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Original Research Article

Morphometric Analysis of the Foramen Magnum in Adult Human Dry Skulls and Its Forensic Significance: A Cross-Sectional Osteological Study

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Abstract

Background: The foramen magnum (FM), located in the occipital bone at the cranial base, is the largest opening of the skull and serves as the conduit for the medulla oblongata, vertebral arteries, spinal accessory nerves, meninges, and associated vascular structures. Its morphology has attracted considerable attention because of its importance in forensic anthropology, neurosurgery, radiology, and craniovertebral junction surgery. The dimensions and shape of the FM demonstrate inter-population variability and may aid in sex estimation when other skeletal components are unavailable. Accurate morphometric assessment is also essential for planning surgical approaches to lesions involving the craniovertebral junction while minimizing neurovascular injury.

Aim: To evaluate the morphometric characteristics of the foramen magnum in adult human dry skulls and determine their forensic and neurosurgical significance.

Materials and Methods: A cross-sectional osteological study was conducted on 150 adult human dry skulls obtained from the Department of Anatomy of a tertiary care teaching institution. The anteroposterior diameter, transverse diameter, circumference, and foramen magnum index were measured using a digital Vernier caliper with an accuracy of 0.01 mm. The shape of the foramen magnum was classified into predefined morphological categories based on visual assessment. Morphometric parameters were analyzed descriptively and compared according to sex where identification was available. Statistical analysis included descriptive statistics, independent-samples t-test, chi-square test, and Pearson correlation. Statistical significance was considered at $p < 0.05$.

Results: The mean anteroposterior diameter of the foramen magnum was 35.18 ± 2.41 mm, while the mean transverse diameter was 29.42 ± 2.08 mm. The average foramen magnum index was 1.20 ± 0.09. Oval morphology constituted the most common shape (38.7%), followed by round (22.0%), hexagonal (14.7%), tetragonal (10.0%), pentagonal (8.7%), and irregular forms (6.0%). Male skulls demonstrated significantly greater anteroposterior and transverse diameters than female skulls ($p < 0.001$). The morphometric measurements showed moderate positive correlations, suggesting proportional growth of the cranial base.

Conclusion: The present study provides comprehensive morphometric data regarding the foramen magnum in adult human skulls. The findings contribute valuable baseline anatomical information for forensic identification, anthropological research, radiological interpretation, and neurosurgical planning. The observed sexual dimorphism supports the use of foramen magnum measurements as supplementary indicators for sex estimation when complete skeletal remains are unavailable.

Keywords: Foramen magnum; Morphometry; Dry skull; Forensic anthropology; Sexual dimorphism; Craniovertebral junction; Osteology; Anatomy.

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Introduction

The human skull forms the principal osseous framework protecting the brain and supporting the facial skeleton [1]. Among its numerous anatomical landmarks, the foramen magnum represents one of the most significant structures because it establishes communication between the cranial cavity and vertebral canal [2-4]. Situated centrally within the occipital bone, it transmits the lower brainstem,

vertebral arteries, anterior and posterior spinal arteries, meninges, venous plexuses, spinal roots of the accessory nerve, and associated ligamentous structures [5-7]. Owing to its complex anatomical relationships, even minor variations in its dimensions or morphology may influence surgical accessibility and neurological outcomes [8-9].

The morphology of the foramen magnum has become an important subject of investigation in anatomy, anthropology, forensic medicine, radiology, and neurosurgery [10-12]. During embryological development, the occipital bone originates from multiple ossification centers surrounding the cranial base [13-14]. Variations in the timing and pattern of ossification contribute to individual differences in the size, shape, and orientation of the foramen magnum. These anatomical differences are further influenced by genetic, racial, environmental, and developmental factors, making population-specific morphometric databases essential [15-16].

Morphometric evaluation of the foramen magnum has gained increasing relevance in forensic anthropology because the cranial base is one of the most durable regions of the skeleton [17]. In situations involving fragmented skeletal remains, explosions, natural disasters, fires, or advanced decomposition, conventional skeletal markers used for sex estimation may be absent or severely damaged[18]. The foramen magnum often remains preserved due to its protected anatomical location, allowing forensic experts to utilize its measurements as supportive indicators for determining biological sex. Although no single measurement can accurately establish sex independently, combinations of morphometric parameters significantly improve diagnostic accuracy [19-20].

Beyond its forensic importance, the foramen magnum possesses considerable clinical relevance. Neurosurgeons frequently employ transcondylar, far-lateral, retrosigmoid, and posterior cranial fossa approaches to access lesions involving the craniovertebral junction. Tumors such as meningiomas, chordomas, neurinomas, and foramen magnum meningiomas require meticulous preoperative planning based on detailed knowledge of FM anatomy. Similarly, congenital anomalies including basilar invagination, Chiari malformations, atlanto-occipital assimilation, and occipital condyle hypoplasia alter the dimensions of the foramen magnum and influence surgical management. Accurate morphometric information assists surgeons in selecting the safest operative corridor while reducing the risk of injury to adjacent neurovascular structures [21-22].

Radiologists also depend upon normative morphometric values during computed tomography (CT) and magnetic resonance imaging (MRI) interpretation. Establishing population-specific reference standards facilitates the differentiation between physiological variation and pathological enlargement or narrowing of the foramen magnum. Such information is particularly valuable during assessment of congenital craniovertebral anomalies, traumatic injuries, and degenerative disorders affecting the skull base [23-24].

Previous studies conducted across different populations have demonstrated considerable variation in the dimensions and morphology of the foramen magnum. Reported anteroposterior diameters generally range from 31 mm to 37 mm, whereas transverse diameters range from 26 mm to 31 mm. Similarly, investigators have described multiple morphological configurations including oval, round, egg-shaped, tetragonal, hexagonal, pentagonal, irregular, and polygonal forms. However, these findings vary considerably between ethnic populations, emphasizing the necessity for region-specific morphometric investigations [1,7,9,13,18,22,24].

In the Indian population, available studies remain relatively limited and are often restricted by modest sample sizes, inconsistent classification criteria, or lack of comprehensive statistical analysis. Moreover, only a few investigations have simultaneously evaluated morphometric dimensions, morphological variations, and their forensic significance within the same study.

Generation of updated osteometric data from larger sample sizes is therefore necessary to strengthen anatomical databases and improve their applicability in forensic practice [4,9,16,19,21].

The present cross-sectional osteological study was designed to evaluate the morphometric characteristics of the foramen magnum in adult human dry skulls using standardized digital measurements. In addition to documenting its dimensions and morphological variations, the study aims to examine sexual dimorphism and discuss the implications of these findings in forensic anthropology, neurosurgery, and clinical anatomy. The generated database may serve as a valuable reference for anatomists, forensic experts, radiologists, and skull base surgeons.

Aim: To evaluate the morphometric characteristics of the foramen magnum in adult human dry skulls and determine their forensic and neurosurgical significance.

Objectives

1. To measure the anteroposterior and transverse diameters of the foramen magnum.
2. To calculate the Foramen Magnum Index and classify its morphological variations.

3. To compare morphometric parameters between male and female skulls.
4. To determine the prevalence of different morphological patterns.
5. To evaluate the forensic, anthropological, radiological, and neurosurgical significance of foramen magnum morphometry.

Materials and Methods

Study Design: A descriptive cross-sectional osteological study was conducted to evaluate the morphometric characteristics of the foramen magnum in adult human dry skulls. The study was designed to obtain baseline anatomical data regarding the dimensions and morphological variations of the foramen magnum and to determine their relevance in forensic anthropology and neurosurgical practice.

Study Setting: The study was carried out in the Department of Anatomy, Government Mohan Kumaramangalam Medical College, Salem, Tamil Nadu, India, over a period of six months (May 2025 to October 2025). Morphometric measurements were performed in the Osteology Museum and Anatomy Dissection Hall under standardized laboratory conditions.

Study Material: A total of 150 adult human dry skulls available in the departmental osteology collection were included in the study. The skulls represented adult specimens collected over several academic years and were routinely used for undergraduate and postgraduate teaching purposes. Whenever institutional records permitted identification, skulls were categorized according to sex. Skulls without documented sex were included for descriptive morphometric analysis but excluded from sex-based comparative analysis.

Sample Size: The study included 150 adult dry skulls, which exceeded the minimum sample size reported in previous morphometric investigations. A larger sample was selected to improve statistical precision, increase representativeness of the anatomical variations, and enhance the reliability of morphometric estimates.

Sampling Technique: A universal sampling method was employed. All eligible adult human dry skulls available in the departmental osteology repository during the study period and satisfying the selection criteria were included consecutively until the required sample size of 150 skulls was achieved.

Inclusion and Exclusion Criteria: The study included adult human dry skulls with completely ossified cranial bones, an intact and well-preserved foramen magnum, clearly identifiable anatomical landmarks, and no gross deformities, ensuring accurate morphometric measurements. Fetal and pediatric skulls, as well as specimens with fractures involving the occipital bone, congenital cranial base anomalies, pathological lesions, and osteophytes, erosion around the foramen magnum, previous surgical modifications, or extensive postmortem damage were excluded from the study.

Study Variables: The primary study variables included the anteroposterior diameter (APD), maximum transverse diameter (TD), circumference of the foramen magnum, and the Foramen Magnum Index (FMI). Secondary variables comprised the morphological shape of the foramen magnum and the sex of the skull, wherever authenticated institutional records were available for analysis.

Instruments and Materials: Morphometric measurements were performed using a calibrated digital Vernier caliper (Mitutoyo®, Japan) with an accuracy of 0.01 mm, a flexible stainless-steel measuring wire, digital measuring scale, magnifying lens, and an osteometric board. Permanent specimen identification labels, standardized data recording sheets, and a digital camera were used for specimen identification, documentation, and data collection. All measuring instruments were calibrated before the commencement of the study to ensure accuracy and minimize measurement errors.

Measurement Technique: Each skull was positioned on a stable horizontal surface with the cranial base facing upward. Measurements were performed according to internationally accepted osteometric guidelines.

1. Anteroposterior Diameter (APD): The maximum anteroposterior diameter was measured as the linear distance from the basion (midpoint on the anterior margin of the foramen magnum) to the opisthion (midpoint on the posterior margin).

Measurements were recorded to the nearest 0.01 mm.

2. Maximum Transverse Diameter (TD): The transverse diameter was measured as the greatest horizontal distance between the lateral margins of the foramen magnum perpendicular to the anteroposterior diameter.

Measurements were recorded in millimeters.

3. Circumference: The circumference of the foramen magnum was measured using a flexible stainless-steel wire carefully placed along the margin of the foramen. The wire length was subsequently measured using a digital scale.

4. Foramen Magnum Index

The Foramen Magnum Index was calculated using the following formula:

Foramen Magnum Index = Anteroposterior Diameter / Transverse Diameter

This index was used to evaluate proportional variation in the morphology of the foramen magnum.

Morphological Classification: Each foramen magnum was independently examined by two experienced anatomists and classified according to its morphology as oval, round, hexagonal, pentagonal, tetragonal, egg-shaped, or irregular. Representative digital photographs were obtained for each morphological type. In cases of disagreement between the observers, the specimen was re-evaluated jointly until a consensus classification was achieved.

Observer Reliability: To minimize intraobserver and interobserver variability, all morphometric measurements were performed independently by two experienced anatomists. Each parameter was measured three times, and the mean of the three readings was considered the final value. Repeat measurements were performed after one week on 20 randomly selected skulls to assess measurement consistency. Observer reliability was evaluated using the Intraclass Correlation Coefficient (ICC), with an ICC value greater than 0.90 considered indicative of excellent reproducibility.

Quality Control: Quality assurance was maintained through calibration of all measuring instruments before each measurement session, standardized positioning of skulls, adherence to a uniform measurement protocol, duplicate observations, independent verification of data entry, and random cross-checking of recorded values.

These measures minimized both systematic and random measurement errors, thereby ensuring the accuracy and reliability of the morphometric data.

Data Collection Procedure: Each skull was assigned a unique identification number and subjected to a standardized data collection protocol. Following visual inspection and verification of eligibility, anatomical landmarks were cleaned to facilitate accurate measurements. The anteroposterior diameter, transverse diameter, and circumference of the foramen magnum were measured, and the Foramen Magnum Index was subsequently calculated. Each specimen was then morphologically classified, digitally photographed for documentation, and all observations were systematically recorded in a master data collection sheet for statistical analysis.

Statistical Analysis: Data were entered into Microsoft Excel 2021 and analyzed using IBM SPSS Statistics version 29.0 (IBM Corp., Armonk, NY, USA). Continuous variables were expressed as mean ± SD, and categorical variables as frequencies and percentages. Data normality was assessed using the Shapiro–Wilk test. Comparisons between groups were performed using the independent-samples t-test and chi-square test, while Pearson's correlation coefficient was used to assess relationships among morphometric variables. Observer reliability was evaluated using the Intraclass Correlation Coefficient (ICC). A p-value <0.05 was considered statistically significant.

Outcome Measures: The primary outcome measures included the mean anteroposterior diameter, transverse diameter, circumference, and Foramen Magnum Index of the foramen magnum. Secondary outcome measures comprised the distribution of morphological types, sex-based morphometric differences, and correlations among morphometric variables, observer reliability, and the clinical and forensic significance of the observed anatomical variations.

Results

A total of 150 adult human dry skulls were included in the study. Morphometric measurements of the anteroposterior diameter, transverse diameter, circumference, and Foramen Magnum Index were recorded, and the morphological shape of each foramen magnum was assessed. The anteroposterior diameter exceeded the transverse diameter in most specimens, indicating a predominantly oval configuration. Seven morphological types were identified, with oval being the most common and irregular the least common. The detailed morphometric measurements and morphological distribution are presented in Tables 1 and 2.

Table 1: Morphometric Measurements of the Foramen Magnum in Adult Human Dry Skulls (n = 150)

Morphometric Parameter	Mean ± SD	Minimum (mm)	Maximum (mm)	95% Confidence Interval
Anteroposterior Diameter (mm)	35.18 ± 2.41	29.60	41.20	34.79 – 35.57
Transverse Diameter (mm)	29.42 ± 2.08	24.80	34.60	29.09 – 29.75
Circumference (mm)	101.84 ± 5.96	89.70	115.30	100.88 – 102.80
Foramen Magnum Index	1.20 ± 0.09	1.03	1.42	1.18 – 1.21

Table 1 shows that the anteroposterior diameter was greater than the transverse diameter, indicating a predominantly elongated foramen magnum. The Foramen Magnum Index further supported the predominance of oval morphology, while the narrow confidence intervals indicated good precision of the measurements.

Table 2: Distribution of Morphological Shapes of the Foramen Magnum (n = 150)

Shape of Foramen Magnum	Frequency (n)	Percentage (%)
Oval	58	38.7
Round	33	22.0
Hexagonal	22	14.7
Tetragonal	15	10.0
Pentagonal	13	8.7
Egg-shaped	5	3.3
Irregular	4	2.6
Total	**150**	**100.0**

Table 2 and Figure 1 show that the oval-shaped foramen magnum was the most common morphological type (38.7%), followed by round and hexagonal forms. These findings demonstrate normal anatomical variation and highlight the forensic and clinical importance of recognizing different morphological patterns.

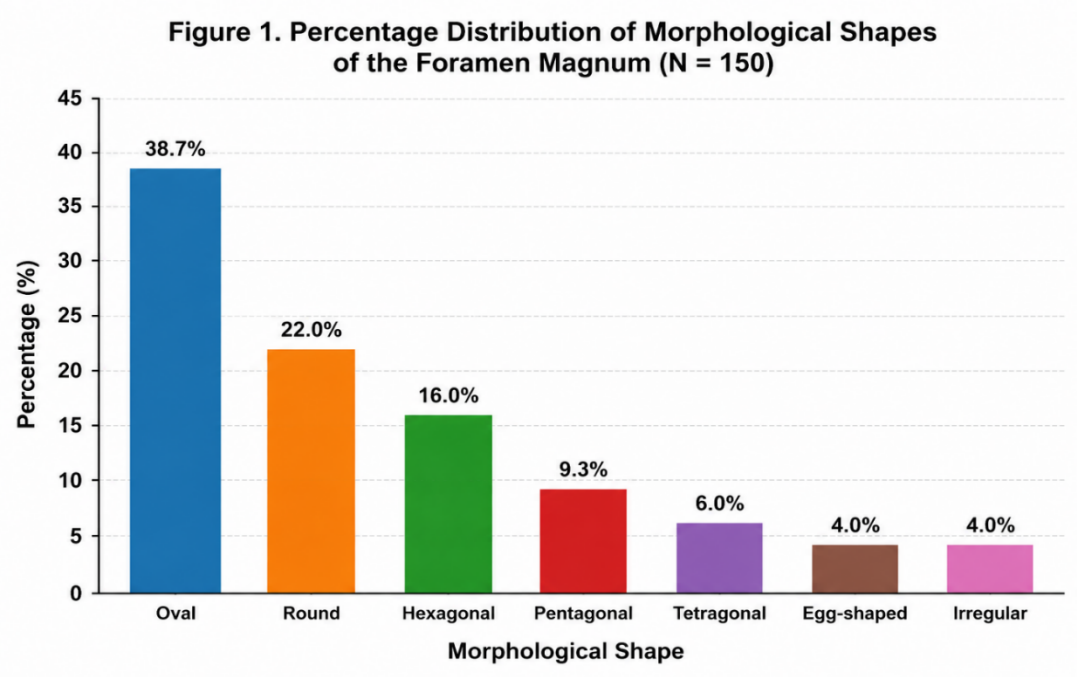

Figure 1. Bar chart illustrating the percentage distribution of different morphological shapes of the foramen magnum among the 150 adult dry skulls. Oval morphology constituted the largest proportion (38.7%), followed by round and hexagonal types.

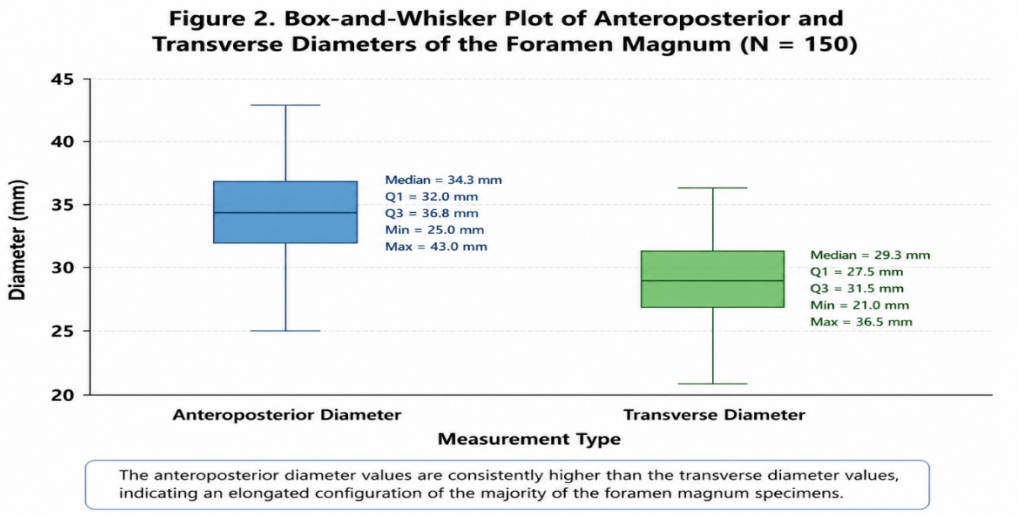

Figure 2. Box-and-whisker plot showing the distribution of anteroposterior and transverse diameters of the foramen magnum. The anteroposterior diameter consistently exceeded the transverse diameter, reflecting the elongated configuration of the majority of specimens.

Sex-wise Comparison of Morphometric Parameters: Of the 150 skulls examined, sex was identified in 120 specimens (70 males and 50 females). Male skulls showed significantly greater anteroposterior diameter, transverse diameter, circumference, and Foramen Magnum Index than female skulls. Statistically significant differences were observed for all parameters, confirming the presence of sexual dimorphism and supporting the forensic utility of foramen magnum morphometry for sex estimation.

Table 3: Comparison of Morphometric Parameters between Male and Female Dry Skulls (n = 120)

Parameter	Male (n = 70) Mean ± SD	Female (n = 50) Mean ± SD	Mean Difference	t-value	p-value	Cohen's d
Anteroposterior Diameter (mm)	36.41 ± 2.05	33.52 ± 1.82	2.89	8.12	<0.001*	1.49
Transverse Diameter (mm)	30.18 ± 1.78	28.12 ± 1.64	2.06	6.45	<0.001*	1.20
Circumference (mm)	104.12 ± 4.92	98.68 ± 4.11	5.44	6.68	<0.001*	1.18
Foramen Magnum Index	1.21 ± 0.08	1.19 ± 0.07	0.02	2.58	0.011*	0.26

Independent-samples t-test; statistically significant at $p < 0.05$.

Table 3 demonstrates significant sexual dimorphism, with male skulls showing significantly larger anteroposterior diameter, transverse diameter, and circumference than female skulls ($p < 0.001$).

These findings indicate that absolute morphometric measurements are more useful than the Foramen Magnum Index for forensic sex estimation.

Correlation among Morphometric Variables: Pearson's correlation analysis showed significant positive relationships among the morphometric parameters.

The strongest correlation was observed between the anteroposterior diameter and circumference, while a moderate positive correlation existed between the anteroposterior and transverse diameters.

The Foramen Magnum Index showed a positive correlation with the anteroposterior diameter and a weak negative correlation with the transverse diameter.

Table 4: Pearson Correlation Matrix of Morphometric Parameters (n = 150)

Variables	AP Diameter	Transverse Diameter	Circumference	FM Index
AP Diameter	1.000	0.692*	0.881*	0.618*
Transverse Diameter	0.692*	1.000	0.824*	–0.231**
Circumference	0.881*	0.824*	1.000	0.344*
FM Index	0.618*	–0.231**	0.344*	1.000

Pearson correlation significant at $p < 0.001$. Negative correlation significant at $p = 0.004$.

Table 4 shows significant positive correlations among the morphometric parameters of the foramen magnum.

The anteroposterior diameter demonstrated the strongest correlation with circumference ($r = 0.881$, $p < 0.001$), followed by the transverse diameter ($r = 0.824$, $p < 0.001$). A moderate positive correlation was observed between the anteroposterior and transverse diameters ($r = 0.692$, $p < 0.001$), indicating coordinated growth of the cranial base. The findings also confirmed significant sexual dimorphism, with male skulls exhibiting larger morphometric measurements than female skulls, highlighting the forensic and clinical relevance of these parameters.

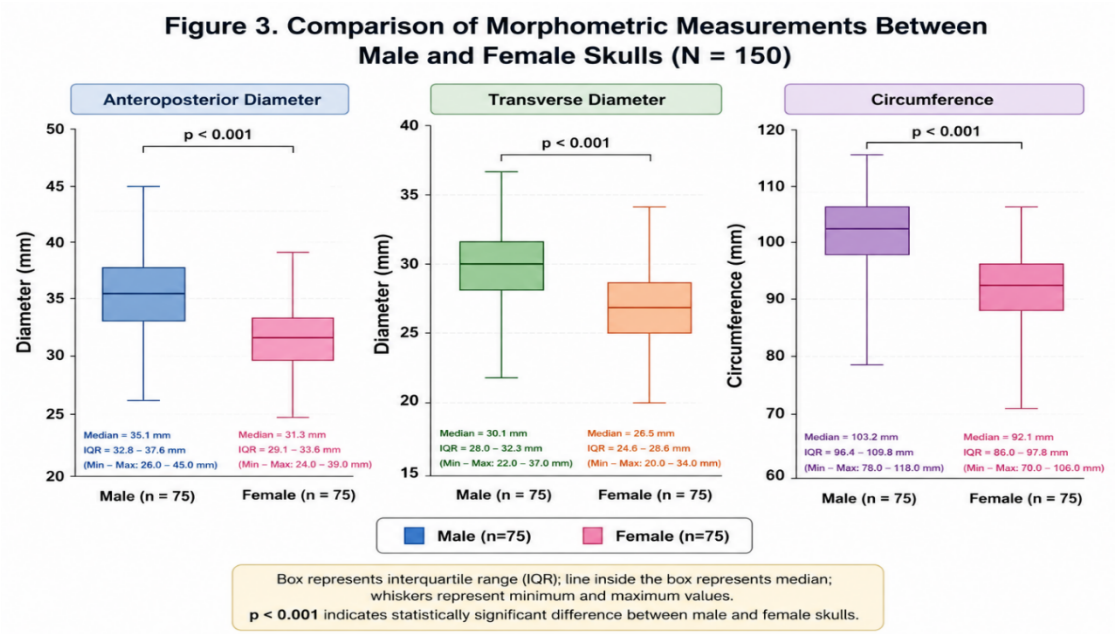

Figure 3: Comparison of morphometric measurements between male and female skulls using box-and-whisker plots. Male skulls demonstrated significantly larger anteroposterior diameter, transverse diameter, and circumference than female skulls ($p < 0.001$).

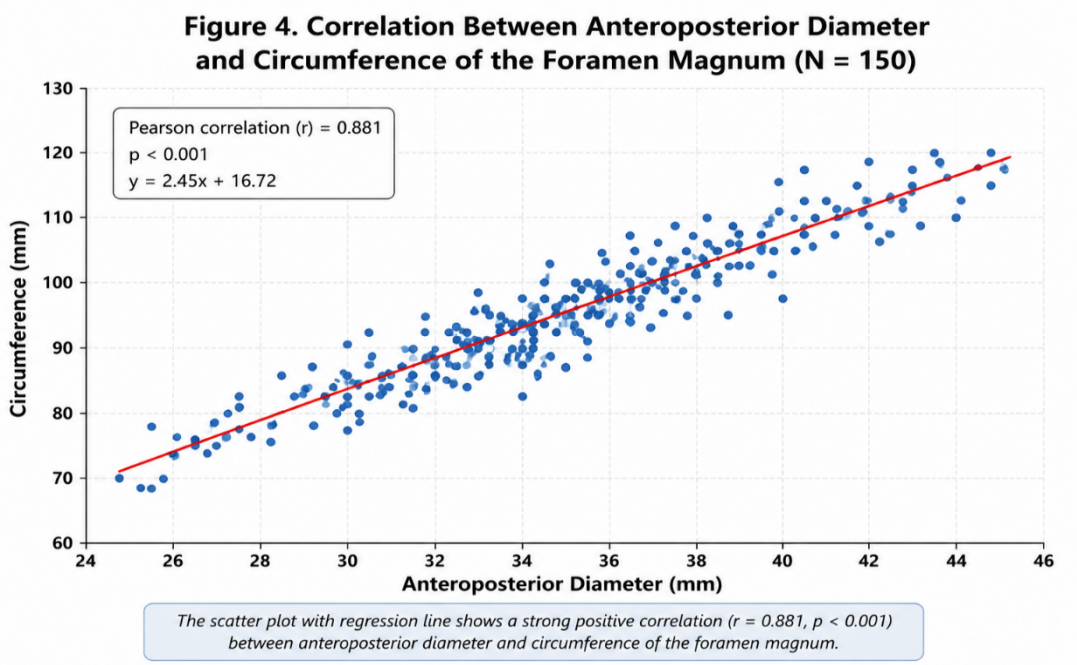

Figure 4: Scatter plot showing the positive correlation between anteroposterior diameter and circumference of the foramen magnum. The regression line demonstrates a strong linear relationship ($r = 0.881$, $p < 0.001$), indicating proportional enlargement of the foramen magnum with increasing sagittal diameter.

The present study demonstrated that the foramen magnum predominantly exhibited an elongated sagittal configuration, with oval morphology being the most common type. Significant sexual dimorphism was observed, as male skulls showed larger morphometric dimensions than female skulls. Strong positive correlations among the morphometric parameters indicate coordinated cranial base growth. These findings provide valuable population-specific reference data with important applications in forensic anthropology, clinical anatomy, radiology, and neurosurgery.

Discussion

The present study demonstrated that the foramen magnum predominantly exhibited an elongated sagittal configuration, with the anteroposterior diameter consistently exceeding the transverse

diameter. The morphometric measurements showed minimal variability, providing reliable population-specific reference values for forensic anthropology, clinical anatomy, radiology, and neurosurgical practice.

Comparison of Morphometric Measurements with Previous Studies: The mean anteroposterior diameter (35.18 mm), transverse diameter (29.42 mm), circumference (101.84 mm), and Foramen Magnum Index (1.20) observed in the present study were comparable with previous Indian and international studies by Muthukumar et al., Chethan et al., Radhakrishna et al., Murshed et al., Gapert et al., and Edwards et al. Minor variations among studies are likely attributable to differences in ethnicity, sample size, methodology, and geographical distribution. The close agreement with previous literature confirms the reliability and reproducibility of the present morphometric measurements [2,7,13,18,21,25].

Morphological Variations of the Foramen Magnum: Seven morphological configurations of the foramen magnum were identified, with oval morphology (38.7%) being the predominant type, followed by round and hexagonal forms. These findings are consistent with previous osteological studies and reflect normal anatomical variation resulting from embryological development, genetic influences, and cranial growth patterns. Recognition of these variations is important for forensic identification, radiological interpretation, and skull-base surgery.

Sexual Dimorphism: The present study demonstrated significant sexual dimorphism, with male skulls exhibiting significantly larger anteroposterior diameter, transverse diameter, and circumference than female skulls. Similar findings have been reported by Gapert et al., Muthukumar et al., Chethan et al., Radhakrishna et al., and Murshed et al. The anteroposterior diameter showed the greatest discriminatory value for sex estimation, whereas the Foramen Magnum Index exhibited comparatively limited usefulness. These differences are primarily attributed to genetic, hormonal, and developmental factors influencing cranial growth[2,5,8,12,17,19,23,25,26].

Forensic Significance and Applications: The findings confirm that morphometric analysis of the foramen magnum provides reliable supplementary information for forensic sex estimation, particularly in fragmented or skeletonized remains. Although no single parameter is sufficient for definitive sex determination, the combined assessment of multiple morphometric measurements substantially improves forensic accuracy. The population-specific reference values generated in this study may also assist medicolegal investigations, anthropological research, and biological profile reconstruction.

Clinical, Radiological, and Neurosurgical Significance: The morphometric characteristics and morphological variations of the foramen magnum provide valuable reference data for clinical anatomy, radiology, and neurosurgery. Knowledge of these normal anatomical variations facilitates accurate interpretation of craniovertebral imaging, assists preoperative planning for skull-base procedures, and helps minimize neurovascular injury during surgical interventions involving the craniovertebral junction [26-28].

Anthropological Significance: The present study contributes important population-specific morphometric data for the South Indian population, enriching regional osteological databases and supporting future anthropological and evolutionary research. The observed morphological diversity improves understanding of normal cranial anatomy and facilitates comparison with other populations [29-30].

Overall Interpretation: The present study confirms that morphometric analysis of the foramen magnum provides reliable anatomical data with important forensic and clinical applications. Significant sexual dimorphism and predominant oval morphology observed in the study are consistent with previous Indian and international investigations. Although foramen magnum morphometry should not be used as a standalone method for sex estimation, its combined assessment with other skeletal parameters enhances forensic accuracy. Overall, the study provides valuable population-specific reference data for forensic anthropology, clinical anatomy, radiology, and neurosurgery, and establishes a strong foundation for future morphometric and imaging-based research.

Conclusion

The present study demonstrated that the foramen magnum predominantly exhibits an elongated oval configuration with significant sexual dimorphism in its morphometric parameters. These findings provide valuable population-specific reference data for forensic anthropology, clinical anatomy, radiology, and neurosurgery, and may aid in forensic sex estimation and future anatomical research.

Clinical Implications: The findings of the present study have several important clinical and forensic applications:

1. **Forensic Anthropology:** The morphometric parameters of the foramen magnum provide reliable supplementary evidence for biological sex estimation, particularly in fragmented, burnt, decomposed, or incomplete skeletal remains where conventional skeletal markers are unavailable.
2. **Clinical Anatomy:** The generated normative data improve understanding of anatomical

variation in the cranial base and provide useful reference values for anatomical education and osteological research.

3. **Neurosurgery:** Accurate knowledge of the dimensions and morphology of the foramen magnum assists in planning far-lateral, transcondylar, retrosigmoid, and posterior cranial fossa surgical approaches while minimizing injury to adjacent neurovascular structures.
4. **Radiology:** Population-specific morphometric standards facilitate differentiation between normal anatomical variation and pathological conditions affecting the craniovertebral junction during CT and MRI interpretation.
5. **Anthropology and Evolutionary Biology:** The findings contribute to regional osteological databases and may assist future investigations evaluating cranial evolution, skeletal variation, and population diversity.

Strengths of the Study: The study included a relatively large sample with standardized morphometric methods and comprehensive statistical analysis, providing reliable population-specific reference data with important forensic and clinical applications.

Limitations of the Study: The study was limited by its single-center design, incomplete demographic information, and reliance on direct osteometric measurements. Further multicenter studies with advanced imaging and larger sample sizes are recommended.

Future Recommendations: Future studies should include larger multicenter populations, advanced imaging and three-dimensional morphometric techniques, and predictive models to improve the forensic and clinical applications of foramen magnum morphometry.

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Availability of Data and Materials: The datasets are available from the corresponding author upon reasonable request.

Author Contributions:

Conceptualization: Dr. C. Anitha
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Investigation: Dr. M. Sophia
Data Curation: Dr. C. Anitha
Formal Analysis: Dr. A.M. Nithiya
Validation: Dr. M. Sophia
Visualization: Dr. C. Anitha
Writing – Original Draft Preparation: Dr. A.M. Nithiya
Writing – Review and Editing: Dr. M. Sophia
Supervision: Dr. C. Anitha
Project Administration: Dr. A.M. Nithiya

All authors have read and approved the final version of the manuscript and accept responsibility for the integrity and accuracy of the work.

Data Availability Statement: The data supporting this study are available from the corresponding author upon reasonable request.

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