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Research Article

Morphometric Analysis of the Foramen Magnum and Its Application in Sex Estimation: A Combined Dry Skull and Computed Tomographic Study in a Central Indian Population

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ABSTRACT
Background: The foramen magnum (FM) exhibits population-specific sexual dimorphism of established forensic value, but classification accuracy reported across populations varies widely and no dedicated morphometric database exists for the Central Indian population.
Objective: To establish population-specific FM morphometric norms and evaluate their utility for sex estimation using a cross-validated statistical approach.
Methods: A cross-sectional study of 220 specimens (110 dry adult skulls, 110 head CT scans; 110 male, 110 female) measured FM anteroposterior diameter (APD), transverse diameter (TD), circumference, area, index, and shape morphotype using a digital vernier calliper and DICOM multiplanar reconstruction respectively. Sex differences were tested by Welch's t-test/Mann-Whitney U as appropriate; sex classification used multivariable logistic regression evaluated by leave-one-out cross-validation (LOO-CV).
Results: Mean FM APD was 33.80±2.80 mm and TD 29.06±2.26 mm. Males exceeded females on APD, TD, circumference and area (all $p<0.05$); the FM index did not differ by sex ($p=0.856$). The oval morphotype predominated (44.1%). A four-parameter logistic model classified sex with 69.1% LOO-CV accuracy (AUC=0.762), comparable to similarly cross-validated figures in the international literature.
Conclusion: FM morphometry is significantly sexually dimorphic in this population and provides a supportive, cross-validated tool for forensic sex estimation, though not a stand-alone method.

Keywords: Foramen Magnum, Sex Estimation, Forensic Anthropology, Craniometry, Cross-Validation, Computed Tomography.

INTRODUCTION
The foramen magnum (FM) is the largest aperture at the cranial base, transmitting the medulla oblongata, vertebral arteries, and accessory nerve [1,2]. Its protected anatomical position means it frequently survives trauma, decomposition and mass-disaster scenarios that destroy the calvaria and pelvis, making its morphometry a recurring focus of forensic sex-estimation research since the 1980s [3,4].
A consistent finding across this literature is that sex-classification accuracy is population-specific: formulae derived in one population classify individuals from another population with markedly reduced accuracy, and reported multivariate classification accuracy ranges from approximately two-thirds to the low eighties depending on population and validation method [5,6,7,8,9]. No dedicated FM morphometric database exists for the Central Indian (Malwa region) population. The present study measured FM morphometry in a combined dry-skull and computed tomographic (CT) sample from this population and evaluated its sex-classification utility using cross-validation, a stricter and more externally valid standard than the apparent (in-sample) accuracy reported in much of the comparison literature.

MATERIALS AND METHODS
This cross-sectional, observational study was conducted in the Department of Anatomy, in collaboration with the Department of Radiodiagnosis, Index Medical College,

Hospital and Research Centre, Indore, India, after Institutional Ethics Committee approval. The study comprised two arms: 110 dry adult human skulls from the departmental osteology collection, and 110 archived, anonymised CT scans of the head and neck from the Department of Radiodiagnosis, each arm comprising 55 male and 55 female subjects. Skulls or scans with fracture, tumour, congenital anomaly, previous craniovertebral surgery, or incomplete demographic data were excluded.

FM anteroposterior diameter (basion to opisthion) and transverse diameter (maximum width perpendicular to the APD) were measured using a digital vernier calliper (accuracy 0.01 mm; [manufacturer to be inserted]) on dry skulls, and on multiplanar DICOM reconstructions (bone window) for CT scans, each parameter measured three times and averaged. FM circumference was measured along the inner margin; area was calculated as $\pi \times (APD/2) \times (TD/2)$; the FM index was calculated as $TD \times 100/APD$. FM shape was classified as oval, round, tetragonal, pentagonal, hexagonal, egg-shaped, or irregular.

Statistical analysis was performed in Python 3 (pandas, SciPy, scikit-learn). Normality was assessed by the Shapiro-Wilk test; sex comparisons used Welch's t-test (normal data) or the Mann-Whitney U test (non-normal data). Sex classification used multivariable logistic regression (FM APD, FM TD, and two occipital condyle parameters as predictors, reported separately for the craniovertebral junction component of this work), evaluated by leave-one-out cross-validation to obtain an out-of-sample classification accuracy, sensitivity, specificity and receiver-operating-characteristic area under the curve (ROC-AUC). A p-value <0.05 was considered statistically significant.

RESULTS AND DISCUSSION

Descriptive morphometry of the foramen magnum, overall and by sex, is shown in Table 1. Males exceeded females significantly on all linear and area parameters (all $p<0.05$), but the FM index — the ratio of transverse to anteroposterior diameter — did not differ by sex ($p=0.856$), indicating that while absolute FM size is dimorphic, its overall proportion is preserved across sexes. This dissociation between absolute-size dimorphism and shape/proportion stability is consistent with several previously published series [3,5,7].

Table 1. Foramen Magnum Morphometry, Overall and by Sex (Mean ± SD)

Parameter	Overall (N=220)	Male (N=110)	Female (N=110)	p-value
FM APD (mm)	33.80 ± 2.80	34.42 ± 2.61	33.19 ± 2.87	<0.001
FM TD (mm)	29.06 ± 2.26	29.61 ± 2.19	28.50 ± 2.21	<0.001
FM Circumference (mm)	98.75 ± 5.70	100.61 ± 5.32	96.89 ± 5.49	<0.001
FM Area (mm²)	771.25 ± 86.74	800.11 ± 82.09	742.38 ± 81.84	<0.001
FM Index	86.58 ± 10.21	86.57 ± 9.69	86.60 ± 10.75	0.856

The present study's mean APD (33.80 mm) and TD (29.06 mm) are closely comparable to a North Indian dry-skull series reporting 34.68 mm and 27.24 mm respectively [3], a difference well within the between-population variation reported across the wider Indian literature (approximately 32–36 mm for APD and 27–30 mm for TD).

Table 2. Foramen Magnum Shape Distribution (N = 220)

Shape	n (%)
Oval	97 (44.1%)
Round	44 (20.0%)
Tetragonal	26 (11.8%)
Pentagonal	25 (11.4%)
Hexagonal	12 (5.5%)
Egg-shaped	9 (4.1%)
Irregular	7 (3.2%)

The oval morphotype predominated (44.1%), followed by round (20.0%) — a pattern consistent with the majority of published Indian series [3,4].

Sex Estimation

A multivariable logistic regression model incorporating FM APD, FM TD and two occipital condyle parameters classified sex with 69.1% leave-one-out cross-validated accuracy (sensitivity 69.1%, specificity 69.1%; AUC=0.762). This cross-validated figure is comparable to, but on the lower end of, the range reported across the international literature (65–89% depending on population and validation method) [5,6,7,8,9]. Critically, the higher accuracy figures reported in several comparable studies do not describe cross-validation of their discriminant models; apparent (resubstitution) accuracy — where a model is evaluated on the same data used to fit it — is well established in the statistical literature to overestimate true out-of-sample performance. The present study's LOO-CV accuracy should therefore be regarded as a more conservative and externally valid estimate of real-world classification performance than several higher figures reported elsewhere, and supports FM morphometry as a supportive rather than a stand-alone forensic sexing tool in this population.

CONCLUSION

Foramen magnum morphometry is significantly sexually dimorphic in this Central Indian population, with males exceeding females on all linear and area parameters, while the FM index and overall shape distribution are comparatively sex-independent. A cross-validated logistic regression model achieved 69.1% classification accuracy, a realistic estimate supporting the use of FM morphometry as a supportive, population-specific tool for forensic sex estimation in this region.

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