



OPEN A new golden ratio for foramen magnum in pre- and post-adolescent children

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The foramen magnum (FM) is a crucial transition zone between the skull and spine, with its growth mostly completed by the end of the age of four. A study on adults reported that the ratio of the anteroposterior to transverse diameter of the FM and skull aligns with the golden ratio (4.62), suggesting a harmonious relationship. Our study aims to investigate whether this ratio is present in children by analyzing Computed Tomography (CT) images, and whether FM shape variations affect this ratio. We analyzed CT images of 201 Turkish children (male: 117, female: 84), measuring maximum cranial length (MCL), width (MCW), foramen magnum length (FML), and width (FMW). Group comparisons were made using the Independent t-test and ANOVA. Relationships between continuous variables were examined using Pearson correlation analysis. Ratios of MCW to FMW and MCL to FML were consistent in children aged 6–17. The ratio of 4.90 obtained from these parameters observed between the skull and FM reveals the presence of a unique anatomical balance in the skull. FM shapes were classified morphologically, with their frequency and incidence recorded. For categorical variables, associations were analyzed using the Chi-Square test. A total of 12 distinct FM shapes were identified, with the two semicircle shape being the most prevalent, appearing in 32.8% of cases. In contrast, the pentagonal and triangular shapes were the rarest, each representing only 0.5% of the cases. Recalculating these ratios across different FM shapes may provide a clearer understanding of the validity of the golden ratio.

Keywords Foramen magnum, Golden ratio, Morphometry, Morphology

The foramen magnum (FM), derived from Latin meaning “large opening,” is a three-dimensional aperture situated in the basal central region of the occipital bone. It serves as a transition zone between the spine and the skull, acting as a critical anatomical landmark due to its role in connecting the brain and spinal cord^{1–3}. As the growth of the FM is largely complete by approximately at the end of the four years of age³. While there is no definitive data regarding changes in the FM’s size with age in children, studies have indicated that its dimensions alter during the fusion of the surrounding bone structures. Complete fusion of these structures typically occurs around the age of five years^{4–6}. A comprehensive understanding of the FM’s anatomy and variations is essential, particularly because its morphometric analyses are frequently examined in clinical, orthopedic, neurosurgical, anthropological, and forensic contexts. Such knowledge is crucial for safeguarding the health of the vital structures it encases⁷.

Evaluating the dimensions and anatomical characteristics of the FM and its surrounding structures plays a crucial role in preoperative planning for surgical interventions⁸. Various morphometric parameters, including the shape and size of the FM, should be carefully considered during procedures involving the posterior and lateral craniovertebral junction to ensure optimal surgical outcomes⁹. Surgical interventions at the craniovertebral junction are associated with significant morbidity and technical challenges. Tumor resection in this region remains a highly complex procedure¹⁰. In neurosurgical practice, the transcondylar approach is commonly employed to access lesions in this area. Studies emphasize that a detailed understanding of the bony anatomy of the condylar region is crucial for the successful application of this technique¹¹. A detailed understanding of FM shapes and its anatomical variations can influence various surgical procedures, including

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vertebral artery interventions, posterior inferior cerebellar artery aneurysm repairs, FM meningioma resections, and FM decompression^{1,7,9,12–14}. Additionally, these data provide valuable insights for neurological assessments and play a significant role in diagnostic, clinical, and radiological evaluations^{7,9,14}. Variations in FM types may be influenced by factors such as ethnic diversity, sample size, sexual dimorphism, and population characteristics. Additionally, FM morphometry can vary across populations due to genetic predisposition, environmental influences, and socio-economic factors¹⁵.

The first study on the FM, which plays a critical role in various developmental malformations, diseases, and cranial deformities, was conducted in 1982. Since then, numerous investigations have explored the FM across individuals from different populations, identifying a wide range of shapes and sizes^{7,16–21}. Understanding the dimensions of the FM contributes significantly to the diagnosis, prognosis, and treatment of many developmental malformations or cranial deformities caused by various conditions⁴. Research has demonstrated that Chiari Malformation is closely linked to FM dimensions. In addition, FM stenosis was identified in a 5-month-old child with achondroplasia, and patients with Crouzon and Pfeiffer syndromes were found to have a statistically significant reduction in FM surface area compared to control groups^{22–24}.

Studies have been conducted to evaluate whether there is a mathematical ratio in the human cranium^{7,25,26}. Meyvaci et al.²⁵ stated that the ratio of the distance between the spina nasalis anterior and nasion to the height of the apertura piriformis in males falls within the limits of the golden ratio, while George and Bhat²⁶ found a golden ratio between the intercanthal distance and the width of the two maxillary incisors in the South Indian population. In their study on 60 adult skulls with 8 different FM shapes, Ulcay et al.⁷ measured the MCL, MCW, FML, and FMW, reporting a proportional relationship between FML and FMW, identifying a golden ratio of 4.62, and recommending further studies on skulls with a greater number and variety of FM shapes. Öksüzler et al.²⁷ investigated whether there is a ratio between cranial length measurements and FM length measurements in their study, which included CT images of 185 healthy adults (95 males and 90 females) and 15 dry skulls. Güler and Yilmaz²⁸ stated that they found a ratio of 1.4 between orbital width and FM width in their study on 21 dry skulls.

Morphometric and morphological variations of the FM have been extensively studied across different populations. However, research on the proportional harmony between cranial structures remains limited. Given that FM dimensions are analyzed in various disciplines, we hypothesized that they could be estimated through cranial measurements. The predictability of FM size based on MCL and MCW values may provide surgeons or clinicians with insights into the anatomy of the region in certain anomalies, facilitating prognosis, disease susceptibility assessment, and diagnosis.

The aim of our study is to investigate the relationship between the anteroposterior diameter of the FM and the MCL, as well as between the transverse diameter of the FM and the MCW in children. Additionally, we seek to determine if there is a proportional ratio between FM dimensions and overall skull dimensions, and to identify the various shapes of the FM.

Materials and methods

Our study was conducted retrospectively on 201 children who presented with complaints of headaches to the pediatric outpatient clinic of Kırşehir Ahi Evran University Training and Research Hospital between 2020 and 2021. These children had no underlying diseases or anatomical deformities and had undergone brain tomography (CT) imaging in the Department of Radiology. The inclusion criteria for participants in the present study were being child aged 6–17 years, while the exclusion criteria were having craniofacial anomalies, a history of head trauma, and the inability to obtain clear measurements on CT images. The CT images were obtained from the hospital's Picture Archiving and Communication Systems (PACS) system.

Ethical approval of our study was obtained by Ahi Evran University Ethics Committee with the date and number 2021-17/173. Since this study was retrospective in nature, informed consent was not obtained from any of the subjects, and we were notified by the Ahi Evran University Ethics Committee that the need for informed consent for participation was waived by unanimous decision (E-77504701-204.01.07-00000690472). All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and the 1964 Helsinki declaration and its subsequent amendments or comparable ethical standards.

Using tools in the PACS system, we measured the anteroposterior and transverse diameters of each FM with a precision of 0.1 millimeter (mm). The FM shapes were morphologically classified into the following categories: two semicircles, oval, round, triangular, egg-shaped, tetragonal, pentagonal, hexagonal, heptagonal, octagonal, drop-shaped, and irregular (See Supplementary Fig. S2). To avoid observational bias, the shapes were determined through discussions among a three-member team. The number and incidence of each FM shape in the studied skulls were recorded.

Morphometric measurements

FMW was measured by determining the most concave points on the left and right edges (See Supplementary Fig. S1). MCL was measured as the distance between the glabella (g) and the opisthocranium (op) (g-op) in sagittal images (See Supplementary Fig. S1). The MCW was measured as the distance between the eurion (eu) points (eu-eu), which represent the farthest points on both sides of the skull, using images obtained in the coronal section (See Supplementary Fig. S1).

The individuals in the study were divided into three age groups: 6–10 years, 11–13 years, and 14–17 years. To estimate both the index and dimensions of the FM using new indices derived from cranial measurements (MCW and MCL), the FML was calculated using formulas based on cranial width (Eq. 1) and cranial length (Eq. 2). The FML was measured as the distance from the basion to the opisthion (See Supplementary Fig. S1).

$$\text{FM} - \text{cranial width index} = \text{FMW}/\text{MCW} * 100 \quad (1)$$

$$\text{FM} - \text{cranial length index} = \text{FML}/\text{MCL} * 100 \quad (2)$$

Statistical analysis

The statistical analyses of the study were conducted using the Statistical Package for Social Sciences for Windows (IBM SPSS version 29.0, Armonk, NY, USA) software. The normality assumption of continuous variables was tested using the Kolmogorov-Smirnov and Shapiro-Wilk tests. A *p*-value greater than 0.05 was considered indicative of normal distribution. Additionally, normality was assessed using graphical methods, including histograms and Q-Q plots. The homogeneity of variances was evaluated using Levene's test. Descriptive statistics for the variables were presented as Mean \pm standard deviation (SD) (95% Confidence Interval (CI): Lower-Upper). Group comparisons were made using the Independent t-test and ANOVA. For categorical variables, associations were analyzed using the Chi-Square test, considering the row \times column structure and expected cell values. In cases where the expected frequencies were below the threshold, the Fisher-Freeman-Halton Exact test was applied. Relationships between continuous variables were examined using Pearson correlation analysis.

Since no identical study was available in the literature to serve as a direct reference, the sample size was determined based on Cohen's recommendations for effect size estimation. A priori power analysis was conducted using G*Power software (version 3.1.9.6). The effect size was set to $f=0.25$, with an alpha error probability of 0.05 and a statistical power of 0.85. Given that the study involved three groups, the minimum required sample size was calculated as $n=180$. To account for potential data loss and ensure robustness, an additional 10% was included, resulting in a final sample size of 201 participants.

A *p*-value of less than 0.05 was considered statistically significant.

Results

Participants

A total of 201 pediatric individuals, comprising 117 males (58.2%) and 84 females (41.8%), were included in our study. The distribution of genders across age groups is presented in Table S1. According to these results, the correlation between gender and age groups is not statistically significant ($p=0.532$). The distribution of genders across age groups is homogeneous.

The study was based on CT measurements from patients aged 6 to 17, with the mean measurement values presented in Table S1 (See Supplementary Table S1).

Morphometrical evaluation

According to our results, the MCW/FMW ratio (4.90 ± 0.82) and the MCL/FML ratio (4.90 ± 0.44) were found to be equal. There was no statistically significant difference between these two ratios ($p=0.958$) (See Supplementary Table S2).

In this study, the ratios of MCW to FMW and MCL to FML, stratified by age groups and gender, are presented in Table S3 (See Supplementary Table S3). The results demonstrated that the MCW/FMW and MCL/FML ratios did not exhibit statistically significant differences between genders ($p=0.751$ and $p=0.942$, respectively). Similarly, no statistically significant differences were observed in MCW/FMW and MCL/FML ratios among different age groups ($p=0.972$ and $p=0.951$, respectively).

A negative correlation was found between age and the MCW/FMW ratio ($r = -0.060$, $p=0.522$), and a similar negative relationship was observed between age and the MCL/FML ratio ($r = -0.070$, $p=0.643$). Although neither correlation was statistically significant, the data suggest a tendency for both the MCW/FMW and MCL/FML ratios to decrease as age advances (See Supplementary Table S4).

Morphological evaluation

A total of 11 different FM shapes were identified, with the Two Semicircle shape being the most common, observed in 32.8% of cases (See Supplementary Table S5). The Pentagonal and Triangular shapes were the least common, each accounting for only 0.5% of cases (See Supplementary Table S5).

Discussion

Considering the critical structures that pass through the FM and may be subjected to compression, potentially leading to various pathologies, the FM's dimensions are of substantial clinical importance. Given the FM's significant relationship with the skull base and the complex structure of this region, a detailed and topographical examination of FM dimensions is essential²⁹. From a radiographic perspective, knowing the FM diameters is particularly crucial for diagnosing conditions such as Arnold-Chiari syndrome. This malformation is often characterized by expansions in the anteroposterior and transverse diameters of the FM, highlighting the importance of these measurements for identifying related pathologies³⁰.

In our study, the MCL/FML ratio was found to be 4.90 ± 0.46 in males and 4.89 ± 0.42 in females, while the MCW/FMW ratio was 4.87 ± 0.99 in males and 4.91 ± 0.51 in females. This study indicates a consistent ratio of approximately 4.90 for both MCL to FML and MCW to FMW.

The observed differences in ratios compared to other studies may be attributed to the distinction between pediatric and adult populations. As age increases, the MCW to FMW and MCL to FML values in our study tend to decrease, aligning more closely with the values reported by Ulcay et al.²¹. Although there are limited studies on adults regarding this topic, and no previous studies specifically on children, our study is unique in evaluating the potential mathematical ratio between skull size and FM size in pediatric individuals.

In addition to being the first study in the literature to morphometrically examine the FM in pediatric patients, the inclusion of 201 participants in this study further enhances its reliability. In this study, the MCL/FML ratio was found to be 4.90 ± 0.44 , and the MCW/FMW ratio was found to be 4.90 ± 0.82 , with the length and width ratios determined to be within the golden ratio confidence interval [%95 CI: 4.85–4.98 (95% CI: 4.78–5.00)]. Conducted on participants aged 6–17 using CT images, the finding that the MCW/FMW and MCL/FML values are equal, regardless of FM shape types, fully supports the prediction methods of Ulcay et al.²¹. The fact that these ratios are also equal in patients aged 6–17 and approach the ratio identified by Ulcay et al.²¹ as age increases in this age group demonstrates an exceptional balance between the anatomical measurements of the human skull. Variations in the shape of the FM hold both clinical and radiological significance. A comprehensive understanding of FM morphology is crucial, as it has significant clinical implications for the prognosis and management of various neurological pathologies, including Arnold-Chiari syndrome and posterior cranial fossa lesions³¹. The shape of the FM is variable, and previous studies conducted on different populations have reported differing views regarding the FM shape². Although standard textbooks describe the FM as an oval structure, studies have shown that the FM is not entirely oval^{2,9,18,21,32–35}. Our study also supports the presence of different FM shape types (See Supplementary Fig. S2) (See Supplementary Table S3). The most common FM type was reported as oval by Singh et al.³⁶ (33.3%), round by Chethan et al.¹⁴ (22.6%) and Sharma et al.³⁴ (22%), tetragonal by Govsa et al.⁹ (25.66%), pear-shaped by Aragão et al.³² (25.66%), egg-shaped by Moodley et al.³⁵ (20.67%), and Two Semicircle by Ulcay et al.²¹ (23.9%). In our study, the most common FM shape was the Two Semicircle shape (32.8%) (See Supplementary Table S3). Additionally, two FM shape types introduced into the literature by Ulcay et al.²¹ (drop-shaped and triangular shapes) were also identified (See Supplementary Fig. S2) (See Supplementary Table S3). During early fetal development, the FM serves as one of the primary ossification centers, and its shape varies due to evolutionary adaptations. Its irregular shape may contribute to developmental anomalies affecting both the bony and soft tissue structures at the craniovertebral junction²⁷. In the study conducted by Govsa et al.⁹, variations in the length, width, and morphology of the FM at the craniovertebral junction were meticulously examined. The findings were analyzed in the context of embryological data. Consequently, discrepancies in FM dimensions and shape may stem from the ossification of residual primordial cranial structures that integrate with endochondral ossification sites at varying locations. Ossification anomalies can have detrimental effects on an individual's functional capacity and overall quality of life. In cases involving complex neurological and respiratory symptoms associated with FM abnormalities, the utilization of CT and magnetic resonance imaging proves to be invaluable for both diagnosis and treatment⁹. When examining the distribution of FM shapes across gender groups, no significant correlation was found between gender and FM shape ($p = 0.886$). The gender factor does not influence FM shape. In both genders, the most common FM shape was the “Two Semicircle” type. Similarly, the correlation between age groups and FM shapes was not statistically significant ($p = 0.929$). Age groups do not have a significant effect on FM shape.

In conclusion, in this study, conducted on participants aged 6 to 17 using CT images, it was observed that the MCW to FMW and MCL to FML values were equal. In the present study, a ratio of 4.90 was found, and it is noteworthy that this ratio approaches the values reported in other studies in the literature as age increases^{7,17,18,37,38} (See Supplementary Table S6) (See Supplementary Table S7). The equality of the MCW to FMW and MCL to FML values in patients aged 6 to 17 demonstrates an exceptional balance in the anatomical measurements of the human skull, supporting the existence of the golden ratio in these dimensions.

Strength, limitations and recommendations

The strength of this study lies in the fact that the sample group consists of children, that it was conducted using CT imaging—unlike other studies—and that a single fixed ratio was obtained instead of multiple varying ratios. The limitations of the study include the exclusion of participants younger than six years old and the unequal number of male and female participants. As one of the first studies to examine CT images of children's skulls, this research lays a foundation for further exploration. Repeating the calculated coefficients with a larger sample of children's skulls and including a wider variety of FM shapes will enhance the robustness of the proposed golden ratio. Such additional studies could provide more comprehensive insights and validate the applicability of the golden ratio across different FM shapes and age groups.

Data availability

Data availability All data generated during this study are included in this published article.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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