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Research Article

Digital Morphometric Assessment of the Mandible and Maxillary Sinus for Sex Estimation: Integrating Anatomical Landmarks with Forensic Identification

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Abstract

Background: Accurate sex estimation is a fundamental primary step in forensic anthropology and medicolegal identification. While the pelvis remains the most sexually dimorphic osseous structure, skull and facial bones, particularly the mandible and maxillary sinuses, are often better preserved in mass disasters, severe decomposition, or fragmented remains. Digital radiomorphometric analysis utilizing cone-beam computed tomography and multi-detector computed tomography allows for precise, non-invasive metric evaluation of these anatomical structures.

Objective: To evaluate the diagnostic accuracy of digital morphometric parameters of the mandible and maxillary sinus, individually and in combination, for forensic sex estimation in an adult population.

Methods: This cross-sectional study evaluated high-resolution head CT scans of 160 adult individuals (80 males and 80 females; aged 20 to 65 years) retrieved from the picture archiving and communication system at Jinnah Medical and Dental College.

Digital morphometric measurements of the mandible (gonial angle, bicondylar breadth, bigonial breadth, ramus height, and minimum ramus width) and maxillary sinus (height, width, depth, volume, and inter-sinus distance) were obtained using three-dimensional multiplanar reconstruction software. Sex differences were evaluated using independent sample t-tests and Mann-Whitney U tests. Discriminant function analysis and multivariable binary logistic regression models were developed to determine classification accuracy and identify key dimorphic parameters.

Results: All evaluated mandibular and maxillary sinus dimensions, except the gonial angle, were significantly larger in males than in females ($p < 0.001$). Mandibular ramus height (53.4 +/- 4.2 vs. 46.2 +/- 3.8 mm) and bigonial breadth (98.6 +/- 5.4 vs. 91.2 +/- 4.9 mm) demonstrated high sexual dimorphism. Maxillary sinus volume was significantly greater in males (15.8 +/- 3.2 vs. 11.4 +/- 2.6 cubic centimeters, $p < 0.001$). Stepwise discriminant function analysis revealed that mandibular measurements alone achieved an overall sex classification accuracy of 83.8 percent, while maxillary sinus metrics alone achieved 78.1 percent accuracy. Combining mandibular and maxillary sinus parameters in a unified discriminant function model yielded the highest predictive accuracy at 88.8 percent (88.8 percent for males, 88.8 percent for females), with mandibular ramus height, bigonial breadth, and maxillary sinus volume identified as the most powerful discriminating variables.

Conclusion: Digital morphometric evaluation of the mandible and maxillary sinus provides a reliable, objective, and highly accurate method for forensic sex estimation. Integrating mandibular dimensions with maxillary sinus volumetric parameters significantly improves sex classification rates, offering an indispensable diagnostic model for medicolegal identification when incomplete craniomaxillofacial remains are encountered.

Keywords: Forensic anthropology; Sex estimation; Digital morphometry; Mandible; Maxillary sinus; Computed tomography; Discriminant function analysis; Forensic identification.

1. Introduction

Human identification represents a cornerstone of forensic medicine, disaster victim identification, and physical

anthropology. Establishing biological identity from skeletal remains relies on the four primary parameters: sex, age at death, stature, and ancestry. Among these, sex estimation is the critical initial step, as it narrows the pool of possible decedents by approximately 50 percent and dictates the selection of subsequent sex-specific standards for estimating age and stature.

While the adult pelvis provides the highest anatomical reliability for sex determination (approaching 95 percent accuracy due to obstetric adaptations), pelvic bones are frequently fragmented or destroyed in high-energy trauma, thermal destruction, mass disasters, or advanced decomposition. In such circumstances, the skull and mandible serve as the next most sexually dimorphic skeletal elements.[1-4]

The mandible is the strongest and largest bone of the facial skeleton, possessing a high resistance to mechanical disruption and post-mortem degradation. Its morphometric features, including ramus height, minimum and maximum ramus width, bigonial breadth, bicondylar breadth, and gonial angle, exhibit marked sexual dimorphism due to differential masticatory muscle force vectors, hormone-driven bone remodeling during puberty, and overall skeletal size disparities between biological males and females.[5-7]

Concurrently, the maxillary sinuses are the largest paranasal cavities, encapsulated within the robust facial architecture of the maxilla. Owing to their protected anatomical location, the maxillary sinuses frequently remain intact even in severe craniomaxillofacial trauma or high-temperature incineration. Computed tomography studies demonstrate that maxillary sinus dimensions (height, width, depth, and three-dimensional volume) expand differentially during adolescent facial growth, influenced by pneumatization kinetics and cranial vault sexual dimorphism.

Advances in digital radiology, specifically multi-detector computed tomography and cone-beam computed tomography, have transformed forensic anthropology. Three-dimensional multiplanar reconstruction software enables virtual, contact-free osteometric analysis, eliminating soft-tissue interference, avoiding specimen destruction, and allowing precise landmark localization with sub-millimeter measurement accuracy.[8-10]

Although mandibular metrics and maxillary sinus dimensions have been evaluated independently across various populations, few studies have assessed the synergistic predictive accuracy obtained by integrating mandibular and maxillary sinus digital morphometrics into a unified discriminant function model.

Therefore, this cross-sectional study was undertaken to evaluate the digital morphometric parameters of the mandible and maxillary sinus using computed tomography and to construct an integrated discriminant model for forensic sex estimation.

2. Rationale of the Study

In forensic casework and mass disaster scenarios, skeletal remains are frequently incomplete or fragmented. Relying on a single anatomical bone or isolated landmark increases the risk of misclassification due to individual morphological variation or partial structural trauma. The mandible and maxilla/maxillary sinus complex represent dense, durable facial structures that often survive severe thermal and mechanical degradation. Developing a standardized, non-destructive digital protocol that combines upper (maxillary sinus) and lower (mandible) facial morphometrics provides forensic pathologists and anthropologists with a highly accurate, reproducible model for sex estimation when pelvis or whole skull remains are unavailable.

3. Objectives

Primary Objective

To evaluate and compare three-dimensional CT-based digital morphometric measurements of the mandible and maxillary sinus between adult males and females for forensic sex estimation.

Secondary Objectives

1. To quantify individual mandibular parameters (gonial angle, bicondylar breadth, bigonial breadth, ramus height, minimum ramus width) and maxillary sinus parameters (height, width, depth, volume).

2. To determine the individual sex classification accuracy of mandibular metrics versus maxillary sinus metrics using univariate and stepwise discriminant function analysis.

3. To construct an integrated multivariable discriminant function equation combining

mandibular and maxillary sinus parameters and evaluate its overall classification accuracy.

4. To identify the most sexually dimorphic digital morphometric predictors within the craniomaxillofacial complex.

4. Materials and Methods

4.1 Study Design and Setting

A retrospective cross-sectional study was conducted at the Department of anatomy and Forensic Medicine and Toxicology at Jinnah Medical and Dental College.

4.2 Study Duration

The study was conducted over an eight-month period, encompassing PACS image selection, digital landmark identification, virtual three-dimensional morphometric processing, double-observer reliability testing, and discriminant function statistical modeling.

4.3 Sample Population and Scan Retrieval

High-resolution head MDCT scans of 160 adult individuals (80 males, 80 females; age range 20 to 65 years) were selected from the institutional PACS database.

4.4 Sample Size

A sample size of 160 cases (80 per sex) was established. The sample size was calculated using G-Power software for discriminant function analysis, assuming a medium effect size (f squared = 0.15), an alpha error level of 0.05, a statistical power of 85 percent, and up to 10 predictor variables.

4.5 Inclusion Criteria

1. Age between 20 and 65 years at the time of CT acquisition (ensuring complete skeletal maturity and avoiding senile osteoporotic changes).

2. High-resolution volumetric head CT scans with slice thickness <= 1.0 mm.

3. Fully intact mandibular and maxillary sinus osteology with complete permanent dentition (excluding third molars) or minimal tooth loss without alveolar ridge resorption.

4. Known biological sex recorded in medical records.

4.6 Exclusion Criteria

1. Evidence of past or acute facial fractures, mandibular or maxillary bone disease, or osteomyelitis.

2. Maxillary sinus pathology (e.g., severe acute or chronic sinusitis, sinus polyposis, antroliths, mucocele, or expansive sinonasal tumors altering bony walls).

3. Congenital craniomaxillofacial deformities, cleft lip or palate, or orthognathic surgical interventions.

4. Extensive edentulism or severe alveolar bone atrophy causing alterations in mandibular angle or height.

5. Presence of severe metal streak artifacts obscuring bony landmarks on CT.

4.7 Digital Computed Tomography Acquisition and Image Processing

CT scans were performed using a multi-detector CT scanner (120 kVp, 150 mAs, matrix size 512 x 512, slice thickness 0.625 mm). DICOM data were imported into DICOM viewer and 3D reconstruction software (RadiAnt DICOM Viewer v2023.1).

Multiplanar reconstruction in axial, coronal, and sagittal planes, alongside 3D surface-rendered volume models, was utilized to locate standard anatomical landmarks:

Mandibular Morphometric Metrics:

- Gonial Angle (degrees): The angle formed by the intersection of the tangent to the inferior border of the mandibular body and the posterior border of the ramus.
- Bicondylar Breadth (mm): Straight-line distance between the most lateral points of the mandibular condyles (Condylion to Condylion).
- Bigonial Breadth (mm): Straight-line distance between the right and left Gonion points.
- Mandibular Ramus Height (mm): Distance from the highest point of the condyle to the inferior border of the ramus.
- Minimum Ramus Width (mm): Smallest anteroposterior diameter of the mandibular ramus.

Maxillary Sinus Morphometric Metrics:

- Maxillary Sinus Height (mm): Maximum distance from the lowest point of the sinus floor to the highest point of the sinus roof on coronal slices.

- Maxillary Sinus Width (mm): Maximum distance from the medial wall to the lateral wall perpendicular to the septum on coronal slices.

- Maxillary Sinus Depth or Length (mm): Maximum anteroposterior distance from the anterior wall to the posterior wall on axial slices.

- Maxillary Sinus Volume (cubic centimeters): Total 3D volume obtained via automated or semi-automated voxel threshold segmentation (air-tissue boundary threshold set between -1000 and -400 HU). Right and left sinus volumes were summed to yield Total Maxillary Sinus Volume.

4.8 Observer Reliability

To ensure measurement precision, all metrics were independently measured by two forensic radiologists. A subset of 30 scans was re-measured 3 weeks later by the primary observer to assess intra-observer reliability. Intra-class correlation coefficients were calculated, yielding values > 0.92 for all continuous parameters, demonstrating excellent measurement reproducibility.

4.9 Statistical Analysis

Data were analyzed using SPSS version 26.0 (IBM Corp., Armonk, NY). Continuous variables were tested for normality using the Kolmogorov-Smirnov test and expressed as mean +/- standard deviation. Differences between male and female measurements were evaluated using Student's independent t-test or Mann-Whitney U test.

Univariate and stepwise multivariable discriminant function analyses were conducted to construct sex-estimation equations. Unstandardized canonical discriminant function coefficients, standardized coefficients, structure matrix correlations, and cross-validated classification accuracy percentages were derived. Logistic regression models were also calculated for secondary validation. Statistical significance was set at a two-sided $p < 0.05$.

5. Results

5.1 Demographic Characteristics and Sex Comparisons of Mandibular Parameters

The study sample comprised 160 subjects (mean age 41.8 +/- 11.4 years for males; 40.6 +/- 10.9 years for females; $p = 0.502$). All mandibular metric measurements were significantly larger in males compared to females ($p < 0.001$). Conversely, the mean gonial angle was significantly greater in

females (124.6 +/- 5.2 degrees) than in males
(118.2 +/- 4.8 degrees, $p < 0.001$).

Mandibular Metric	Male (n = 80)	Female (n = 80)	Total (n = 160)	t-value / Z	p-value
Gonial Angle (degrees)	118.2 +/- 4.8	124.6 +/- 5.2	121.4 +/- 5.9	-8.08	<0.001
Bicondylar Breadth (mm)	122.4 +/- 5.8	114.2 +/- 5.1	118.3 +/- 6.8	9.48	<0.001
Bigonial Breadth (mm)	98.6 +/- 5.4	91.2 +/- 4.9	94.9 +/- 6.2	9.08	<0.001
Mandibular Ramus Height (mm)	53.4 +/- 4.2	46.2 +/- 3.8	49.8 +/- 5.2	11.37	<0.001
Minimum Ramus Width (mm)	30.8 +/- 2.6	27.2 +/- 2.2	29.0 +/- 3.0	9.46	<0.001

Table 1: Comparison of mandibular morphometric parameters between males and females.

5.2 Sex Comparisons of Maxillary Sinus Parameters

All maxillary sinus linear and volumetric parameters demonstrated significant sexual dimorphism ($p < 0.001$). Males displayed greater mean sinus height (38.2 +/- 3.1 vs. 33.4 +/- 2.8 mm), width (26.4 +/- 2.5 vs. 22.8 +/- 2.2 mm), and depth (38.8 +/- 3.2 vs. 34.6 +/- 2.9 mm). Total maxillary sinus volume in males was 15.8 +/- 3.2 cubic centimeters, compared to 11.4 +/- 2.6 cubic centimeters in females ($p < 0.001$).

Maxillary Sinus Metric	Male (n = 80)	Female (n = 80)	Total (n = 160)	t-value	p-value
Right Sinus Height (mm)	38.2 +/- 3.1	33.4 +/- 2.8	35.8 +/- 3.8	10.28	<0.001
Right Sinus Width (mm)	26.4 +/- 2.5	22.8 +/- 2.2	24.6 +/- 2.9	9.68	<0.001
Right Sinus Depth (mm)	38.8 +/- 3.2	34.6 +/- 2.9	36.7 +/- 3.7	8.69	<0.001
Left Sinus Height (mm)	37.9 +/- 3.0	33.1 +/- 2.7	35.5 +/- 3.7	10.64	<0.001
Left Sinus Width (mm)	26.1 +/- 2.4	22.5 +/- 2.1	24.3 +/- 2.8	10.10	<0.001
Left Sinus Depth (mm)	38.5 +/- 3.1	34.2 +/- 2.8	36.4 +/- 3.6	9.20	<0.001
Total Sinus Volume (cubic cm)	15.8 +/- 3.2	11.4 +/- 2.6	13.6 +/- 3.7	9.54	<0.001

Table 2: Comparison of maxillary sinus linear and volumetric parameters between sexes.

5.3 Discriminant Function Analysis Models

Stepwise discriminant function models were generated separately for mandibular parameters, maxillary sinus parameters, and their combination.

- Model 1 (Mandible Only): Entered variables were Ramus Height, Bigonial Breadth, and Gonial Angle. Wilks Lambda = 0.482 ($p < 0.001$), yielding an overall cross-validated sex classification accuracy of 83.8 percent (85.0 percent for males, 82.5 percent for females).

- Model 2 (Maxillary Sinus Only): Entered variables were Total Sinus Volume, Right Sinus Height, and Left Sinus Width. Wilks Lambda = 0.541 ($p < 0.001$), yielding an overall cross-validated accuracy of 78.1 percent (78.8 percent for males, 77.5 percent for females).

- Model 3 (Integrated Mandible and Maxillary Sinus): Entered variables were Mandibular Ramus Height, Bigonial Breadth, Gonial Angle, Total Maxillary Sinus Volume, and Right Sinus Height. Wilks Lambda = 0.312 ($p < 0.001$), resulting in an overall cross-validated sex classification accuracy of 88.8 percent (88.8 percent for males, 88.8 percent for females).

Model / Anatomical Region	**Wilks Lambda**	**Eigenvalue**	**Canonical Correlation**	**Male Accuracy (%)**	**Female Accuracy (%)**	**Overall Accuracy (%)**
Model 1: Mandible Alone	0.482	1.075	0.720	85.0	82.5	83.8
Model 2: Maxillary Sinus Alone	0.541	0.848	0.677	78.8	77.5	78.1
Model 3: Integrated (Combined)	0.312	2.205	0.829	88.8	88.8	88.8

Table 3: Discriminant function analysis performance metrics across anatomical models.

5.4 Integrated Canonical Discriminant Function Coefficients

The unstandardized discriminant function equation for the integrated model (Model 3) is expressed as: D = -14.281 + (0.128 * Ramus Height) + (0.084 * Bigonial Breadth) - (0.042 * Gonial Angle) + (0.165 * Total Sinus Volume) + (0.098 * Right Sinus Height)

Where distances are measured in millimeters, angles in degrees, and volume in cubic centimeters.

- Sectioning Cutoff Point (Centroid): 0.000 (Values > 0.000 classify as Male; values < 0.000 classify as Female).
- Group Centroids: Male = +1.472; Female = -1.472.

Predictor Variable	Unstandardized Coefficient	Standardized Coefficient	Structure Matrix Correlation
Mandibular Ramus Height (mm)	0.128	0.512	0.684
Bigonial Breadth (mm)	0.084	0.428	0.546
Total Maxillary Sinus Volume (cubic cm)	0.165	0.482	0.574
Right Sinus Height (mm)	0.098	0.312	0.618

Predictor Variable	Unstandardized Coefficient	Standardized Coefficient	Structure Matrix Correlation
Gonial Angle (degrees)	-0.042	-0.214	-0.486
Constant	-14.281	Not Applicable	Not Applicable

Table 4: Unstandardized and standardized canonical discriminant function coefficients for the integrated model.

5.5 Multivariable Logistic Regression Validation

Multivariable binary logistic regression confirmed that Mandibular Ramus Height (adjusted OR = 1.38 per mm, 95 percent CI: 1.21 to 1.58, $p < 0.001$), Bigonial Breadth (adjusted OR = 1.24 per mm, 95 percent CI: 1.10 to 1.40, $p < 0.001$), and Total Maxillary Sinus Volume (adjusted OR = 1.42 per cubic cm, 95 percent CI: 1.22 to 1.65, $p < 0.001$) were significant independent predictors of male sex. The Nagelkerke R squared for the combined logistic model was 0.684.

Variable	Unadjusted OR (95% CI)	p-value	Adjusted OR (95% CI)	p-value
Mandibular Ramus Height (mm)	1.54 (1.35–1.76)	<0.001	1.38 (1.21–1.58)	<0.001
Bigonial Breadth (mm)	1.32 (1.22–1.44)	<0.001	1.24 (1.10–1.40)	<0.001
Total Maxillary Sinus Volume (cubic cm)	1.62 (1.41–1.86)	<0.001	1.42 (1.22–1.65)	<0.001

Variable	Unadjusted OR (95% CI)	p-value	Adjusted OR (95% CI)	p-value
Right Sinus Height (mm)	1.48 (1.31–1.68)	<0.001	1.21 (1.04–1.41)	0.014
Gonial Angle (degrees)	0.78 (0.71–0.85)	<0.001	0.88 (0.80–0.97)	0.011

Table 5: Multivariable logistic regression modeling independent predictors of biological sex.

6. Discussion

This study evaluated the diagnostic reliability of 3D CT-based digital morphometrics of the mandible and maxillary sinus for forensic sex estimation. The findings demonstrate that combining mandibular metrics (ramus height, bigonial breadth) with maxillary sinus dimensions (volume, height) in an integrated discriminant model achieves a high sex classification accuracy of 88.8 percent, outperforming models based on either anatomical region alone.

6.1 Sexual Dimorphism in Mandibular Morphometrics

The mandible displays significant sexual dimorphism, driven by developmental and biomechanical factors. During pubertal maturation, male growth spouts are prolonged, and testosterone drives heightened muscular development. The masseter and medial pterygoid muscles exert greater mechanical traction at their insertions on the mandibular angle and ramus in males, stimulating periosteal bone deposition. Consequently, males exhibit greater ramus height (53.4 vs. 46.2 mm) and wider bigonial breadth (98.6 vs. 91.2 mm).

Conversely, the gonial angle was significantly obtuse in females (124.6 degrees vs. 118.2 degrees). The more acute gonial angle in males reflects muscular hypertrophy pulling the posterior border of the ramus anteriorly. In our mandibular discriminant function model (Model 1), ramus height emerged as the single most powerful discriminating parameter, consistent with studies by Saini et al. and

Gamba et al., which identified ramus height as an exceptionally reliable metric for sex determination.[11-13]

6.2 Sexual Dimorphism in Maxillary Sinus Morphometrics

The maxillary sinuses exhibit dimorphic variations linked to overall facial skeleton size and respiratory physiology. Males possess larger skull dimensions and higher somatic oxygen demands, necessitating greater nasal and paranasal cavity volumes. In our cohort, total maxillary sinus volume was significantly larger in males (15.8 cubic centimeters) than in females (11.4 cubic centimeters), representing a 38.6 percent volumetric difference. [14-16]

Because the maxillary sinus reaches full anatomical maturation by age 18 and undergoes minimal age-related resorption (provided posterior dentition remains intact), its volume and height serve as robust markers in mature remains. Maxillary sinus metrics alone achieved a classification accuracy of 78.1 percent (Model 2), corroborating findings by Jehan et al. and Masri et al. [17-18]

6.3 Synergistic Power of Integrated Craniomaxillofacial Profiling

A key finding of this study is the marked improvement in predictive performance when mandibular and maxillary sinus parameters are evaluated together. Combining both anatomical regions in Model 3 increased classification accuracy to 88.8 percent, reducing the Wilks Lambda to 0.312.

This synergistic gain occurs because the mandible (lower facial skeleton) and maxillary sinus (midfacial complex) reflect distinct developmental and functional influences: the mandible captures masticatory muscular force development, whereas the maxillary sinus reflects midfacial respiratory pneumatization. Combining upper and lower facial metrics mitigates individual anatomical anomalies or localized pathology, creating a balanced, robust forensic diagnostic framework. [19-20]

6.4 Clinical Applications

Virtual anthropology utilizing CT data offers distinct advantages over traditional physical anthropometry. Digital multiplanar sectioning eliminates the need for manual soft-tissue defleshing, preserves evidence, allows repeated non-destructive volumetric analysis, and provides standardized reference databases for medicolegal casework. The

discriminant function equation derived in this study provides forensic pathologists, toxicologists, and odontologists with a quantitative tool for identifying unknown remains in regional forensic investigations.

6.5 Limitations

Several limitations should be noted. First, the study evaluated a population-specific cohort; because craniofacial morphometrics vary across geographic and ethnic populations due to genetic and environmental factors, population-specific equations are recommended. Second, individuals with complete edentulism were excluded; severe alveolar resorption can alter mandibular body height and gonial angle metrics. Third, automated segmentation thresholding requires careful calibration to prevent partial-volume effects during maxillary sinus volume rendering.

7. Conclusion

Digital morphometric assessment of the mandible and maxillary sinus using computed tomography provides a non-invasive, reproducible, and highly accurate approach for forensic sex estimation. Mandibular ramus height, bigonial breadth, and total maxillary sinus volume are the most powerful sexually dimorphic metrics. Integrating mandibular and maxillary sinus metrics into a unified discriminant function equation achieves an overall classification accuracy of 88.8 percent, offering an indispensable diagnostic tool for medicolegal identification when fragmented craniomaxillofacial remains are encountered.

8. Recommendations

1. Utilize combined mandibular and maxillary sinus metrics rather than single isolated parameters when performing forensic sex estimation on craniomaxillofacial remains.

2. Incorporate high-resolution 3D volumetric CT reconstruction and standardized multiplanar thresholding protocols for virtual forensic osteometry.

3. Apply population-specific discriminant function equations for forensic casework to account for regional craniofacial variations.

4. Exercise caution when interpreting mandibular metrics in fully edentulous individuals due to potential alveolar bone remodeling.

5. Establish prospective, multi-center digital anthropological databases combining automated machine-learning algorithms with 3D osteometric parameters to further enhance forensic identification accuracy.

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