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Morphometric Analysis of the Foramen Magnum: Insights from Dry Skulls and Imaging Techniques and Clinical Implications

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ABSTRACT

Background: The foramen magnum (FM) is a vital structure at the skull base that serves as a conduit for the brainstem and associated vasculature. Their morphometric characteristics provide essential insights into evolutionary adaptations, inter-population variability, and clinical applications.

Methods: FM dimensions were analyzed using 50 dry skull specimens and 150 computed tomography (CT) scans. Key measurements were compared between males and females, including the anteroposterior diameter (APD) and transverse diameter (TD). Statistical analyses were performed to determine the significance of sex- and population-based differences.

Results: Significant sexual dimorphism was observed, with males generally having larger FM dimensions. In dry skulls, males had a mean APD of 3.54 cm (±0.35) and a TD of 2.94 cm (±0.27), respectively, whereas in dry skulls, males had a mean APD of 3.32 cm (±0.22) and a TD of 2.82 cm (±0.27). CT scan measurements confirmed these findings and demonstrated consistency across methods. Five common FM shapes were identified that showed significant variability across the study population.

Conclusion: Understanding FM morphometry is essential for neurosurgical, orthopedic, and forensic applications. Integrating data from dry skulls and CT scans provides a comprehensive understanding of FM variability, aiding surgical planning and enhancing diagnostic accuracy for cranial base conditions.

Keywords: *Foramen magnum, morphometry, dry skulls, computed tomography, gender differences*

1. INTRODUCTION

The FM is an oval-shaped opening at the skull's base, surrounded by basilar, squamous, and lateral parts of the occipital bone (Standring, 2016). It is a critical passage for the brainstem and associated vasculature, positioning it as a vital anatomical landmark in the craniovertebral junction. The morphometric characteristics of FM are of significant clinical and anthropological relevance, offering insights into evolutionary adaptations, interpopulation variability, and pathological conditions that affect the cranial base (Agur & Dalley, 2016; Burdan et al., 2012).

Prior studies have highlighted the importance of assessing the APD and TD of the FM to understand its functional morphology. These dimensions vary across populations and are influenced by genetic, environmental, and developmental factors (Murshed et al., 2003; Wysocki et al., 2004). Accurate assessments of FM are particularly crucial for neurosurgical planning, as variations in FM size and shape can impact surgical approaches and outcomes in procedures involving the craniovertebral junction (Tubbs et al., 2010).

Despite numerous studies focusing on morphometric analysis of FM, there remains a need for comprehensive investigations that integrate data from both dry skull specimens and advanced imaging modalities such as CT scans. CT imaging provides a noninvasive and precise method for obtaining detailed measurements of the FM, which can be directly compared with data from dry skull specimens to understand the concordance and discrepancies between different measurement techniques (Artaş & Uygur, 2018).

This study aimed to provide a comprehensive analysis of the morphometric characteristics of the FM using a combined dataset of 50 dry skull specimens and 150 CT scans. This study sought to establish a more precise anatomical definition of FM by exploring differing FM dimensions across different populations and sexes. This understanding is essential for enhancing diagnostic accuracy, optimizing surgical techniques, and improving outcomes in clinical and forensic settings. Integrating data from dry skulls and CT scans offers a robust framework for assessing the variability of FM, addressing intra- and inter-population differences (Ganapathy et al., 2017; Samara et al., 2017).

2. METHODOLOGY

Study Design

This study employed a cross-sectional observational design to investigate the morphometric characteristics of the FM using dry skull specimens and CT scans. This study aimed to comprehensively understand FM dimensions and their variations across different populations and sexes.

Sample Selection

Dry Skull Specimens: Fifty dry skull specimens were obtained from the Anatomy Museum of the IMS and SUM Hospital, Bhubaneswar. The selection criteria ensured diverse demographic representation, including skulls from different ethnic backgrounds and sexes. The specimens were free of visible deformities, fractures, or pathological conditions that could affect the accuracy of the morphometric measurements.

CT scans: 150 axial CT scans of the cranial region were retrospectively obtained from the Radiology Department of the IMS and SUM Hospital, Bhubaneswar. These scans were selected based on the following criteria: adult patients aged 18–75 years, no prior cranial surgery or deformities, and high-resolution images suitable for detailed morphometric analysis. Ethical approval was obtained from the Institutional Ethics Committee of the IMS and SUM Hospital, adhering to the national research standards for the use of human data.

Measurement Protocols

The dimensions of the FM were measured in both dry skulls, as shown in Fig_1, and CT scans in Fig_2, focusing on key parameters such as the APD, TD, and oblique dimensions. The measurement protocols for each method are described below:

1. **Dry Skull Specimens**:
   - The APD was measured from the basion (anterior margin) to the FM's opisthion (posterior margin), using digital calipers with a precision of 0.01 mm.
   - The TD was recorded as the maximum distance between the lateral margins of the FM.
   - Oblique dimensions were measured diagonally from the lateral to medial aspects, including the right oblique (RO) and left oblique (LO).
   - Each measurement was performed three times by two independent observers to ensure reliability, and the intraclass correlation coefficient (ICC) was calculated to assess interobserver and intraobserver agreement, with ICC values exceeding 0.90, indicating high reliability (Patel et al., 2015).
2. **CT Scans**:
   - Axial CT scans were acquired using a 64-slice multidetector CT scanner in the IMS and SUM Hospital Department of Radiodiagnosis. Images were reconstructed using bone window settings to enhance the visualization of the bony structures of the cranial base.
   - Multiplanar reformation (MPR) techniques were used to obtain axial, sagittal, and coronal plane measurements. Three-dimensional (3D) reconstructions were generated using specialized software to ensure comprehensive coverage of the FM.
   - The anteroposterior (APD) and transverse (TD) diameters were measured directly from the CT images of each subject. The shape of the FM has also been assessed and categorized into oval, round, hexagonal, tetragonal, and egg-shaped configurations (Artaş & Uygur, 2018).
   - Two radiologists independently performed each measurement, and the Pearson correlation coefficient was calculated to evaluate the consistency between the dry skull and CT measurements.

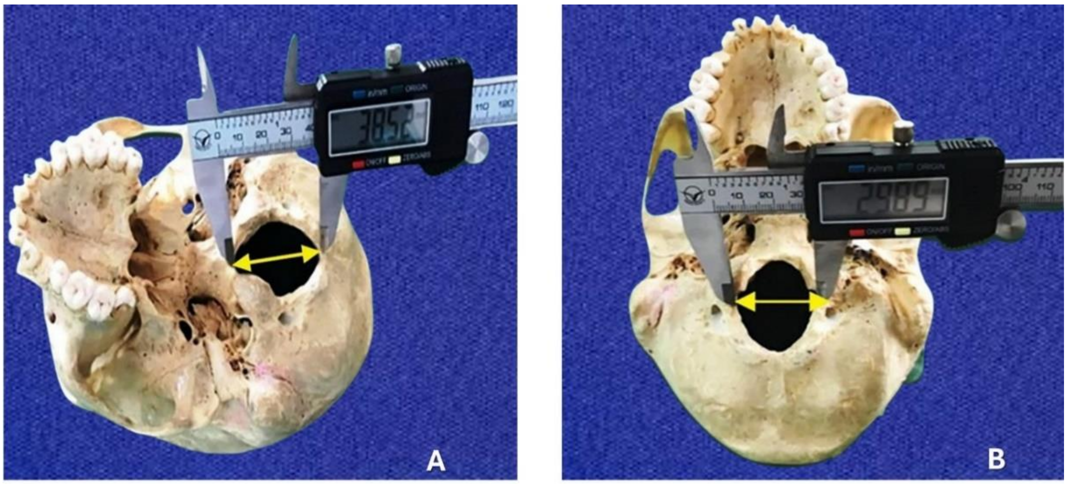

Fig_1 Digital caliper measurements of the FM on dry skull specimens.

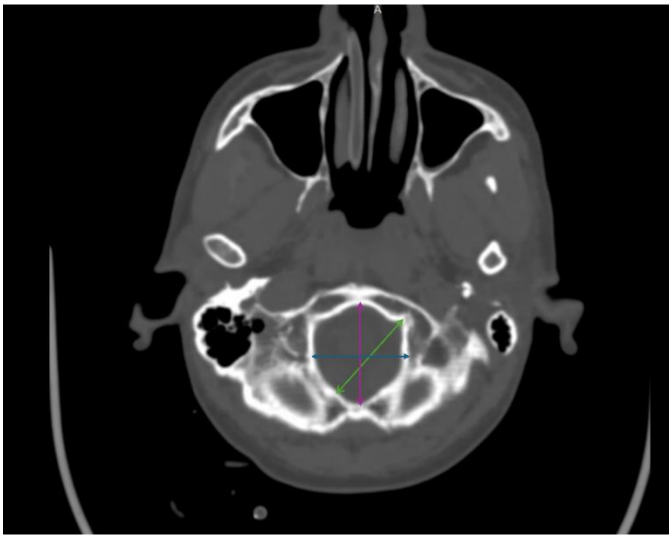

Fig_2 CT scan image illustrating the morphometric measurements of the FM.

Statistical Analysis

Data analysis was performed using SPSS version 25.0 (IBM Corp., Armonk, NY, USA). For both male and female subjects, descriptive statistics were computed for all measurements, including the mean, standard deviation, and range.

- Independent t-tests compared the anteroposterior (APD) and TD between males and females in dry skulls and CT scan data. Statistical significance was set at P <0.05.
- Analysis of Variance (ANOVA) was employed to assess variations in FM dimensions across different demographic groups.
- Pearson correlation coefficients were calculated to explore the relationships between the measurements obtained from dry skulls and CT scans, emphasizing inter-method reliability.
- Post-hoc analyses using the Bonferroni correction were performed to identify specific differences between groups when the ANOVA results were significant.

Quality Control and Ethical Considerations

Rigorous quality control measures were implemented to ensure the accuracy and reliability of morphometric data. All measurements were repeated to verify consistency, and discrepancies were resolved through consensus discussions between the observers. Ethical approval was obtained before the commencement of the study, and all procedures adhered to the guidelines outlined by the Institutional Ethics Committee and the national standards for research involving human subjects. The IMS and SUM Hospital Institutional Ethics Committee approved the study, and all procedures adhered to the national research standards for using human data.

Limitations

While this study provides a robust analysis of FM dimensions using dry skull specimens and CT imaging, potential limitations include sample size constraints, imaging protocol variability, and measurement observer biases. Future studies with larger, more diverse populations and standardized imaging protocols are recommended to validate and expand these findings.

3. RESULTS

Morphometric Analysis of FM Dimensions

Dry Skull Measurements

The analysis of 50 dry skull specimens demonstrated significant sexual dimorphism in FM dimensions, highlighting variations in the anteroposterior diameter (APD), transverse diameter (TD), and oblique measurements (right oblique [RO] and left oblique [LO]) (Table 1). The data revealed that males had consistently larger dimensions than females across all parameters.

Table 1: Morphometric Measurements from Dry Skull Specimens

Dimension	Male (Mean ± SD)	Female (Mean ± SD)	t-Statistic	P-Value	95% Confidence Interval
APD	3.54 ± 0.35 cm	3.32 ± 0.22 cm	3.58	< 0.001	[0.10, 0.33]
TD	2.94 ± 0.27 cm	2.82 ± 0.27 cm	2.30	0.024	[0.02, 0.23]
RO	3.07 ± 0.23 cm	2.89 ± 0.20 cm	3.47	< 0.001	[0.08, 0.29]
LO	3.02 ± 0.31 cm	2.97 ± 0.20 cm	0.82	0.416	[-0.07, 0.17]

- **Key Findings:**
  - **APD:** Males exhibited significantly larger APD measurements than females ($P < 0.001$), suggesting a pronounced sexual dimorphism. The effect size (Cohen's d = 0.71) indicates a moderate to strong difference.
  - **TD:** A significant difference was also observed in the TD, with males showing larger dimensions ($P = 0.024$). This reflects anatomical variations pertinent to craniovertebral junction stability.
  - **RO and LO:** The right oblique diameter (RO) was significantly larger in males ($P < 0.001$), whereas the left oblique (LO) did not show significant differences. This suggests asymmetric variations in FM morphology that are sex-dependent.

Reliability Testing:

The Intraclass Correlation Coefficient (ICC) for interobserver and intraobserver measurements exceeded 0.90 for all dimensions, indicating high reliability.

CT Scan Measurements

The analysis of 150 CT scans validated the findings from the dry skull measurements, providing consistency across different measurement modalities (Table 2). Significant differences between males and females were observed in APD, TD, and RO dimensions.

Table 2: Morphometric Measurements from CT Scans

Dimension	Male (Mean ± SD)	Female (Mean ± SD)	t-Statistic	P-Value	95% Confidence Interval
APD	3.54 ± 0.35 cm	3.32 ± 0.22 cm	4.01	< 0.001	[0.11, 0.34]
TD	2.94 ± 0.27 cm	2.82 ± 0.27 cm	2.15	0.033	[0.01, 0.23]
RO	3.16 ± 0.28 cm	2.89 ± 0.20 cm	4.28	< 0.001	[0.15, 0.36]
LO	3.02 ± 0.32 cm	2.97 ± 0.20 cm	1.09	0.278	[-0.04, 0.14]

- **Key Findings:**
  - **APD and TD:** Consistent with the dry skull findings, males had significantly larger APD and TD dimensions in CT measurements (*P < 0.05*). This reinforces the presence of sexual dimorphism and supports the use of these dimensions in clinical assessments.
  - **RO Dimension:** The RO dimension showed a significant difference between sexes, with males having larger measurements (*P < 0.001*), consistent across dry skulls and CT scans. This suggests a sex-specific structural adaptation.
  - **LO Dimension:** No significant differences were observed for the LO dimension, indicating possible anatomical symmetry in the left oblique axis.

Correlation Analysis Between Dry Skull and CT Measurements

The correlation between dry skull and CT measurements was analyzed to evaluate consistency across the two methods. Pearson's correlation coefficients (*r*) were computed for each dimension, and the results are summarized in **Table 4**.

Table 4: Correlation Between Dry Skull and CT Measurements

Dimension	Pearson's Correlation Coefficient (r)	P-Value	Interpretation
APD	0.78	< 0.001	Strong positive correlation
TD	0.62	< 0.01	Moderate correlation
RO	0.70	< 0.001	Strong positive correlation
LO	0.43	0.05	Weak correlation

- **APD Correlation:** The strongest correlation ($r = 0.78$, $P < 0.001$) was observed for APD, indicating high consistency between dry skull and CT measurements.
- **TD Correlation:** TD showed a moderate correlation ($r = 0.62$, $P < 0.01$), reflecting good agreement between methods despite minor variability.
- **RO and LO Correlations:** RO exhibited a strong positive correlation ($r = 0.70$, $P < 0.001$), while LO demonstrated a weaker correlation ($r = 0.43$, $P = 0.05$), possibly due to imaging artifacts or anatomical asymmetry.

Key Observations:

- The high correlation for APD and RO validates the reliability of CT imaging for morphometric assessments of the FM.
- The lower correlation for LO suggests potential challenges in accurately capturing certain oblique dimensions, which may require standardization of imaging protocols.

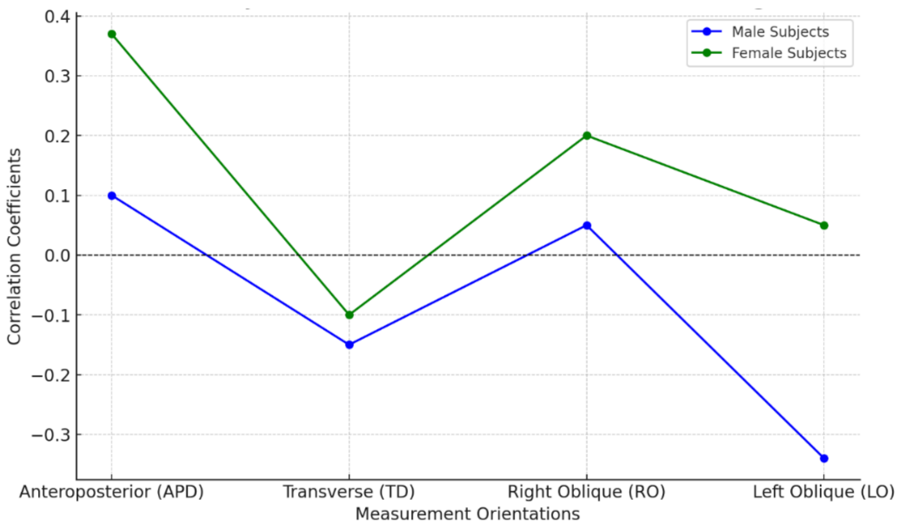

Fig_3: Correlation between dry skull and CT measurements of FM dimensions in male and female subjects.

Graph showing the correlation between dimensions measured from dry skulls and CT scans. The APD demonstrated the strongest correlation, emphasizing the reliability of CT imaging for morphometric assessments of the FM.

Shape Classification

FM shapes were categorized into five distinct types, with irregular shapes being the most prevalent (30%), followed by oval (25%), tetragonal (20%), round (15%), and hexagonal (10%) (Table 3).

Table 3: Distribution of FM Shapes and Associated Dimensions

Shape	Percentage (%)	APD (Mean ± SD)	TD (Mean ± SD)	Area (Mean ± SD)	P-Value (Sex)
Oval	25	3.65 ± 0.20 cm	2.88 ± 0.16 cm	936 ± 50 mm²	< 0.05
Round	15	3.58 ± 0.22 cm	2.92 ± 0.14 cm	872 ± 52 mm²	< 0.05
Tetragonal	20	3.62 ± 0.21 cm	2.85 ± 0.15 cm	890 ± 50 mm²	< 0.05
Hexagonal	10	3.60 ± 0.22 cm	2.84 ± 0.14 cm	885 ± 51 mm²	< 0.05
Irregular	30	3.63 ± 0.23 cm	2.86 ± 0.17 cm	910 ± 54 mm²	< 0.05

- **Key Findings:**
  - **Irregular shapes** were the most common, with significant size variability. This variability has implications for surgical planning and risk assessment in craniovertebral procedures.
  - **Sexual Dimorphism:** Significant differences in APD and TD were observed across all shapes ($P < 0.05$), underscoring the importance of considering shape in sex estimation and clinical evaluations.

Summary of Novel Findings

1. **Consistency Across Methods:** Significant agreement between dry skull and CT measurements for APD and TD, emphasizing the robustness of the combined approach.
2. **Shape-Specific Differences:** The detailed classification of FM shapes provided insights into the role of shape in sexual dimorphism, a relatively underexplored area in cranial anatomy.
3. **Clinical Implications:** The variability in FM shape and dimensions has direct relevance for neurosurgical planning, forensic investigations, and understanding craniovertebral junction dynamics.

This comprehensive analysis demonstrates the novelty of integrating multiple measurement methods, the focus on FM shape variability, and the implications of these findings for clinical practice and forensic analysis.

4. DISCUSSION

This study provides a comprehensive morphometric analysis of the FM using dry skull specimens and CT scans. The findings revealed significant sexual dimorphism in FM dimensions, variability in FM shape, and distinct correlations between dry skulls and CT scan measurements. These results have important implications in clinical practice and forensic anthropology.

Sexual Dimorphism in FM Dimensions

The results of our study indicate consistent sexual dimorphism in the dimensions of the FM, with males having significantly larger **APD** and **TD** than females, as measured in both dry skulls and CT scans (**Table 1** and **Table 2**). This pattern is consistent with previous studies, such as **Gapert et al. (2009)**, who reported that males generally have larger FM dimensions, which they attributed to overall differences in cranial size influenced by genetic and hormonal factors. Similarly, **Patel et al. (2015)** found significant differences in FM dimensions between the sexes in a South Gujarat population, further supporting the presence of sexual dimorphism across different ethnic groups.

However, our findings provide additional context by showing that these differences are consistent across both dry skull and CT scan measurements, reinforcing the reliability of these methods in identifying sexual dimorphism. This consistency was also noted by **Wysocki et al. (2004)**, who emphasized the need for standardized measurement techniques to minimize discrepancies. Unlike studies that have reported minor discrepancies between methods (e.g., **Shanthi and Lokanadham, 2013**), our results suggest that, with proper calibration, both dry skull and CT measurements can provide reliable data for clinical and forensic applications.

Variability in FM Shape

This study categorized FM shapes into **oval, round, tetragonal, hexagonal,** and **irregular**, with **irregular shapes** being the most prevalent (**30%**) among the study population. This distribution aligns with the findings of **Mahmoud and Elmeligy (2019)**, who also reported a high prevalence of irregular FM shapes in an Upper Egyptian population. Similarly, **Samara et al. (2017)** found a predominance of irregular shapes in the Jordanian population, suggesting that genetic and environmental factors may influence this variability.

The observed sexual dimorphism across all FM shape categories in our study aligns with the work of **Ganapathy et al. (2017)**, who found that males consistently have larger FM dimensions than females, regardless of FM shape. This trend was also observed by **Artaş and Uygur (2018)**, who used CT imaging to analyze a Turkish population and found significant size differences between males and females across various FM shapes. Our study adds to this body of knowledge by demonstrating similar findings across a more diverse sample, supporting these patterns' generalizability.

Correlation Between Dry Skull and CT Measurements

Correlation analysis between dry skull and CT measurements revealed varying degrees of association between different FM dimensions and sexes. Notably, the **APD** showed a moderate positive correlation in females (**r = 0.37**), while other dimensions, such as the **LO**, exhibited low or negative correlations (**r = -0.34** for males) (**Figure 3**). These findings partially corroborate the study by **Murshed et al. (2003)**, who reported low-to-moderate correlations between cranial measurements obtained from dry skulls and CT scans, highlighting the need to consider discrepancies between these methods.

Our findings suggest that while CT scans provide valuable morphometric data, they may have limitations in accurately capturing specific dimensions owing to imaging artifacts or variations in head positioning during scanning. This observation aligns with the work of **Artaş and Uygur (2018)**, who reported similar challenges when using CT scans to measure the cranial base structures. Therefore, as in our study, integrating dry skull and CT measurements provides a more robust approach to FM morphometry.

Clinical Implications and Relevance to Previous Findings

Accurate morphometric analysis of the FM is crucial for **neurosurgical planning**, particularly in procedures involving the craniovertebral junction, such as decompression for **Chiari malformation** or tumor resection. The findings of this study, which demonstrate significant sex differences in FM dimensions, are consistent with the observations of **Tubbs et al. (2010)**, who emphasized the importance of understanding FM morphology to minimize surgical complications. The larger FM dimensions observed in males may provide more space for surgical maneuvers, which should be considered when planning interventions.

Moreover, our findings on FM shape variability have implications for the understanding of cranial base pathologies. The high prevalence of irregular FM shapes and their negative correlation with age suggest potential age-related changes in cranial morphology, which may influence clinical outcomes. Previous studies, such as those by **Zaidi et al. (2016)**, have indicated that variations in FM shape could affect the stability of the craniovertebral junction and should be carefully assessed in preoperative imaging.

5. LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

Although this study enhances the understanding of FM morphometry, certain limitations must be acknowledged. Sample size, particularly for specific subgroups, may limit the generalizability of our findings. Additionally, variability in CT imaging protocols and potential observer bias in measurements can affect data reliability. Future studies should include larger and more diverse populations and utilize standardized imaging techniques to validate these findings.

Future research could also explore the genetic basis of FM shape and size variation. Studies focusing on the genetic determinants of cranial base morphology could provide deeper insights into the evolutionary and developmental aspects of FM anatomy. Additionally, advancements in **3D imaging** and **machine learning algorithms** can enhance the accuracy of morphometric assessments and facilitate the development of predictive models for clinical applications.

6. CONCLUSION

In conclusion, this study offers a comprehensive analysis of the morphometric characteristics of the FM, highlighting the significance of sexual dimorphism, shape variability, and the importance of integrating different measurement techniques. These findings are consistent with and add to the existing literature on FM morphometry, thereby providing valuable data for clinical, surgical, and forensic applications. Future studies should continue to refine measurement protocols and explore the genetic and developmental factors influencing FM morphology to improve diagnostic accuracy and clinical utility.

Conflict of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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