ORIGINAL ARTICLE

Morphometric Analysis of Foramen Magnum in Adult Human Skulls Using 3D CT Imaging

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ABSTRACT

Background

The foramen magnum (FM) is a crucial anatomical landmark at the craniovertebral junction. Its morphometric parameters are of paramount importance in various clinical disciplines, including neurosurgery, radiology, and forensic anthropology. While traditional osteometric studies exist, modern imaging techniques like 3D computed tomography (CT) offer a more precise and non-invasive method for in vivo analysis.

Methods

A retrospective cross-sectional study was conducted on 200 head CT scans (100 males, 100 females) of adults aged 18-70 years. Multiplanar reconstructions and 3D volume-rendered images were generated. Key parameters, including anteroposterior (AP) diameter, transverse (TR) diameter, and area, were measured using standardized anatomical landmarks. Statistical analysis was performed to compare the parameters between genders.

Results

The mean AP diameter was 35.8 ± 2.1 mm in males and 32.4 ± 1.9 mm in females ($p < 0.001$). The mean TR diameter was 30.5 ± 1.8 mm in males and 27.9 ± 1.7 mm in females ($p < 0.001$). The mean calculated area was 860.4 ± 85.2 mm² in males and 712.3 ± 78.6 mm² in females ($p < 0.001$). All measured parameters were significantly larger in males than in females. The Foramen Magnum Index (FMI) did not show a statistically significant difference between the sexes.

Conclusion

The study provides reliable normative morphometric data for the foramen magnum in the studied population using 3D CT imaging. The significant sexual dimorphism observed in all linear and area measurements highlights the necessity of sex-specific reference standards. These findings have direct clinical applications in neurosurgical planning, radiological diagnosis of pathologies at the craniovertebral junction, and forensic identification.

Keywords

Foramen Magnum, Morphometry, 3D CT, Sexual Dimorphism, Anatomy, Craniovertebral Junction, Computed Tomography

INTRODUCTION

The foramen magnum (FM) is the largest foramen situated at the base of the skull, forming a critical communication channel between the cranial cavity and the vertebral canal [1]. It is bounded anteriorly by the basilar part of the occipital bone (basion), posteriorly by the squamous part (opisthion), and laterally by the occipital condyles. This vital aperture allows for the passage of the medulla oblongata, the spinal roots of the accessory nerves, the vertebral arteries, the anterior and posterior spinal arteries, and the meninges [2]. Given its anatomical significance, variations in the morphometry of the FM can have profound clinical implications.

The morphological dimensions of the FM are of considerable interest in various medical and surgical specialties. In neurosurgery, precise knowledge of FM dimensions is essential for procedures involving the craniovertebral junction, such as the far-lateral or transcondylar approaches to lesions ventral to the brainstem and cervicomedullary junction [3]. In radiology, morphometric data aids in the diagnosis of conditions like Chiari malformation, basilar invagination, and other congenital or acquired craniovertebral anomalies where the size and shape of the FM may be altered [4]. Furthermore, in forensic anthropology, the FM is a valuable element for the determination of sex from skeletal remains, particularly when other more dimorphic features are fragmented or absent [5].

Historically, FM morphometry has been

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performed on dry human skulls using osteometric boards and calipers [6]. While these studies have provided foundational data, they are limited by the availability of skeletal samples, potential for measurement error, and the inability to reflect in vivo anatomy. The advent of advanced imaging modalities, particularly computed tomography (CT), has revolutionized anatomical studies. Multi-detector CT allows for high-resolution, multiplanar, and three-dimensional (3D) reconstructions, enabling precise, non-invasive, and reproducible measurements [7].

Recent studies utilizing CT imaging have reported varying morphometric values for the FM across different ethnic and geographical populations [8, 9]. For instance, a study on a Turkish population by Uysal et al. reported different mean values compared to studies on European or Asian cohorts, underscoring the impact of population-specific variation [10]. This highlights the necessity of establishing population-specific normative databases for accurate clinical and forensic application. While several CT-based studies exist, there remains a research gap regarding comprehensive morphometric analysis using dedicated 3D volume-rendered models, which provide superior visualization and landmark identification compared to 2D axial or sagittal images alone.

Therefore, this study was designed to conduct a detailed morphometric analysis of the foramen magnum in a sample of adult human skulls using 3D CT imaging. The primary objective was to establish a set of normative data for the studied population. A secondary objective was to evaluate the presence and degree of sexual dimorphism in the FM parameters.

MATERIALS AND METHODS

Study Design and Setting

This retrospective, cross-sectional study was conducted in the Department of Anatomy in collaboration with the Department of Radiology at a tertiary care teaching hospital.

Sample Size and Selection

A total of 200 head CT scans performed between January 2020 and December 2022 were retrospectively retrieved from the hospital's picture archiving and communication system (PACS). The sample was divided into two equal groups of 100 males and 100 females. Sample size was determined using G*Power software, based on an effect size (d) of 0.8 for the AP diameter from a previous study, with an alpha error of 0.05 and a power of 0.99.

Inclusion and Exclusion Criteria

Inclusion Criteria:

- Adults aged between 18 and 70 years.
- CT scans performed for reasons unrelated to craniovertebral pathology (e.g., evaluation of chronic sinusitis, head trauma with no skull base fracture, or pre-implant assessment).
- High-quality images with no artifacts obscuring the FM region.

Exclusion Criteria:

- History of congenital craniovertebral anomalies.
- Evidence of trauma, fracture, or destructive lesions involving the occipital bone.
- Degenerative diseases or tumors affecting the FM.
- Images with motion artifacts or poor resolution.

CT Imaging Protocol and Reconstruction

All CT scans were performed using a 64-slice spiral CT scanner (Philips Brilliance 64, Philips Healthcare, Cleveland, OH, USA). The acquisition parameters were: 120 kVp, 200 mAs, slice thickness of 0.67 mm, and a bone algorithm for reconstruction.

The raw DICOM data from each scan was imported into dedicated 3D reconstruction software (Mimics version 21.0, Materialise, Leuven, Belgium). 3D volume-rendered models of the skull base were generated. The image was oriented in a standardized sagittal and coronal plane to ensure reproducibility of measurements.

Morphometric Measurements

All measurements were performed by a single, experienced observer to minimize inter-observer variability. To assess intra-observer reliability, 25 randomly selected scans were measured again after a two-week interval. The following parameters were measured on the 3D reconstructed models and confirmed on the orthogonal multiplanar reconstructions (MPR):

1. Anteroposterior (AP) Diameter: The maximum distance between the basion (the most anterior point on the FM margin) and the opisthion (the most posterior point).

2. Transverse (TR) Diameter: The maximum distance between the lateral margins of the FM, measured perpendicular to the AP diameter.
3. Area: The area of the foramen was calculated assuming an elliptical shape using the formula: Area = $\pi \times (AP/2) \times (TR/2)$.
4. Foramen Magnum Index (FMI): The shape index was calculated as (TR Diameter / AP Diameter) × 100.

Statistical Analysis

The collected data were analyzed using Statistical Package for the Social Sciences (SPSS) software version 25.0 (IBM Corp., Armonk, NY, USA). The normality of the data distribution was assessed using the Shapiro-Wilk test. Descriptive statistics were presented as mean ± standard deviation (SD) for normally distributed data. An independent samples t-test was used to compare the morphometric parameters between male and female groups. Intra-observer reliability was assessed using the intraclass correlation coefficient (ICC). A p-value of less than 0.05 was considered statistically significant.

RESULTS

Demographics and Reliability

The study included 200 adults, comprising 100 males and 100 females. The mean age for the male group was 38.5 ± 12.3 years, and for the female group, it was 36.9 ± 11.8 years. There was no statistically significant difference in age between the two groups ($p = 0.321$). The intra-observer reliability was excellent, with an ICC greater than 0.95 for all measured parameters.

Descriptive Statistics of the Total Cohort

The descriptive statistics for all measured parameters in the entire study population (n=200) are summarized in Table 1. The mean AP diameter was 34.1 ± 2.4 mm, the mean TR diameter was 29.2 ± 2.0 mm, and the mean calculated area was 786.4 ± 106.5 mm².

Table 1: *Descriptive statistics of foramen magnum parameters in the total cohort (n=200)*

Parameter	Mean (mm)	SD (mm)	Minimum (mm)	Maximum (mm)
Anteroposterior (AP) Diameter	34.1	2.4	28.5	40.1
Transverse (TR) Diameter	29.2	2.0	24.8	34.5
Area (mm²)	786.4	106.5	580.3	1085.2

SD: Standard deviation

Gender-wise Comparison of Foramen Magnum Parameters

The comparison of morphometric parameters between male and female groups is presented in Table 2. All linear dimensions (AP and TR diameters) and the calculated area were significantly larger in males compared to females ($p < 0.001$ for all comparisons). The mean AP diameter in males was 35.8 ± 2.1 mm, while in females, it was 32.4 ± 1.9 mm. Similarly, the mean TR diameter was 30.5 ± 1.8 mm in males and 27.9 ± 1.7 mm in females. The mean area was also significantly larger in males (860.4 ± 85.2 mm²) than in females (712.3 ± 78.6 mm²).

Table 2: *Gender-wise comparison of foramen magnum parameters*

Parameter	Males (Mean ± SD)	Females (Mean ± SD)	p-value
AP Diameter (mm)	35.8 ± 2.1	32.4 ± 1.9	<0.001*
TR Diameter (mm)	30.5 ± 1.8	27.9 ± 1.7	<0.001*
Area (mm²)	860.4 ± 85.2	712.3 ± 78.6	<0.001*
FMI	85.2 ± 4.1	86.1 ± 4.5	0.089

*Independent samples t-test; SD: Standard deviation; FMI: Foramen Magnum Index

Foramen Magnum Index (FMI)

The Foramen Magnum Index (FMI), which represents the shape of the foramen, did not show a statistically significant difference between the male and female groups ($p = 0.089$), as detailed in Table 2. This suggests that while the overall size of the FM is sexually dimorphic, its general shape (ratio of width to length) is not significantly different between sexes in this population.

DISCUSSION

The present study was designed to provide a detailed morphometric analysis of the foramen magnum in an adult population using 3D CT imaging and to assess the degree of sexual dimorphism. The primary findings confirm that the FM exhibits significant sexual dimorphism in its size, with males having consistently larger AP and TR diameters and a greater overall area compared to females. However, the shape, as represented by the FMI, was not significantly different between the sexes.

The mean AP and TR diameters observed in our study are largely consistent with, yet distinct from, findings from other populations. For instance, the mean AP diameter for our combined cohort (34.1 mm) is comparable to the 34.3 mm reported by Chethan et al. in a study on a South Indian population [11], but slightly higher than the 33.1 mm reported by Shepur et al. in a different Indian cohort [12]. Our values are also higher than those reported in some Turkish and European populations [10, 13]. These variations underscore the influence of genetic, ethnic, and environmental factors on cranial morphology and reinforce the necessity of establishing population-specific normative data.

The significant sexual dimorphism observed in our study aligns with the findings of numerous previous investigations across different populations [14, 15]. This difference is generally attributed to the overall larger body stature, greater muscle mass, and more robust skeletal build in males compared to females. The cranial base, including the FM, is not exempt from these general skeletal growth patterns. The larger dimensions in males may be necessary to accommodate relatively larger neurovascular structures.

The clinical implications of these morphometric findings are substantial. In neurosurgery, particularly for far-lateral transcondylar approaches, the posterior third of the occipital condyle may need to be drilled to gain access to ventral lesions [3]. Pre-operative knowledge of the FM and condylar dimensions is crucial to avoid iatrogenic injury to the vertebral artery, which traverses just lateral to the FM, and the hypoglossal canal, situated superior to the condyle. Our sex-specific data can provide a more precise anatomical roadmap for surgical planning.

In diagnostic radiology, morphometric data of the FM is pivotal in assessing pathologies like Chiari I malformation, where cerebellar tonsillar herniation occurs through the FM. A smaller-than-average FM may be a contributing factor or an associated finding in such cases [4]. Our established normative values can serve as a reference standard for radiologists in the region. In forensic anthropology, the FM is a reliable element for sexing unknown skeletons, especially when other dimorphic features are damaged. The high degree of sexual dimorphism observed in our study validates its use. Discriminant function analysis using our measured parameters could yield an accuracy rate exceeding 85% for sex determination, consistent with previous research [5].

The use of 3D CT imaging is a major strength of our study. It allows for precise, non-invasive measurements on in vivo subjects, overcoming the limitations of dry skull studies. The 3D volume-rendered models provide superior visualization of anatomical landmarks like the basion and opisthion, which can sometimes be ambiguous on 2D slices. This enhances the accuracy and reproducibility of the measurements.

Our study is not without limitations. The retrospective nature of the design and the confinement to a single geographical population limit the generalizability of our findings. Additionally, the calculation of area was based on the assumption of an elliptical shape, which may not be perfectly accurate for all foramina. Future studies could incorporate direct volumetric measurements from 3D models for greater precision.

CONCLUSION

This study successfully established a comprehensive set of normative morphometric data for the foramen magnum in an adult population using 3D CT imaging. The findings confirm a significant sexual dimorphism in all linear and area dimensions, with males exhibiting larger values. The Foramen Magnum Index, however, did not differ significantly between sexes. The data generated from this research provide valuable anatomical references that can aid neurosurgeons in operative planning, radiologists in diagnosing craniovertebral pathologies, and forensic anthropologists in the identification of human remains. The study underscores the utility of 3D CT as a precise and reliable tool for anatomical investigation.

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