CBCT assessment of maxillary sinus sexual dimorphism: morphometry and sex-classification performance in Peruvian adults

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KEYWORDS

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ABSTRACT

The maxillary sinus exhibits sexual variation that is useful for forensic identification. Cone-beam computed tomography (CBCT) enables precise quantification of linear and volumetric dimensions; however, evidence regarding the most discriminative parameter remains heterogeneous. This study aimed to determine whether CBCT-derived morphometry of the maxillary sinuses discriminates biological sex in adults and to quantify classification performance. We conducted a retrospective observational study and randomly selected 108 CBCT scans from 150 eligible records (age 20–70 years, permanent dentition). Height, width, length, and volume were measured bilaterally from standardized multiplanar reconstructions; normality was assessed and sexes were compared using Student's t test. Males showed larger sinus volumes than females (right: 17.41 ± 1.61 vs 15.38 ± 1.79 cm^3; left: 17.46 ± 1.37 vs 15.86 ± 2.02 cm^3; $p < 0.001$). In side-specific univariate linear discriminant analysis with 10-fold cross-validation, width was the best single predictor: right width AUC = 0.80 (95% CI: 0.72–0.88) and accuracy = 0.72 (95% CI: 0.63–0.79); left width AUC = 0.74 (0.64–0.83) and accuracy = 0.68 (0.59–0.76). In multivariable models using width + age, linear discriminant analysis achieved AUC = 0.771 (95% CI: 0.676–0.858) and accuracy = 0.722 (95% CI: 0.631–0.798), with sensitivity = 0.729 (95% CI: 0.590–0.834) and specificity = 0.717 (95% CI: 0.592–0.815); logistic regression performed similarly (AUC = 0.771; accuracy = 0.713). Conclusions: CBCT-based morphometry of the maxillary sinus discriminates sex with moderate performance; width is the most informative single metric in this cohort. For forensic application, population-specific external validation and multivariable models integrating shape and volume descriptors are recommended.

INTRODUCTION

Sex determination is a core component of the biological profile in human identification because it narrows the search spectrum and guides subsequent stages of forensic analysis. Although the pelvis and skull are the most reliable references, remains are often incomplete or fragmented in the context of disasters, conflicts, or accidents. In this scenario, the paranasal sinuses preserve radiologic features that are useful due to their anatomic robustness and individual variability.[1]

Cone-beam computed tomography (CBCT) provides

reproducible three-dimensional measurements of the maxillary sinus at reduced radiation dose and has become a complementary technique for sex determination and population studies; recent syntheses concur that males tend to present larger dimensions and that classification accuracy is typically moderate when linear and/or volumetric measures are combined in discriminant functions.[2-4]
Even so, the evidence is heterogeneous owing to differences in 3D segmentation, software and thresholds, as well as sample composition (age, dentition, skeletal pattern) and population specificity.
Internationally, studies from India, Brazil, Egypt, Turkey, and the United States have shown the usefulness of linear and volumetric dimensions to predict sex, with discrepancies regarding the "best" predictor (height, width, or volume) and accuracies typically in the 70–80% range.[5-8] Craniofacial factors - such as sagittal pattern - modulate sinus volume and may explain part of the variability across studies.[9]
From a forensic perspective, the anatomical uniqueness of the maxillary sinus supports 3D–3D comparison, with calls to standardize protocols and to conduct local validation to ensure transportability.[10-11] Advances in automated CBCT segmentation are beginning to improve inter-center reproducibility, although adoption in forensic series remains incipient.[12-14]
In Latin America, research is more limited, yet consistent results have been reported in countries such as Peru and Colombia; in Peru, recent studies confirm sexual dimorphism with moderate performance.[15] Given the region's ethnic and geographic diversity - which underscores the need to expand databases to ensure representativeness— and the inter- and intrapopulation variability of maxillary sinus dimensions,[2,3] the objective of this study was, using discriminant analysis, to determine whether linear and volumetric morphometric measurements obtained from CBCT of the maxillary sinuses allow sex determination in a Peruvian adult population, thereby contributing evidence that can be integrated into the global map of forensic anthropology.

MATERIALS AND METHOD

Study design and population
Observational, cross-sectional, analytical, retrospective study based on CBCT scans obtained at a single radiology center in Lima. The sampling frame comprised 150 examinations performed between August 2023 and September 2024 at the "Instituto de Diagnóstico Maxilofacial" (IDM). From this population, a sample size of 108 scans was calculated and selected by simple random probabilistic sampling. Inclusion criteria were age 20–70 years and complete permanent dentition; scans were excluded if they showed maxillary sinus pathology, deciduous dentition, or artifacts/ defects precluding anatomical assessment. The final sample included 48 males and 60 females.

CBCT acquisition and image processing
CBCT examinations were acquired using a Planmeca ProMax® 3D Plus unit (Planmeca Oy, Helsinki, Finland) and exported in DICOM format. Acquisition and reconstruction parameters were retrieved from DICOM metadata using PointNix RealScan 2.0-CDViewer-3D (PointNix Co., Ltd., Seoul, Republic of Korea), registering 90 kVp, 5 mA, and 31.895 mAs (≈ 6.38 s), with an approximate voxel size of 0.25 mm (250 µm).

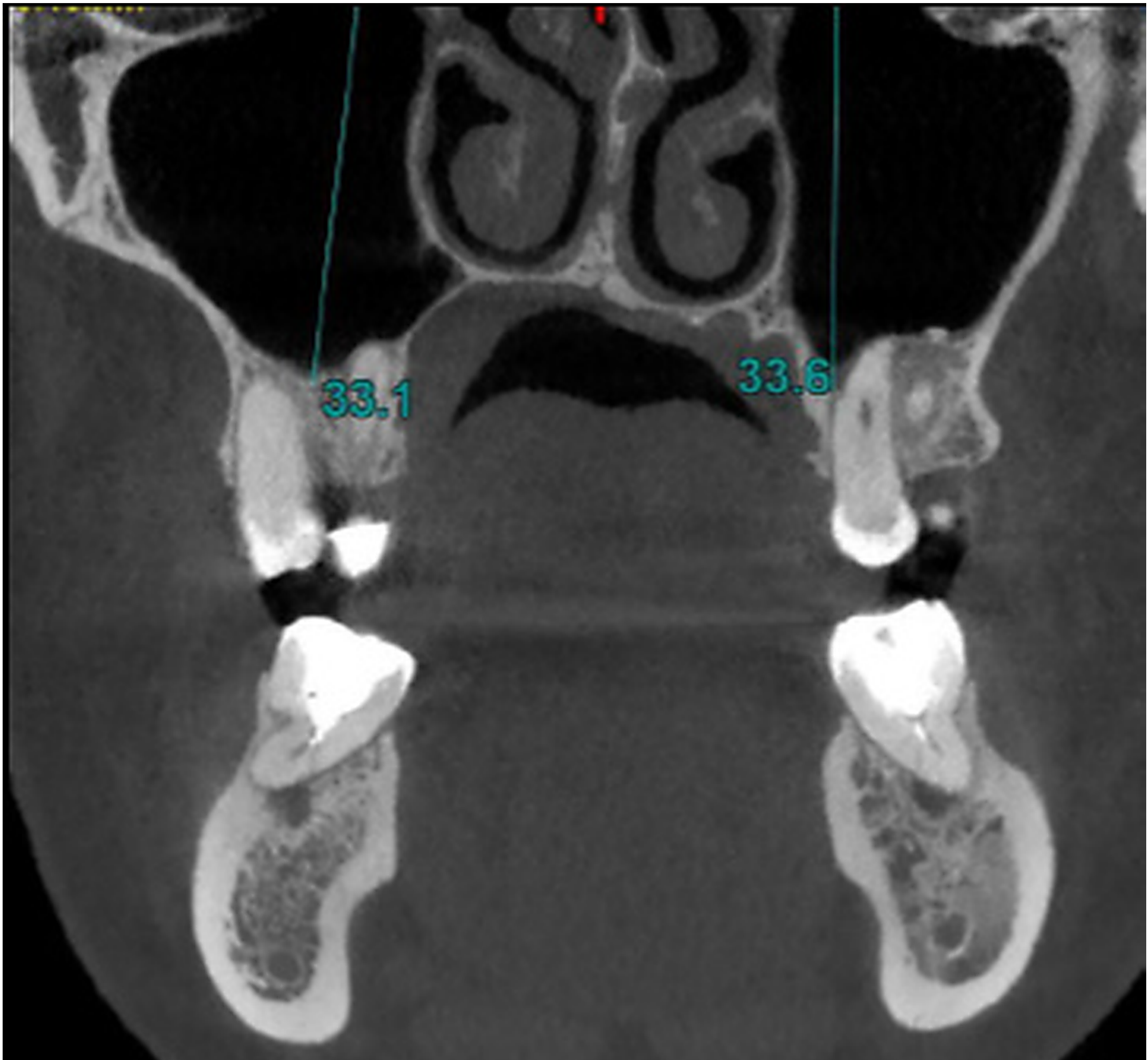
Patient data acquisition
Before measurements, sex and age were recorded for each CBCT, and compliance with the eligibility criterion of complete permanent dentition was verified.

Selection of anatomical landmarks and measurement protocol
Images were analyzed in PointNix RealScan 2.0-CDViewer-3D using multiplanar reconstructions (MPR) in maximum intensity projection (MIP) mode with 2-mm slab thickness. All measurements were performed with the head oriented in a standardized fashion and recorded bilaterally in millimeters. To minimize variability due to slice selection, a standardized rule was applied for all linear measurements. Using MPR views (MIP mode, 2-mm slab thickness), the observer first scrolled through the dataset to identify the axial slice where the maxillary sinus showed its maximum mediolateral extent; width and length were measured on that slice. Height was then measured on the coronal slice that provided the maximum superoinferior dimension between the orbital floor and the sinus floor, aligned to the axis of the greatest axial width. When similar maximum values were observed across adjacent slices, the middle slice among

those candidates was selected to ensure consistency. This slice-selection rule was applied bilaterally and consistently across all scans.

Height was defined as the maximum superoinferior distance from the orbital floor to the floor of the maxillary sinus (see Figure 1).

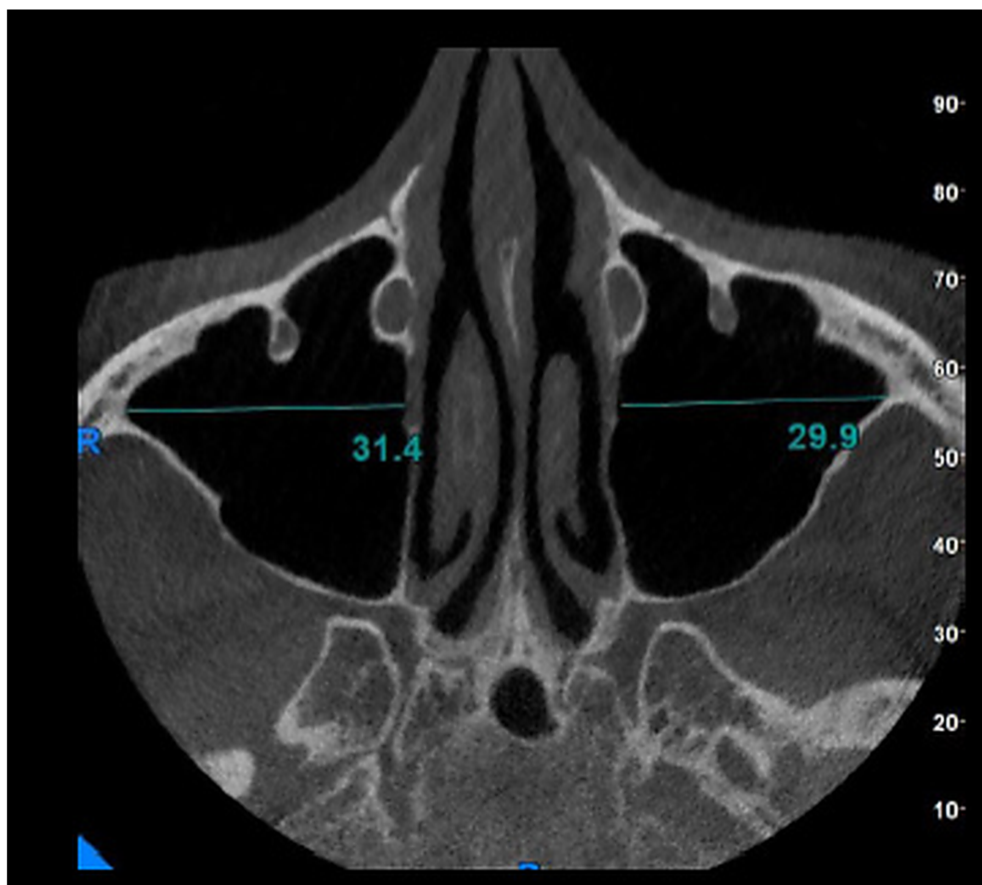
Figure 1. Maximal supero-inferior height of the maxillary sinus on a coronal slice (bilateral measurement, mm). Coronal image obtained after multiplanar reconstructions (MPR) in maximum-intensity projection (MIP) with a 2-mm slab. The lines indicate the maximal supero-inferior distance between the superior and inferior cortical walls of the right and left maxillary sinuses.



Width was defined as the maximum mediolateral distance between the lateral and medial sinus walls, and length as the maximum anteroposterior distance between the anterior and posterior walls, following the protocol described by Urooge and Patil (see Figure 2).

From these linear dimensions, derived variables were calculated using predefined geometric approximations: perimeter = 2×length + 2×width (mm); area = length × width (mm^2); and volume = (length × width × height)/2 (mm^3). Where appropriate, results were expressed in cm or cm^3, preserving traceability to the original measurements in mm.

Figure 2. Maximal mediolateral width of the maxillary sinus on an axial slice (bilateral measurement, mm). Axial image in the plane of greatest mediolateral expansion; the lines show the distance between the medial and lateral walls of each sinus.



Statistical analysis
Data were tabulated and analyzed in R v4.5.1 (R Foundation for Statistical Computing, Vienna, Austria). An independent-samples Student's t test was used to compare sexes. To evaluate classification ability, we applied side-specific univariate linear discriminant analysis (LDA) and, complementarily, multivariable models (LDA and logistic regression) with width and age as predictors. Performance was estimated using stratified 10-fold cross-validation (positive class = male, decision threshold = 0.50), reporting AUC with 95% CIs by bootstrap (1,000 replicates), accuracy, sensitivity, and specificity with Wilson 95% CIs, as well as balanced accuracy and the confusion matrix. ROC analysis was additionally performed using pooled out-of-fold predicted probabilities from the stratified 10-fold cross-validation, and the optimal decision cutoff was determined using the Youden index.

Calibration and reliability
An expert trained the investigator in applying the measurement protocol. Intraobserver reproducibility was assessed using the intraclass correlation coefficient (ICC), yielding high values across all dimensions (ICC 0.862–0.956).

Ethical considerations
The study was conducted with anonymized images under guaranteed confidentiality, with authorization from the Instituto de Imágenes Maxilofacial for secondary data use, and approval from the Institutional Ethics Committee of Universidad Privada Norbert Wiener (Exp. No.: 0822-2023).

RESULTS

Sample characteristics and reliability
A total of 108 CBCT scans were evaluated (48 males, 60 females; 20–70 years). Variable distributions were compatible with normality (Kolmogorov–Smirnov, all $p > 0.05$), so parametric tests were used. Intraobserver reproducibility was high to excellent (ICC = 0.862–0.956, $p < 0.001$), supporting the stability of the measurement protocol.

Between-group comparisons of tomographic measurements

Bilateral maxillary-sinus measurements were systematically larger in males. For perimeter, means (±SD) were 12.60 ± 0.47 cm (right) and 12.60 ± 0.38 cm (left) in males versus 12.07 ± 0.56 cm and 12.20 ± 0.59 cm in females (Student's t test, both $p < 0.001$). For area, males averaged 9.71 ± 0.73 cm^2 (right) and 9.69 ± 0.54 cm^2 (left), whereas females averaged 8.87 ± 0.88 cm^2 and 9.07 ± 0.91 cm^2 (both $p < 0.001$). For volume, differences were larger: 17.41 ± 1.61 vs 15.38 ± 1.79 cm^3 (right) and 17.46 ± 1.37 vs 15.86 ± 2.02 cm^3 (left), corresponding to reductions of ~2.0 cm^3 and ~1.6 cm^3 in females relative to males (both $p < 0.001$). Full estimates and ranges are provided in Tables 1–3.

Table 1. Distribution of maxillary sinus perimeter (cm) from CBCT morphometric analysis in Peruvian adults.

Maxillary sinus	Sex	n	x̄	sd	Min.	Max.	p value*
Right perimeter	M	48	12.6	0.47	11.42	14.1	<0.001
	F	60	12.1	0.56	11.14	14.5	
Left perimeter	M	48	12.6	0.38	11.76	13.6	<0.001
	F	60	12.2	0.59	10.74	14.1	

M: male, F: female, n: sample size, x̄: arithmetic mean, SD: standard deviation, Min.: mínimum, Max.: máximum, p value*: Student's t test.

Table 2. Distribution of maxillary sinus area (cm^2) from CBCT morphometric analysis in Peruvian adults.

Maxillary sinus dimension	Sex	n	x̄	s	Min.	Max.	p value*
Right area	M	48	9.71	0.73	7.61	12.3	<0.001
	F	60	8.87	0.88	7.47	12.9	
Left area	M	48	9.69	0.54	8.4	11.1	<0.001
	F	60	9.07	0.91	7.06	12.2	

M: male, F: female, n: sample size, x̄: arithmetic mean, SD: standard deviation, Min.: mínimum, Max.: máximum, p value*: Student's t test.

Table 3. Distribution of maxillary sinus volume (cm^3) from CBCT morphometric analysis in Peruvian adults.

Maxillary sinus dimension	Sex	n	x̄	s	Min.	Max.	p value*
Right volume	M	48	17.41	1.61	14.04	22.3	<0.001
	F	60	15.38	1.79	12.42	21.2	
Left volume	M	48	17.46	1.37	14.6	20.1	<0.001
	F	60	15.86	2.02	11.22	21.5	

M: male, F: female, n: sample size, x̄: arithmetic mean, SD: standard deviation, Min.: mínimum, Max.: máximum, p value*: Student's t test.

Univariate linear discriminant analysis by dimensión

In side-specific univariate LDA, width was the most discriminative metric. Right width achieved AUC = 0.80 (95% CI: 0.72–0.88) and accuracy = 0.72 (95% CI: 0.63–0.79), with sensitivity = 0.66 (95% CI: 0.52–0.78) and specificity = 0.76 (95% CI: 0.64–0.85); left width showed AUC = 0.74 (0.64–0.83) and accuracy = 0.68 (0.59–0.76). Heights exhibited intermediate performance (AUC = 0.66–0.67; accuracy = 0.67), whereas lengths were the least informative (AUC = 0.62–0.63; accuracy = 0.63–0.64), penalized by sensitivity ≈ 0.50. Between-sex comparisons were significant for all dimensions (Welch's t test: $p < 0.001$ for widths and heights; $p = 0.005$ and $p = 0.022$ for lengths). Overall, widths consistently outperformed heights and lengths and were therefore prioritized as predictors in the multivariable analysis. Details are summarized in Table 4.

Table 4. Side-specific univariate linear discriminant analysis (LDA) of the maxillary sinus on CBCT for sex determination.

Dimension (side)	Right width (mm)	Left width (mm)	Right length (mm)	Left length (mm)	Right height (mm)	Left height (mm)
AUC (95%CI)	0.80 (0.72–0.88)	0.74 (0.64–0.83)	0.63 (0.53–0.75)	0.62 (0.51–0.73)	0.67 (0.57–0.78)	0.66 (0.56–0.76)
Accuracy (95% CI)	0.72 (0.63–0.79)	0.68 (0.59–0.76)	0.63 (0.54–0.72)	0.64 (0.55–0.73)	0.67 (0.58–0.75)	0.67 (0.58–0.75)
Sensitivity (95% CI)	0.66 (0.52–0.78)	0.66 (0.52–0.78)	0.50 (0.36–0.63)	0.50 (0.36–0.63)	0.68 (0.54–0.80)	0.68 (0.54–0.80)
Specificity (95% CI)	0.76 (0.64–0.85)	0.70 (0.57–0.80)	0.75 (0.62–0.84)	0.76 (0.64–0.85)	0.66 (0.54–0.77)	0.66 (0.54–0.77)
TN	46	42	45	46	40	40
FP	14	18	15	14	20	20
FN	16	16	24	24	15	15
TP	32	32	24	24	33	33
p (Welch's t test)	<0.001	<0.001	0.005	0.022	<0.001	< 0.001

AUC: área under the ROC curve, TN: true negatives (females correctly classified), FP: false positives (females misclassified as males), FN: false negatives (males misclassified as females), TP: true positives (males correctly classified).

Performance of multivariable models (logistic regression and linear discriminant analysis) with cross-validation

Using width and age as predictors with cross-validation, both models showed comparable, moderate performance. Linear discriminant analysis (LDA) achieved AUC = 0.771 (95% CI: 0.676–0.858), accuracy = 0.722 (95% CI: 0.631–0.798), sensitivity = 0.729 (95% CI: 0.590–0.834), and specificity = 0.717 (95% CI: 0.592–0.815), with balanced accuracy = 0.723. Logistic regression yielded AUC = 0.771 (95% CI: 0.675–0.858), accuracy = 0.713 (95% CI: 0.621–0.790), sensitivity = 0.729 (95% CI: 0.590–0.834), and specificity = 0.700 (95% CI: 0.575–0.801), with balanced accuracy = 0.715. The confusion matrices were TN/FP/FN/TP = 43/17/13/35 for LDA and 42/18/13/35 for logistic regression. Overall, LDA showed a slight advantage in accuracy, specificity, and balanced accuracy and was therefore considered the reference model (see Table 5).

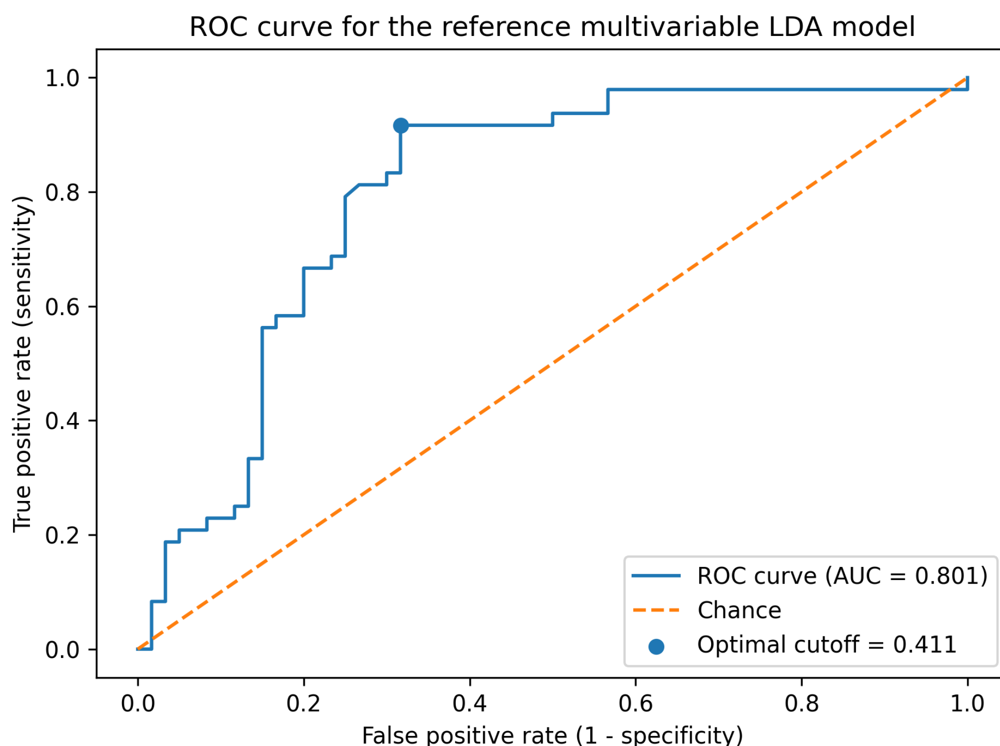
Table 5. Performance of multivariable models (logistic regression and linear discriminant analysis) to estimate sex from maxillary-sinus CBCT.

Model	Logistic	Linear
AUC (95%CI)	0.771 (0.675–	0.771 (0.676–
Accuracy (95%	0.713 (0.621–	0.722 (0.631–
Sensitivity (95%	0.729 (0.590–	0.729 (0.590–
Specificity (95%	0.700 (0.575–	0.717 (0.592–
Balanced	0.715	0.723
TN	42	43
FP	18	17
FN	13	13
TP	35	35

AUC: area under the ROC curve, TN: true negatives (females correctly classified), FP: false positives (females misclassified as males), FN: false negatives (males misclassified as females), TP: true positives (males correctly classified), Balanced accuracy = (sensitivity + specificity) / 2.

ROC analysis and optimal cutoff
ROC analysis of the reference multivariable model (linear discriminant analysis using right maxillary-sinus width and age) yielded an AUC of 0.801 based on pooled out-of-fold predicted probabilities from the stratified 10-fold cross-validation. The optimal decision threshold for sex classification (positive class = male), defined by the Youden index, was 0.411, corresponding to a sensitivity of 0.917 and a specificity of 0.683 (Figure 3).

Figure 3. ROC curve for sex determination using the reference multivariable model (linear discriminant analysis with right maxillary-sinus width and age; positive class = male). AUC = 0.801 (stratified 10-fold cross-validation, pooled out-of-fold probabilities). Optimal cutoff (Youden) = 0.411 (sensitivity 0.917, specificity 0.683).



DISCUSSION

In this study, we demonstrated sexual dimorphism of the maxillary sinus on CBCT, with statistically significant differences across all dimensions and moderate performance of univariate classifiers; in this cohort, width was the best predictor. Indeed, in side-specific univariate discriminant analysis with cross-validation, right width reached an AUC of 0.80 and accuracy of 0.72, outperforming heights and lengths; and in the multivariable analysis (width + age), linear discriminant analysis yielded an AUC of 0.77 and accuracy of 0.72, with performance comparable to logistic regression. This pattern is consistent with recent reviews supporting the forensic utility of the maxillary sinus and the dependence of performance on population, parameter, and protocol.[2-4] Our results also align with reports from India and Brazil and exceed the accuracy reported by previous studies in Peru, reinforcing the value of three-dimensional CBCT for this purpose. The reliability of linear CBCT measurements described in the literature supports the use of these metrics in applied research.[16] In contemporary series, the "most informative" metric varies - height, width, or volume - with typical accuracies of 60–80% in simple analyses.[17,18]

Part of the heterogeneity among studies is attributable to clinical factors that modify pneumatization (e.g., tooth loss, age), thereby affecting morphometry and its anatomic context.[19] Methodologically, cross-validation tends to reduce the optimism of apparent classification percentages, which helps explain differences with series that do not apply validation procedures, even when the ranking of metrics - with the predominance of width - remains stable. Segmentation choices and

acquisition parameters also influence estimates; comparisons between automated and manual/semi-automatic segmentation show operational advantages of the former.[20] In parallel, craniofacial determinants - such as sagittal pattern and cranio-maxillary relationships - modulate sinus volume and may account for population-level discrepancies.[21] AI-based standardization (U-Net/nnU-Net) reduces operator variability and improves pipeline traceability,[22-24] while 3D models of the paranasal sinuses offer a more robust framework for identification than isolated linear descriptors.[23] In the same vein, in forensic odontology, sinus metrics should be employed as auxiliary indicators, prioritizing externally validated multivariable models and reporting uncertainty with explicit decision thresholds.[2-4,23] Population differences have also been documented (e.g., U.S. series with 3D-CT),[24] as well as effects of age/tooth loss[24] and facial asymmetry.[25] Inter-sinus integration (frontal/sphenoidal) is an additional avenue to strengthen estimation,[26] and nasal septal deviation may act as a relevant anatomic covariate.[27]

This study contributes three elements: an explicitly three-dimensional methodological approach; the quantification of performance with cross-validation and confidence intervals in both univariate and multivariable settings; and the inclusion of an urban Peruvian population that complements high-Andean series, thereby expanding the Latin American evidence base, which remains limited relative to other regions. The reproducibility of our protocol was high, consistent with CBCT reliability assessments.[16] Nevertheless, univariate models constrain accuracy; the literature favors multivariable models and 3D shape/volume descriptors to improve sex separation.[18,23] Limitations include the retrospective, single-center design, lack of external validation, and potential confounders (granular age, tooth loss, asymmetries, septal deviation) not modeled explicitly.[19,24,25,27] The urban character of the sample restricts generalization yet ensures technical homogeneity; multicenter studies will allow broader testing and contrast of these findings.

Future work should include: development and validation of population-specific multivariable functions integrating linear, volumetric, and 3D shape measurements;[18,23] multicenter evaluation of the impact of automated segmentation on classification accuracy;[20.22-24] modeling of clinical confounders - age, tooth loss, facial asymmetry, septal deviation - through stratified analyses;[19,24,25,27] exploration of inter-sinus combinations (maxillary, frontal, sphenoidal) to increase discriminative capacity;[26] and standardization of uncertainty reporting with promotion of external validation for disaster victim identification applications.

Overall, this study provides additional local evidence that 3D CBCT–based morphometric measurements of the maxillary sinus - particularly width - show sexual dimorphism and can achieve moderate discriminatory performance in an urban Peruvian adult sample. However, given the single-center retrospective design, the sample size, and the lack of external validation, these findings should be interpreted cautiously and should not be assumed transferable to other Latin American populations. Further multicenter studies with larger samples and external validation are needed before broader forensic implementation.

CBCT-based morphometry of the maxillary sinus demonstrated sexual dimorphism in adults. Width was the most discriminative single parameter, yielding classification rates above 70%, and area, perimeter, and volume showed consistent between-sex differences. Taken together, these findings support CBCT as a complementary tool for sex determination in forensic contexts; however, the moderate performance of univariate models argues for its use in conjunction with other forensic indicators.

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