

## Anatomical Variations and Sex Determination of the Foramen Magnum: A Morphometric Study in South Indian Skulls

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### Abstract

**Background:** The foramen magnum (FM) is the largest aperture in the base of the skull, located in the occipital bone, and serves as the principal communication between the cranial cavity and the spinal canal. It transmits the medulla oblongata, vertebral arteries, spinal accessory nerves, and meningeal coverings. Its dimensions and morphological configuration are of considerable importance to neurosurgeons, otolaryngologists, and forensic anthropologists for procedures such as transcondylar approaches to ventral foramen magnum tumours, far-lateral skull base craniotomy, and sex determination from skeletal remains. **Aim:** To determine the morphometric parameters and morphological variants of the foramen magnum in adult dry skulls of South Indian origin and to evaluate their surgical, sex-determining, and diagnostic implications. **Materials and Methods:** A descriptive observational study was conducted in the Department of Anatomy, Karpaga Vinayaga Institute of Medical Sciences and Research Centre, between July 2015 and March 2016. One hundred and twenty (n=120) adult dry skulls of known sex were retrieved from the osteology collection. The antero-posterior diameter, transverse diameter, foramen magnum index, and foramen magnum area (computed by both Radinsky and Teixeira formulas) were measured using a digital vernier calliper (Mitutoyo, Japan; resolution 0.01 mm). The shape of the foramen magnum was classified into seven categories. Statistical analysis was performed using SPSS version 26.0. **Results:** The mean antero-posterior diameter was  $33.62 \pm 2.71$  mm, the mean transverse diameter was  $28.94 \pm 2.34$  mm, and the mean foramen magnum area (Radinsky) was  $767.20 \pm 89.40$  mm<sup>2</sup>. Male skulls demonstrated significantly greater dimensions than female skulls ( $p < 0.001$ ). The most common shape was oval (36.7%), followed by round (19.2%) and egg-shaped (15.0%). Discriminant function analysis showed a sex-determination accuracy of 78.3%. **Conclusion:** The morphometric parameters and shape variations of the foramen magnum demonstrate clinically relevant sexual dimorphism and population specificity. The findings serve

as a normative reference for South Indian populations and are of practical value to neurosurgeons planning posterior fossa surgery and forensic anthropologists determining sex from skeletal remains.

***Keywords***

Foramen magnum; Morphometry; Sexual dimorphism; Forensic anthropology; Skull base surgery; Transcondylar approach; South Indian skulls.

**1. Introduction**

The foramen magnum (FM), literally translated as the 'great hole', is the largest opening in the human skull and lies at the base of the occipital bone[1]. It transmits the medulla oblongata as it transitions into the spinal cord, the vertebral arteries, the anterior and posterior spinal arteries, the spinal roots of the accessory nerves (cranial nerve XI), and the dural and arachnoid coverings of the central nervous system [2,3]. Owing to the strategic location of the foramen, even minor pathological changes in its dimensions or surrounding structures can produce profound neurological consequences [4,5].

Knowledge of the precise morphometry of the foramen magnum is of immense practical importance. To the neurosurgeon, the dimensions and shape of the FM determine the feasibility of approaches such as the transoral, transclival, far-lateral, and transcondylar trajectories used to address ventral foramen magnum meningiomas, vertebral artery aneurysms, and clival chordomas [6,7]. To the obstetrician and paediatric neurosurgeon, the dimensions of the FM influence the diagnosis of conditions such as Chiari malformation, achondroplasia, and craniovertebral junction anomalies [8]. To the forensic anthropologist, the relatively well-protected position of the FM at the base of the skull means that it often survives when more delicate skeletal regions are damaged, and its dimorphic dimensions provide useful evidence in sex determination [9,10].

Despite the practical relevance of FM morphometry, normative data from the Indian subcontinent remain limited and methodologically heterogeneous. Existing studies have employed differing measurement techniques (calliper, computed tomography, photogrammetry), variable shape classifications, and small sample sizes [11,12]. Furthermore, considerable population-specific variation has been documented in FM dimensions and shape across geographic and ethnic groups [13,14]. The need for ethnically-specific reference data is therefore well established [15].

Against this background, the present study was undertaken with the following objectives: (i) to determine the linear, indexical, and areal dimensions of the foramen magnum in adult South Indian dry skulls, (ii) to classify the morphological shape of the FM, (iii) to assess sexual dimorphism in FM dimensions, and (iv) to discuss the surgical, radiologic, and forensic implications of the findings.

## **2. Materials and Methods**

### **2.1 Study Site and Setting**

This descriptive cross-sectional osteological study was conducted in the Department of Anatomy, South India, over a period of nine months from July 2015 and March 2016.

### **2.2 Sample and Inclusion Criteria**

A total of 120 adult dry skulls of known sex (78 male, 42 female) were retrieved from the departmental osteology collection. Inclusion criteria comprised dry, fully ossified adult skulls (estimated age above 25 years) without obvious pathology or fracture in the basioccipital region. Skulls with fragmentation, post-mortem damage to the basal occiput, congenital anomalies (e.g., basilar invagination, occipitalisation of the atlas), or evidence of pathological erosion were excluded. The age and sex of the specimens had been documented at the time of cadaveric receipt by the institutional bequeathal programme. Demographic characteristics of the sample are presented in Table 1.

**Table 1. Demographic Distribution of the Skulls Studied (n=120)**

<b>Variable</b>	<b>Number (n=120)</b>	<b>Percentage (%)</b>
Male skulls	78	65.0
Female skulls	42	35.0
Source: Cadaveric (anatomy lab)	88	73.3
Source: Osteology repository	32	26.7
Estimated age 30-50 years	46	38.3
Estimated age 51-70 years	58	48.3
Estimated age >70 years	16	13.4

### **2.3 Morphometric Parameters and Measurements**

All measurements were obtained by a single trained observer using a digital vernier calliper with a resolution of 0.01 mm (Mitutoyo Corporation, Japan) to minimise inter-observer variation. Each

measurement was taken three times, and the mean was used for analysis. The following parameters were recorded: (i) Antero-posterior diameter of the foramen magnum (FM-AP) — the maximum distance between the basion and the opisthion, measured along the median sagittal plane; (ii) Transverse diameter of the foramen magnum (FM-T) — the maximum distance between the right and left lateral margins, measured perpendicular to the antero-posterior diameter; (iii) Foramen magnum index (FMI) — calculated as  $(FM-T / FM-AP) \times 100$ ; (iv) Foramen magnum area, calculated using two established formulas — Radinsky's formula:  $Area = \pi \times (FM-AP/2) \times (FM-T/2)$ ; and Teixeira's formula:  $Area = \frac{1}{4} \times \pi \times FM-AP \times FM-T$  (corrected with empirical factor) [16,17].

#### ***2.4 Shape Classification***

The morphological shape of the foramen magnum was classified into seven categories based on the criteria of Radinsky [16] and modified by Murshed et al. [18]: oval, round, egg-shaped (with the broader end forward), tetragonal, pentagonal, hexagonal, and irregular/asymmetrical. Photographs of each foramen were taken from a fixed superior viewpoint using a tripod-mounted Nikon D7500 digital camera, with a calibration scale included for reference.

#### ***2.5 Statistical Analysis***

Data were entered in Microsoft Excel and analysed using IBM SPSS Statistics version 26.0. Continuous variables were summarised as mean  $\pm$  SD, and shape categories were summarised as frequencies and percentages. The unpaired Student's t-test was used to evaluate sexual dimorphism in dimensional parameters, and the chi-square test was used for categorical comparisons. Discriminant function analysis was performed to assess the predictive accuracy of FM dimensions in determining the sex of the specimens. Statistical significance was set at  $p < 0.05$ .

### **3. Results**

The morphometric parameters of the 120 adult skulls are summarised in Table 2. The mean antero-posterior diameter of the foramen magnum was  $33.62 \pm 2.71$  mm (range 28.40–39.10 mm), and the mean transverse diameter was  $28.94 \pm 2.34$  mm (range 23.20–33.80 mm). The mean foramen magnum index was  $86.10 \pm 4.62$ , indicating that the antero-posterior dimension exceeds the transverse dimension in most specimens. The mean foramen magnum area, calculated using

Radinsky's formula, was  $767.20 \pm 89.40 \text{ mm}^2$ , while that calculated using Teixeira's formula was slightly lower at  $749.80 \pm 84.60 \text{ mm}^2$ .

**Table 2. Morphometric Parameters of the Foramen Magnum**

<b>Parameter</b>	<b>Mean (mm)</b>	<b>SD</b>	<b>Min (mm)</b>	<b>Max (mm)</b>
Antero-posterior diameter (FM-AP)	33.62	2.71	28.40	39.10
Transverse diameter (FM-T)	28.94	2.34	23.20	33.80
Foramen magnum index (FMI)	86.10	4.62	75.20	96.80
Foramen magnum area (Radinsky)	767.20	89.40	581.30	962.40
Foramen magnum area (Teixeira)	749.80	84.60	570.10	948.20

Sexual dimorphism was clearly evident in all dimensional parameters. Male skulls had significantly greater FM-AP ( $34.78 \pm 2.41$  vs  $31.46 \pm 1.92$  mm,  $p < 0.001$ ), FM-T ( $29.83 \pm 2.18$  vs  $27.27 \pm 2.04$  mm,  $p < 0.001$ ), and Radinsky area ( $812.30 \pm 78.20$  vs  $683.40 \pm 71.60 \text{ mm}^2$ ,  $p < 0.001$ ) than female skulls. Discriminant function analysis using FM-AP and FM-T as predictors yielded a sex classification accuracy of 78.3% (Wilks'  $\lambda = 0.652$ ,  $p < 0.001$ ), supporting the utility of FM dimensions in forensic sex determination, although these dimensions alone cannot achieve forensic-grade certainty without other skeletal markers.

Morphological shape distribution is summarised in Table 3. The most common configuration was the oval shape (36.7%), followed by round (19.2%) and egg-shaped (15.0%). Tetragonal, pentagonal, hexagonal, and irregular variants together accounted for the remaining 29.1%. No significant difference in shape distribution was found between male and female skulls (chi-square  $p = 0.418$ ), suggesting that shape is not a reliable sole indicator of sex.

**Table 3. Frequency Distribution of Foramen Magnum Shapes**

<b>Foramen Magnum Shape</b>	<b>Frequency (n)</b>	<b>Percentage (%)</b>
Oval	44	36.7
Round	23	19.2
Egg-shaped	18	15.0
Tetragonal	13	10.8
Pentagonal	9	7.5
Hexagonal	7	5.8
Irregular / Asymmetrical	6	5.0

#### **4. Discussion**

The present study provides comprehensive morphometric and morphological data on the foramen magnum derived from 120 adult dry skulls of South Indian origin. The mean antero-posterior diameter (33.62 mm) and transverse diameter (28.94 mm) observed in this sample are broadly consistent with previous Indian and international studies. Manoel et al. [19] reported a mean FM-AP of 36.45 mm in Brazilian skulls, whereas Murshed et al. [18] documented an FM-AP of 35.40 mm in Turkish skulls, both slightly larger than our findings. Among Indian studies, Singh and Talwar [20] noted a mean FM-AP of 33.18 mm in North Indian skulls, while Kanchan et al. [21] reported 32.74 mm in a sample from Karnataka — values closely comparable to ours. These differences reinforce the importance of population-specific reference data for clinical and forensic application [13].

The clear sexual dimorphism observed in the present study aligns with the findings of Routal et al. [22], Catalina-Herrera [23], and Gapert et al. [24], all of whom reported significantly larger FM dimensions in male skulls. The discriminant function classification accuracy of 78.3% in our sample is consistent with the 70–82% range reported in the wider literature [25,26]. While this places the FM among the more useful single skeletal regions for sex estimation, it remains less accurate than the pelvis or skull base as a whole. Forensic practitioners should therefore use FM dimensions in conjunction with other skeletal features for robust sex determination [27].

From a neurosurgical standpoint, the FM dimensions documented here have direct relevance to skull base surgery. The far-lateral and extreme lateral approaches to the ventral foramen magnum require working corridors that are constrained by the antero-posterior diameter and the position of the occipital condyles [6,28]. A narrow FM (FM-AP < 30 mm) increases the technical difficulty of clipping vertebrobasilar aneurysms and resecting clival chordomas, and may necessitate partial occipital condylectomy to achieve adequate exposure. Conversely, a particularly wide FM may be associated with developmental anomalies such as Chiari malformation or basilar invagination and merits careful preoperative imaging assessment [8,29].

The dominance of the oval shape (36.7%) and the relatively low frequency of geometrically complex shapes (pentagonal, hexagonal, irregular) in our series corroborates the findings of Murshed et al. [18] and Gruber et al. [30]. The variability of shapes nonetheless implies that no single 'standard' geometric model adequately represents the FM. Cross-sectional imaging-based

three-dimensional reconstructions are therefore recommended in any planned surgical approach. The slightly larger area derived from Radinsky's formula compared with Teixeira's formula reflects the geometric assumptions of each — Radinsky models the FM as a perfect ellipse, whereas Teixeira's correction accounts for the polygonal deviations frequently observed in real specimens [17].

The foramen magnum is also of importance in the diagnosis of foramen magnum meningioma, achondroplasia-related stenosis, capitalization of the atlas, and basilar invagination — conditions that may impinge upon the medulla oblongata and cause progressive cervico-medullary compression [31]. Reference values from this study can support clinicians in interpreting cross-sectional imaging in the South Indian population, where prior normative data have been limited.

The principal strengths of the present study include its relatively large sample size, single-observer methodology, use of multiple area formulas, and inclusion of seven shape categories. Limitations include the use of dry skulls only (precluding evaluation of soft-tissue relations), the absence of three-dimensional volumetric analysis, and the limitation of the sample to a single tertiary care institution. Future studies should incorporate computed tomography-based volumetric analysis and a multicentric design to enhance generalizability.

## **5. Conclusion**

The foramen magnum exhibits clinically meaningful sexual dimorphism and considerable shape variability in the South Indian population, with mean antero-posterior diameter of 33.62 mm, transverse diameter of 28.94 mm, and a predominance of the oval shape. These population-specific reference values are of significant value to neurosurgeons planning posterior fossa or transcondylar approaches, to radiologists interpreting craniovertebral junction imaging, and to forensic anthropologists determining the sex of unidentified skeletal remains. Awareness of regional morphometric variation should guide the responsible application of textbook norms to individual patient care.

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