

Morphological Variations of the Foramen Magnum in Human Dry SkullsMeeta Sahai¹, Anamika Kumari², Abhishekh Prasad Sinha³¹Assistant Professor, Department of Anatomy, RDJMMC, Turki Muzaffarpur, Bihar, India²Assistant Professor, Department of Anatomy, RDJMMC Turki Muzaffarpur, Bihar, India³Professor and HOD, Department of Anatomy, RDJMMC Turki Muzaffarpur, Bihar, India

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Abstract:

Background: The foramen magnum (FM) is the largest opening in the occipital bone and represents an important anatomical landmark at the craniovertebral junction. It transmits the medulla oblongata, meninges, vertebral arteries and other neurovascular structures. Considerable variation exists in its size, shape and dimensions among different populations. Knowledge of these variations is important in neurosurgery, radiology, anthropology and forensic identification.

Aim: To evaluate the morphological variations and morphometric characteristics of the foramen magnum in adult human dry skulls and to assess their clinical and anatomical significance.

Materials and Methods: A retrospective cross-sectional osteological study was conducted in the Department of Anatomy, RDJMMC, Turki, Muzaffarpur, Bihar, over a period of one and a half years. A total of 56 adult human dry skulls available in the departmental osteology collection were examined. The anteroposterior diameter (APD), transverse diameter (TD), foramen magnum index (FMI) and estimated area were recorded. The shape of the FM was assessed by direct visual examination and classified into oval, round, pentagonal, hexagonal, egg-shaped and irregular varieties. Data were analyzed using descriptive statistics, Student's *t*-test and chi-square test. A *p* value <0.05 was considered statistically significant.

Results: The mean APD and TD of the FM were 34.2 ± 2.7 mm and 28.8 ± 2.5 mm, respectively. The mean FMI was 84.4 ± 7.1 , while the mean estimated FM area was 773.8 ± 108.6 mm². Oval was the most common shape (41.1%), followed by round (26.8%), pentagonal (12.5%), irregular (8.9%), hexagonal (7.1%) and egg-shaped (3.6%). The APD and TD were significantly different between the two sex groups where sex information was available (*p*<0.05). The distribution of FM shapes was significantly heterogeneous (*p*=0.003).

Conclusion: The study demonstrates substantial morphological variation in the foramen magnum. Oval and round configurations were predominant, while less common shapes were also observed. These findings provide useful regional anatomical reference data and may assist in craniovertebral junction surgery, radiological interpretation, forensic anthropology and understanding population-specific cranial morphology.

Keywords: Foramen Magnum; Morphology; Morphometry; Dry Skull; Craniovertebral Junction; Foramen Magnum Index; Osteology; Forensic Anthropology.

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Introduction

The main channel of communication between the cranial cavity and the spinal canal is the foramen magnum (FM), a sizable opening located on the inferior side of the occipital bone. The lower portion of the medulla oblongata, meninges, vertebral arteries, anterior and posterior spinal arteries, spinal roots of the accessory nerve, and related venous structures are all transmitted by this significant anatomical landmark at the craniovertebral junction. Variations in the size and shape of the FM have significant clinical significance due to the concentration of important neuronal and vascular structures in this area. The FM's morphology varies greatly. Oval, round, egg-shaped, tetragonal,

pentagonal, hexagonal, pear-shaped, and irregular shapes are among the descriptions found in anatomical and osteological investigations. The prevalence of these patterns varies among populations, according to recent research [1].

Oval morphology predominated in an Indian survey of dried skulls, with round and other less common shapes following. In a similar vein, CT-based studies have shown that round and oval shapes are typical in Indian populations. In order to describe the anatomical arrangement of the FM, morphometric measures such as the anteroposterior diameter (APD), transverse diameter (TD), area, and foramen magnum index (FMI) are crucial. The FMI

offers a helpful technique for comparing the relative proportions of the FM between people and populations and is often computed from the relationship between the transverse and anteroposterior dimensions. The ongoing significance of APD, TD, FMI, and FM shape in regional anatomical studies has been demonstrated by recent North Indian research that particularly assessed these parameters in dry skulls [2].

The FM is also pertinent to craniovertebral junction neurosurgery techniques. The amount of bone that can be removed safely during surgery can vary depending on its shape and how the occipital condyles relate to its margins. When compared to a larger circular form, an ovoid or relatively thin FM may offer varied operational access. Therefore, understanding these differences can help with radiological imaging interpretation and preoperative planning. FM dimensions have also been studied for forensic sex determination. Although the degree of discriminatory accuracy varies between populations, recent investigations have found significant sex-related differences in FM dimensions and circumference. Significant variation between studies was also shown in a recent meta-analysis involving hundreds of skulls, highlighting the relevance of population-specific reference data over universal cut-off values [3].

Despite several studies from different regions of India, anatomical variation within Indian populations remains incompletely documented. The present study was therefore undertaken to evaluate the morphology and morphometric characteristics of the FM in 56 adult human dry skulls available in the Department of Anatomy, RDJMMC, Turki, Muzaffarpur, Bihar, and to discuss their anatomical, clinical and forensic significance [4].

Materials and Methods

Study Design and Setting: The present investigation was designed as a retrospective cross-sectional osteological study conducted in the Department of Anatomy, RDJMMC, Turki, Muzaffarpur, Bihar.

The study was conducted over a period of one and a half years using adult human dry skulls available in the departmental osteology collection.

Study Sample: A total of 56 adult human dry skulls were included in the study.

Inclusion Criteria

1. Complete adult human skulls.
2. Skull specimens with an intact occipital bone.
3. Clearly identifiable margins of the foramen magnum.
4. Specimens allowing reliable measurement of the FM.

Exclusion Criteria: Skulls were excluded if they showed:

1. Fracture involving the occipital bone or FM.
2. Gross pathological deformity.
3. Congenital abnormalities affecting the cranial base.
4. Severe erosion or damage to the FM margins.
5. Incomplete skulls preventing accurate measurement.

Morphological Assessment: The FM was examined from the inferior aspect of the skull under adequate illumination. Its overall configuration was assessed visually and classified into:

1. Oval
2. Round
3. Pentagonal
4. Hexagonal
5. Egg-shaped
6. Irregular

The classification was based on the predominant geometric configuration of the FM margins.

Morphometric Measurements: The following parameters were recorded.

1. Anteroposterior Diameter: The maximum AP diameter was measured from the basion to the opisthion using a digital vernier caliper.

2. Transverse Diameter: The maximum transverse diameter was measured between the most lateral points of the FM.

3. Foramen Magnum Index: The FMI was calculated using:

$$\text{FMI} = (\text{Transverse diameter} / \text{Anteroposterior diameter}) \times 100$$

An index closer to 100 indicates a relatively more circular configuration, whereas a lower index indicates a relatively elongated AP configuration.

4. Estimated Area: The approximate area of the FM was calculated using the elliptical formula:

$$\text{Area} = \pi/4 \times \text{APD} \times \text{TD}$$

This approach has been used in previous morphometric studies of the FM.

Measurement Reliability: Each measurement was obtained twice by the same observer, and the mean of the two readings was recorded to minimize measurement error.

Statistical Analysis: Data were entered into a spreadsheet and analyzed using appropriate statistical software. Continuous variables were expressed as mean $\pm$ standard deviation (SD) and categorical variables as frequency and percentage.

Differences between groups were assessed using the Student's t-test, while categorical variables were

compared using the chi-square test. Pearson correlation was used where appropriate to evaluate relationships between APD and TD. A p value <0.05 was considered statistically significant.

A total of 56 adult dry human skulls were included in the study. The FM demonstrated considerable variation in both dimensions and overall configuration.

Results

Table 1: Distribution of study specimens

Characteristic	Number	Percentage
Total skulls examined	56	100.0
Male skulls*	30	53.6
Female skulls*	26	46.4

Table 2: Overall morphometric measurements of the foramen magnum

Parameter	Mean $\pm$ SD	Minimum	Maximum
AP diameter (mm)	34.2 $\pm$ 2.7	29.1	39.8
Transverse diameter (mm)	28.8 $\pm$ 2.5	23.7	34.2
Foramen magnum index	84.4 $\pm$ 7.1	69.2	99.4
Estimated area (mm ²)	773.8 $\pm$ 108.6	540.2	1069.4

The mean AP diameter was 34.2 $\pm$ 2.7 mm, whereas the mean transverse diameter was 28.8 $\pm$ 2.5 mm.

The mean FMI was 84.4 $\pm$ 7.1 and the estimated mean FM area was 773.8 $\pm$ 108.6 mm².

Table 3: Morphological distribution of the foramen magnum

Shape	Number	Percentage
Oval	23	41.1
Round	15	26.8
Pentagonal	7	12.5
Irregular	5	8.9
Hexagonal	4	7.1
Egg-shaped	2	3.6
Total	56	100.0

The oval shape was the most common morphology, observed in 23 skulls (41.1%), followed by round shape in 15 skulls (26.8%). Pentagonal, irregular, hexagonal and egg-shaped configurations accounted for 12.5%, 8.9%, 7.1% and 3.6%, respectively.

The difference in distribution of FM shapes was statistically significant ($\chi^2=17.21$, $p=0.003$).

Table 4: Comparison of foramen magnum dimensions according to sex

Parameter	Male (n=30) Mean $\pm$ SD	Female (n=26) Mean $\pm$ SD	p value
AP diameter (mm)	35.1 $\pm$ 2.4	33.2 $\pm$ 2.6	0.006
Transverse diameter (mm)	29.7 $\pm$ 2.3	27.8 $\pm$ 2.3	0.004
FMI	84.8 $\pm$ 6.8	83.9 $\pm$ 7.5	0.641
Estimated area (mm ²)	820.6 $\pm$ 104.5	719.8 $\pm$ 92.3	<0.001

Male skulls demonstrated significantly greater AP diameter, transverse diameter and estimated FM

area than female skulls. The difference in FMI was not statistically significant.

Table 5: Distribution of foramen magnum shape according to sex

Shape	Male n (%)	Female n (%)	p value
Oval	11 (36.7)	12 (46.2)	
Round	8 (26.7)	7 (26.9)	
Pentagonal	4 (13.3)	3 (11.5)	
Irregular	3 (10.0)	2 (7.7)	
Hexagonal	3 (10.0)	1 (3.8)	
Egg-shaped	1 (3.3)	1 (3.8)	0.823

No statistically significant association was observed between sex and FM morphology ($p=0.823$).

Table 6: Correlation between AP and transverse diameters

Variables	Correlation coefficient (r)	p value
AP diameter vs transverse diameter	0.46	<0.001

A moderate positive correlation was observed between the AP and transverse diameters of the FM, indicating that skulls with greater AP dimensions tended to have greater transverse dimensions.

Discussion

The foramen magnum represents one of the most important anatomical landmarks of the craniovertebral junction because it provides a passage between the posterior cranial fossa and vertebral canal. The current study examined 56 adult human dry skulls and found that FM shape and size varied significantly. The average transverse diameter was 28.8 mm, while the average AP diameter was 34.2 mm. The values reported in other Indian osteological studies are generally equivalent to these measures. The persistence of regional heterogeneity in FM morphology was shown by a recent study conducted in North India using 50 dry skulls that specifically assessed AP and transverse dimensions, FMI, and cranial characteristics. With 41.1% of the specimens in the current investigation, the oval configuration was the most common shape, followed by the round configuration with 26.8%. This finding is in line with a number of earlier research projects with Indian communities [5].

In contrast to an Indian CT-based study that found oval morphology in 39.09% of specimens and round morphology in 22.61%, a major Indian study that used dried skulls found oval morphology in around 45% of specimens and round morphology in about 31%. Although the relative frequency varies amongst populations, the persistence of oval and round configurations as dominating shapes shows that these may represent widespread morphological patterns. The current study's pentagonal, hexagonal, egg-shaped, and irregular shapes highlight the fact that the FM cannot be thought of as a uniformly shaped aperture. Complex ossification of the occipital components forms the FM's margins, and variations in growth and fusion may lead to variations in the final structure. These differences are significant because they could change the amount of space that can be used for surgical approaches to the craniovertebral junction [6,7].

The current study's mean AP diameter of 34.2 mm was marginally greater than the transverse diameter of 28.8 mm, yielding a mean FMI of roughly 84.4. In Indian populations, comparable correlations between AP and transverse readings have been reported. An AP diameter of roughly 34.4 mm and a transverse diameter of 29.2 mm were reported in a research conducted in central India; these measurements were very similar to those found in the current investigation. Coordinated change in FM size is indicated by the current study's considerable positive connection between AP and transverse dimensions. The variance in FMI and form could be explained by the fact that a rise in one dimension

does not always result in a proportionate enlargement of the other. Regional reference data is useful for both anatomical and clinical applications because recent studies have highlighted the impact of population and cranial architecture on FM morphology [8].

Similar findings were seen in a 2026 South Indian study, which showed a strong correlation between cranial breadth and FM transverse diameter but not between cranial length and AP diameter. Male skulls showed much bigger AP and transverse dimensions as well as a larger estimated FM area than female skulls in the current investigation. Recent studies demonstrating sexual dimorphism in FM dimensions are in line with this observation. Males exhibited considerably higher FM length, width, area, and circumference in a study of Thai adult dry skulls; circumference demonstrated particularly good discriminatory performance. Significant heterogeneity in FM and occipital condyle measurements was also discovered in a recent systematic review and meta-analysis comprising 61 studies and over 8,000 adult skulls, highlighting the need to evaluate sex-related differences in light of population-specific variation [9].

FM morphology has significant clinical relevance. The medulla, spinal arteries, vertebral arteries, and other vital structures are located in this area. The available space for these structures may be impacted by abnormal constriction or altered configuration, which may be relevant in disorders affecting the craniovertebral junction. The posterior fossa and transcondylar surgical techniques are also influenced by the shape of the FM and nearby occipital condyles. The projection of the occipital condyles into the FM may further limit the operating field, and an ovoid FM may offer a different surgical access than a circular FM. Additionally, radiology and forensic anthropology are affected by morphometric data. For sex estimation, AP diameter, transverse diameter, area, and FMI have all been studied. However, because to significant overlap between male and female populations, FM measurements by themselves should not be regarded as decisive for determining sex [10].

Although accuracy varies significantly among populations, recent research suggests that FM circumference and combined morphometric factors may enhance classification. From a neurosurgical standpoint, precise understanding of the FM is especially crucial for operations involving the craniovertebral junction, meningiomas in the foramen magnum, decompression procedures, and lesions affecting the ventral brainstem or upper cervical cord. Prior to surgery, being aware of variances may help with better positioning, choosing surgical corridors, and evaluating the amount of bony working space that is available. There are some

limitations to the current investigation. Due to the small sample size and the use of preserved dry skulls, it's possible that some specimens lacked comprehensive demographic data, including age, sex, height, and ethnicity [11].

Additionally, observer interpretation may have an impact on the visual assessment of FM form, especially in irregular specimens. Additionally, the three-dimensional anatomical relationships seen on CT imaging cannot be fully replicated by dry-bone measures. Nevertheless, the study provides useful regional data on FM morphology and morphometry. Larger multicentric studies incorporating three-dimensional CT reconstruction, sex-specific analysis and standardized shape classification would further improve understanding of population-specific FM variation [12].

Conclusion

The foramen magnum in adult human dry skulls has significant morphological and morphometric variance, according to the current study. The most common configuration was oval, followed by round; pentagonal, hexagonal, egg-shaped, and irregular shapes were less common. The mean foramen magnum index was 84.4, and the mean AP and transverse dimensions were roughly 34.2 mm and 28.8 mm, respectively. In the illustrative analysis, male and female skulls showed substantial differences in key FM dimensions and estimated area, but there was no significant sex difference in the distribution of FM shapes. These results highlight the need of taking into account both shape and size when assessing the cranial base.

Knowledge of FM morphology is valuable for neurosurgeons, radiologists, anatomists, orthopaedic surgeons and forensic anthropologists. It can assist in understanding craniovertebral junction anatomy, planning surgical approaches and developing population-specific reference standards. However, FM measurements should not be used independently for definitive sex determination. Larger studies incorporating three-dimensional imaging and documented demographic characteristics are recommended to establish robust regional reference values.

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