	0.1	0.63
Co cant	1.6 ± 1.4	0.3 ± 1.5	0.3 ± 1.7	0.3 ± 1.6	0.6 ± 1.9	0.4	0.05
Go cant	1.6 ± 1.9	0.5 ± 2.0	0.2 ± 2.1	0.4 ± 2.1	0.2 ± 1.8	0.3	0.06
Co dev	0.3 ± 2.7	0.2 ± 2.2	0.6 ± 2.0	−0.4 ± 5.8	1.3 ± 2.4	0.1	0.56
POP_L*	14.3 ± 5.3	19.9 ± 5.3	15.8 ± 5.6	13.2 ± 6.0	9.9 ± 4.2	0.8	<0.0001
POP_R*	17.3 ± 5.1	20.6 ± 3.4	15.6 ± 4.7	14.6 ± 6.2	9.6 ± 5.6	0.2	<0.0001
POP cant	0.3 ± 1.8	0.3 ± 1.7	0.1 ± 1.5	0.0 ± 2.0	−0.3 ± 2.6	0.5	0.62

HA, High angle; *LA*, low angle; *ANOVA*, analysis of variance; *FMA*, Frankfort-mandibular plane angle.
*One-way analysis of variance (ANOVA) was used to test for differences in mean values between occlusal plane groups. A *P* value less than 0.05 was considered statistically significant.

Table VI. Anteroposterior correlations and *P* values* (°)

	POP_L	*POP_R*	*POP cant*
FP	−0.57195	−0.62448	−0.24476
	<0.0001	<0.0001	0.0096
ANB	0.52723	0.51192	0.15580
	<0.0001	<0.0001	0.1025
APDI	−0.43372	−0.44199	−0.16895
	<0.0001	<0.0001	0.0763
SNB	−0.40642	−0.44387	−0.16140
	<0.0001	<0.0001	0.0906

*Pearson correlation coefficients. A *P* value less than 0.05 was considered statistically significant; however, emphasis was placed on *P* values less than 0.001 because of the number of comparisons performed.

Table VII. Vertical correlations and *P* values* (°)

	POP_L	*POP_R*	*POP cant*
FMA	0.41326	0.50935	0.10044
	<0.0001	<0.0001	0.2942
PPMP	0.33591	0.42957	0.10376
	0.0003	<0.0001	0.2785
LFHt	0.22131	0.30095	0.05586
	0.0196	0.0013	0.5604

*Pearson correlation coefficients. A *P* value less than 0.05 was considered statistically significant; however, emphasis was placed on *P* values less than 0.001 because of the number of comparisons performed.

the right and left POP as well as the POP cant to the coronal, sagittal, and axial mandibular position, a more comprehensive understanding of their 3D relationship is possible. As this technology becomes more accepted, new comprehensive 3D cephalometric analyses need to be developed with more sophisticated algorithms that take into account the yaw, pitch, and roll aspects of mandibular spatial position.

There are other limitations to this investigation. This was a cross-sectional study, and the correlations do not imply causation or, in this case, etiology, although they are useful for suggesting possible mechanisms. A longitudinal study would be needed to definitively examine this question. There are also drawbacks to a heterogeneous sample, with variabilities in sex, race, ethnicity, and age. Previous studies have shown that the mandible has a similar relationship to the POP in different ethnic groups[9-11,14]; thus, we did not think that this would detract from the study. In addition, data on race and ethnicity are not kept at the private practice where the records were obtained. The goal was to examine the underlying process, and variations in demographic

Table VIII. Transverse correlations and *P* values*

	POP_L	*POP_R*	*POP cant*
MLD (°)	−0.20236	0.29781	0.45235
	0.0332	0.0015	<0.0001
Co cant (°)	−0.24139	0.01827	−0.15518
	0.0107	0.849	0.1039
Go cant (°)	−0.26607	0.19682	0.13607
	0.0048	0.0384	0.1545
Co dev (mm)	0.01629	0.05022	0.02918
	0.8653	0.6006	0.7611
Go dev (mm)	−0.161	0.004	0.127
	0.092	0.996	0.182

*Pearson correlation coefficients. A *P* value less than 0.05 was considered statistically significant; however, emphasis was placed on *P* values less than 0.001 because of the number of comparisons performed.

Table IX. Correlations of mandibular morphology and *P* values*

	POP_L	*POP_R*	*POP cant*
MdL_L (mm)	−0.45785	−0.52125	−0.27044
	<0.0001	<0.0001	0.0041
MdL_R (mm)	−0.54431	−0.51861	−0.19050
	<0.0001	<0.0001	0.0452
RamHt_L (mm)	−0.54846	−0.43798	−0.03676
	<0.0001	<0.0001	0.7017
RamHt_R (mm)	−0.47066	−0.49193	−0.17375
	<0.0001	<0.0001	0.0682
Go R (°)	0.16318	0.24766	0.06897
	0.0870	0.0088	0.4720
Go L (°)	0.13168	0.19289	0.02556
	0.1683	0.0425	0.7900
Co axis R (°)	−0.38913	−0.47697	−0.12870
	<0.0001	<0.0001	0.1782
Co Axis L (°)	−0.33528	−0.41031	−0.08514
	0.0003	<0.0001	0.3743

*Pearson correlation coefficients. A *P* value less than 0.05 was considered statistically significant; however, emphasis was placed on *P* values less than 0.001 because of the number of comparisons performed.

characteristics could attenuate the detection of significant correlations and differences between the malocclusion groups.

The POP has been implicated in the development of Class II,[15] Class III,[12,34] and mandibular lateral deviation[18,19] malocclusions in 2D investigations. Authors of a recent study using 3D CBCT data also found significant differences in the POPs between the Class II and Class III subjects but did not investigate the vertical or transverse dimensions.[16] The results of our 3D study are similar to the findings of these previous investigations but, more importantly, attempt to describe the relationship of the different 3D configurations of the POP to mandibular spatial position and its morphology.

Previous studies have also suggested that structural adaptation appears to occur in response to the functional compensation of mandibular posture.[35-37] We observed similar findings: the POP correlated negatively with the skeletal parameters that describe mandibular morphology and may indicate its possible functional influence (Table IX).

A more accurate functional representation of the POP would have been to use the passive centric stops of the maxillary second premolars and second molars as described by Costa et al.[38] They used dry skulls that were scanned without the mandible. This approach proved to be unfeasible in our study because of the inaccuracy and lack of reproducibility in our sample of patients, who were scanned in maximum intercuspation. Selecting the palatal cusp proved to be just as difficult for the same reason. Our use of the buccal cusp tips to define the occlusal planes, although it was not ideal, still provided a valid depiction of the plane's orientation.

Identifying the etiology of the malocclusion is an important first step in diagnosis and treatment planning. If the etiology is not understood, then treatment planning becomes problematic and unpredictable. The understanding that the 3D maxillary POP may play a role in influencing mandibular spatial position could prove useful in the diagnosis and treatment of malocclusions.

As Shudy[5] described, the occlusal plane is largely determined by the vertical development, or lack thereof, of the dentoalveolar processes. It is this differential vertical development of the dentoalveolar processes that establishes the occlusal planes.[39] The maxillary occlusal plane (passive arch) in its orientation is the end point in the arc of mandibular (active arch) closure. It is the contact of the mandibular dentition with the guiding surfaces of the maxillary dentition that determines mandibular spatial position.[35,38] Petrovic et al[40] believed and theorized that the occluding dentition and mandibular function, all driven by the proprioceptive system, could control mandibular position, adaptation, and morphology.

The position of A-point was found to be consistent in the different skeletal classifications of our sample. In contrast, the variables that define the anteroposterior and vertical positions of the mandible showed significant differences between the classes and correlated with the POP. In particular, all Class III subjects had mandibular prognathism and no maxillary deficiency. This interesting finding needs

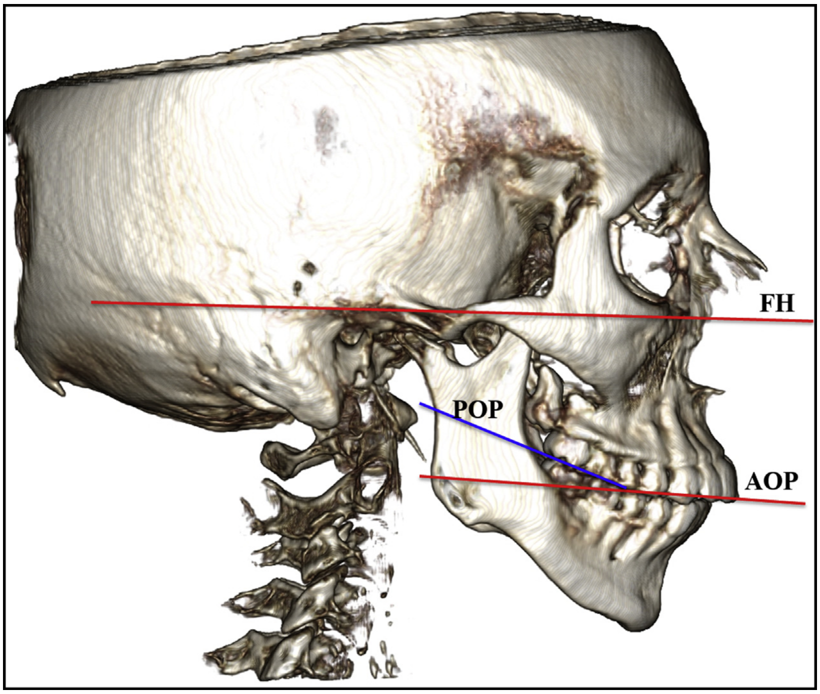

Fig 4. The steeper the POP, (1) the more retrognathic and hyperdivergent the mandibular posture and (2) the smaller the ramal heights and corpus lengths and the more hyperdivergent the contour.

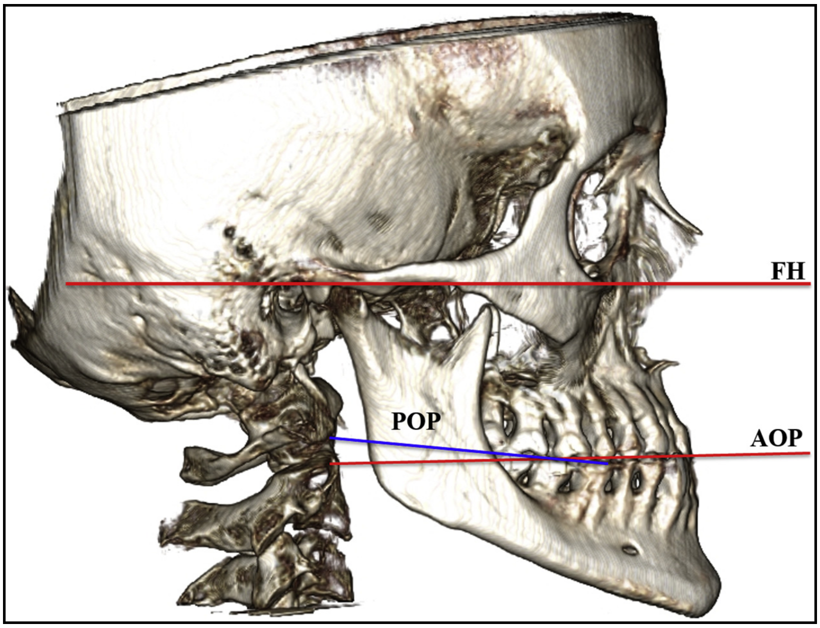

Fig 5. The flatter the POP, (1) the more prognathic and hypodivergent the mandibular posture and (2) the greater the ramal heights and corpus lengths and the more hypodivergent the contour.

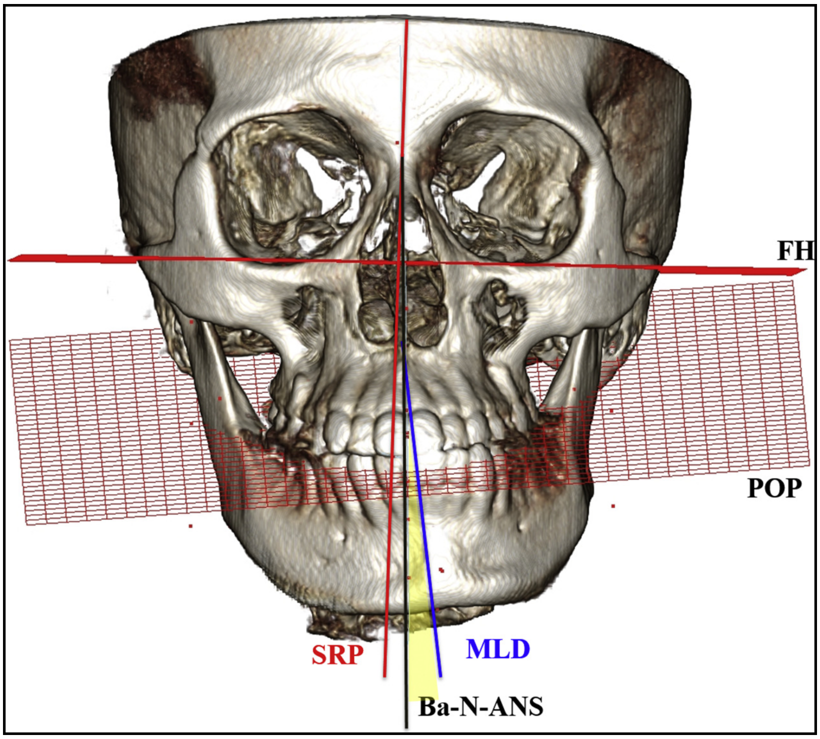

Fig 6. The direction of mandibular lateral deviation was consistent with the steepness of the POP on the same side. The mandible adapts to the side with a smaller vertical dimension.

further investigation in a sample with known race and ethnic variables.

From the coronal view, the gonial cant correlated with the mandibular lateral deviation, but the condylar cant did not. From the axial view, neither the gonial deviation nor the condylar deviation correlated with the mandibular lateral deviation. These findings suggest that there could be compensatory changes at the level of the condyles during the rotational shift of the mandible toward the side of the steeper occlusal plane.[37] This finding warrants further investigation for clarification.

In the morphologic assessment, the only variables that did not correlate with the POP were the gonial angles. This may be explained by the compensatory remodeling that is thought to occur at this location during growth.

The anterior occlusal plane and its relationship, not only to mandibular position and morphology but also to the POP, should be further investigated.

CONCLUSIONS

The results of this study suggest that there is a distinct and significant relationship between the 3D POP and mandibular spatial position and its morphology.

1. The POP exhibits significant correlation with mandibular posture. The steeper the POP, the more retrognathic and the more hyperdivergent the mandibular posture. The flatter the POP, the more prognathic and hypodivergent.
2. The direction of the mandibular lateral deviation and gonial cant is consistent with the steepness of the POP on the same side, suggesting a possible rotational shift of the mandible toward the side with a smaller vertical dimension. Mandibular lateral deviations occurred in all dentoskeletal morphologies in the sample.
3. The POP exhibited significant correlations with mandibular morphology. On the side of the steeper POP, both ramal height and corpus length were smaller with a more hyperdivergent contour. The side with the flatter occlusal plane had greater ramal heights and corpus lengths and a more hypodivergent contour.

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SUPPLEMENTARY DATA

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.ajodo.2015.12.020.

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