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Original Article

A morphometric analysis and study of variations of foramina in the floor of the middle cranial fossa

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ABSTRACT

Introduction: The middle cranial fossa (MCF) in human skulls is characterized by extremely complex architecture and dense crowding of structures traversing the various foramina present in its floor. Despite the numerous variations exhibited by these foramina and their critical importance to neurosurgeons operating in this area, comprehensive accounts of metric and non-metric data on MCF foramina are quite scarce in literature. The present study aims to bridge this gap in knowledge.
Methods: Fifty well-preserved dry, macerated adult (age >20 yrs) skulls were obtained from the Anatomy departments of AIIMS and other medical colleges in Delhi. Each skull was examined for all the MCF foramina and the variations noted. The foramina were digitally photographed for morphometric data with reference to sex and side (left/right) using ImageJ software.
Results: The data survey revealed numerous individual variations in the metric and/or non-metric characteristics of each MCF foramen. The foramina ovale, rotundum, spinosum & lacerum were found to be consistently present in all 50 skulls whereas some skulls exhibited the foramen of Vesalius (unilateral 17%; bilateral 12%) and canaliculus innominatus (5%). The data on maximum diameter and area tabulated for each foramen revealed significant individual, sex and side variations.
Discussion: The present study found several variations in the shape, size, dimensions, laterality and frequency of foramina present in the MCF floor. The little data existing in literature about these foramina compares well with these findings. The neurosurgical importance of baseline data pertaining to MCF foramina among various ethnic and demographic groups cannot be overstated.

1. Introduction

The human middle cranial fossa (MCF) presents an extremely complex bony terrain with many foramina and bony features that seriously challenge the neurosurgeons operating in this region. The MCF foramina are responsible for the dense crowding of structures traversing them, following passage through a relatively narrow area within the skull base. These foramina also exhibit numerous variations in terms of shape, size and frequency of occurrence, some being consistently present while others are infrequent or accessory. Some accessory foramina are traversed by minor structures like emissary veins or occasionally the lesser petrosal nerve, and are not regularly present.[1,2] A survey of the frequency, variations & anomalies among these foramina is presented in this study, together with morphometric data pertaining to their dimensions (diameter, area). This data acquired from the skulls of a primarily North Indian population of mixed ethnicity may serve as a useful baseline for application during various surgical approaches to the MCF or for anthropological and forensic studies.

2. Material and methods

2.1. Material

Fifty well-preserved dry, macerated adult (age >20 yrs) skulls (with calvaria removed 1 cm above the supra-orbital margins and the external occipital protuberance) were obtained from the Anatomy departments of the All India Institute of Medical Sciences and various other medical colleges in Delhi, following due institutional procedure and ethical approval. Skulls with gross anomalies (deformities/fractures) were excluded, and determination of sex (male/female) and age was done for each skull based on established forensic criteria.[3] The skulls included in this study are likely to be of Indian origin, but this could not be absolutely ascertained.

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2.2. Non-metric features

The boundaries of the MCF were defined and each skull meticulously examined on either side (left & right) for the presence of and variations among the following foramina (Fig. 1): foramen ovale, foramen rotundum, foramen spinosum, foramen lacerum, foramen petrosum (of Arnold)/canaliculus innominatus, emissary sphenoidal foramen of Vesalius.

All the aforementioned foramina were identified, their non-metric features directly recorded in detail from the specimens through examination for variations in shape, size, presence of anomalies and accessory foramina. The observed variations in morphology were photographed using a high-end digital camera. Each foramen was carefully probed from outside using a stiff wire (0.1 mm diameter) to confirm its continuity with the MCF.

2.3. Image analysis

All the foramina were scanned using a high definition digital camera and their dimensions calculated in terms of maximum diameter and area, using a computerized image analysis system. Measurement of the maximum diameter was made across the farthest apart points on the bony margin of each foramen, as computed from digital photographs of the MCF.

An image analyzer[4,5] (Image J, an NIH product) was used to record the maximum diameter and surface area of all the aforementioned foramina. The foramina were defined anatomically for their extent and boundaries, following a strict protocol every time while recording the measurement. The image analysis programme was adjusted for irregularities in shape and margins of the measured entity (Fig. 2).

Images were taken using a high-end cyber shot digital camera with intelligent scanning facility and pixel value desired for large monitors. The photographic technique used was intended for a comprehensive view of the desired area of the specimen, with maximum bilateral details. Using an illuminated background behind the skull base ensured proper visualization of the foramina. Each specimen was labeled with a serial number and body side prior to photography, and multiple images from specific views were taken. A paper scale calibrated in millimeter with 0.5 mm precision value, was placed in the area to be scanned without disturbing details. This was done to ensure proportional changes of scale with surrounding area, whenever the imaging distance and angles were adjusted. Possible changes in scale due to the intra/inter-observer variation in imaging technique were reset during analysis in terms of distance and pixel density through a complex internal process in the image analyzer.

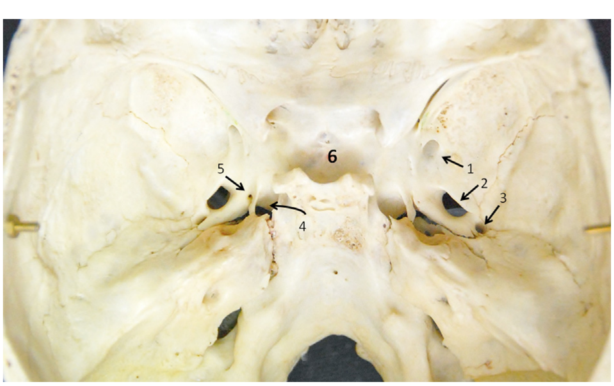

Fig. 1. Foramina in the floor of the Middle Cranial Fossa.
1 – Foramen rotundum 2 – Foramen ovale 3 – Foramen spinosum 4 – Foramen lacerum 5 – Foramen of Vesalius 6 – Hypophyseal fossa (indicated for orientation).

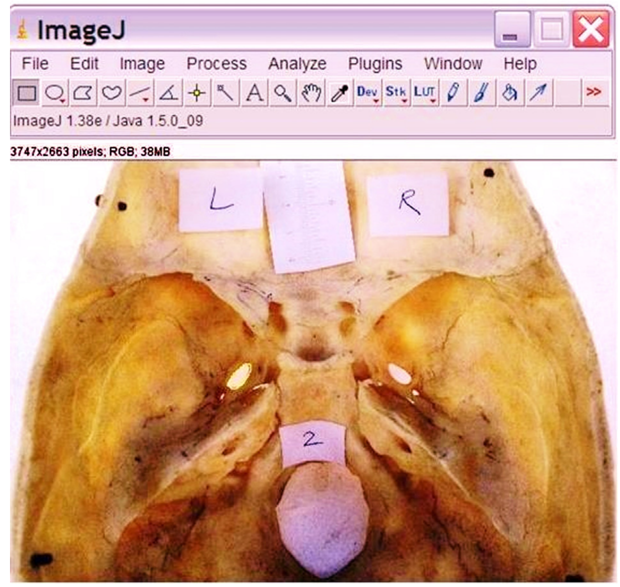

Fig. 2. Captured screen image of image analyzer (ImageJ) showing graphics highlighting shape and margin of Foramen ovale for calculation of area.

The image analyzer used **ImageJ** which is a public domain Java image-processing program inspired by NIH Image (http://rsb.info.nih.gov/ij/features). It can display, edit, analyze and process images. This also assesses the particular structure to be analyzed for specific irregularities in shape, size and margins (Fig. 2).

2.4. Statistical analysis

The metric and non-metric data obtained was analyzed statistically. The metric data is presented with a description of Mean, Range and Standard deviation (SD) for each individual variable. Analysis of Variance (ANOVA) was used to test the statistical significance of the metric data, particularly with reference to gender and body side.

3. Results

3.1. Non-metric features

The **frequency** of presence of the MCF foramina is summarized in Table 1. The foramina ovale, rotundum, spinosum & lacerum were found to be consistently present in all 50 skulls whereas some skulls exhibited the foramen of Vesalius (unilateral 17%; bilateral 12%) and canaliculus innominatus (unilateral 5%).

The **variations** in characteristics of the larger and constant MCF foramina are synopsized in Table 2. The foramen ovale showed several variations such as partial or complete division and differences in shape ranging from triangular to oval. The foramen rotundum was more or less of semicircular shape and bipartite in only one case. The size of the foramen spinosum is too small to warrant comments about its shape but some variations could be appreciated. It was seen to be contiguous with the foramen ovale in a few cases, separated from the latter by an incomplete curved spur. A prominent, thick ridge was observed on both sides in one skull, separating the foramina ovale and spinosum.

3.2. Maximum diameter

Data is presented on the mean maximum diameter (±SD) recorded from digital photographs across the farthest apart points on the bony margin of each major foramen on either side using

Table 1
Frequency of major and minor foramina in relation to the floor of MCF.

S. No.	MCF Foramen (F.)	Unilateral ($n = 50 \times 2 = 100$)*	Bilateral ($n = 50 \times 2 = 100$)*
1.	F. ovale	0	50 (100%)
2.	F. rotundum	0	50 (100%)
3.	F. spinosum	0	50 (100%)
4.	F. lacerum	0	50 (100%)
5.	F. Vesalius (emissary sphenoidal foramen)	17 (17%)	6 (12%)
6.	F. petrosum (*Canaliculus innominatus*)	5 (5%)	0

* Total no. of skulls = 50; observations (Left & Right): $n = 50 \times 2 = 100$; percentage computed with reference to $n = 100$ observations.

Table 2
Variations in non-metric features of foramina in relation to the floor of MCF.

S. No.	MCF Foramen (F.)	Shape	Incomplete division	Complete division	Additional feature(s)
1.	F. ovale	• Oval – 96 (96%) • Triangular – 2 (2%) • Elongated (**<2 mm width**)– 2 (2%)	Lateral Projections: • Bar-like – 2 (2%) • Bony spur – 1 (1%)	Bipartite foramen – 1 (1%)	Bilateral thick ridge intervening with F. Spinosum – 1 (2%)
2.	F. rotundum	Semicircular – 100 (100%)	Nil (0)	Bipartite foramen – 1 (1%)	–
3.	F. spinosum	Tiny, circular – 100 (100%)	Nil (0)	Nil (0)	–
4.	F. lacerum	Irregular margins – 100 (100%)	Nil (0)	Nil (0)	–
5.	F. Vesalius (emissary sphenoidal foramen)	Tiny, circular – 100 (100%)	Nil (0)	Nil (0)	–
6.	F. petrosum (*Canaliculus innominatus*)	Tiny, circular – 100 (100%)	Nil (0)	Nil (0)	–

Total no. of skulls = 50; observations (Left & Right): $n = 50 \times 2 = 100$; percentage computed with reference to $n = 100$ observations.

ImageJ (Table 3). No significant differences were found in mean values between the two sides (left/right) and between sexes (male/female) for any of the larger, constant foramina (ovale, rotundum, spinosum, lacerum).

3.3. Computed area

Data is presented on the computed mean area (±SD) recorded from digital photographs of each major foramen on either side using ImageJ (Table 4). Significant differences were found between the mean area computed for the foramina ovale, spinosum and lacerum, the values of enclosed area in all these foramina being significantly greater on the left side in both sexes and in male skulls. No significant differences between the mean area recorded for each side and sex were found in the values computed for foramen rotundum.

4. Discussion

The MCF remains an enigmatic, complex surgical arena for both the neurosurgeon seeking curative access and the anatomist seeking to explore its challenging terrain. It is a spatially narrow

Table 3
Maximum diameters of major foramina in relation to the floor of MCF.

Name of the foramen	Male skulls (n = 29)		Female skulls (n = 21)		All skulls (n = 50)	
	Left	Right	Left	Right	Left	Right
Foramen ovale	8.11 (2.7) 3.95–16.90	8.67 (1.78) 5.59–11.92	8.36 (1.70) 5–11.35	7.47 (2.25) 2.42–10.29	8.12 (2.33) 3.9–16.9	8.16 (2.06) 2.4–11.92
Foramen rotundum	3.51 (0.82) 2–5.54	2.65 (1.05) 1.2–5.09	2.96 (0.74) 1.96–4.36	3.21 (0.98) 1.58–4.8	3.29 (0.8) 1.9–5.5	2.9 (1.04) 0.62–5.09
Foramen spinosum	2.62 (0.92) 1.33–4.74	2.13 (0.89) 0.38– 4.14	2.34 (0.88) 0.38–3.69	2.1 (0.93) 0.42–3.71	2.49 (0.8) 0.38–4.7	2.11 (0.9) 0.38–4.14
Foramen lacerum	6.74 (1.29) 3.8–9.5	6.83 (1.67) 4.30–10.8	6.8 (1.28) 4–9	6.97 (1.43) 3.85–8.98	6.72 (1.29) 3.8–9.5	6.89 (1.56) 3.8–10.8

All measurements are in mm. Mean values with standard deviations (in parentheses) and ranges (given below) are set out in the appropriate columns.

Table 4
Computed area of major foramina in relation to the floor of MCF.

Name of the foramen	Male skulls (n = 29)		Female skulls (n = 21)		All skulls (n = 50)	
	Left	Right	Left	Right	Left	Right
F. ovale	36.7 (32.82) 10.54–152.07	32.42 (14.68) 9.7–67.54	30.69 (12.77) 3.9–49.83	26.42 (13.87) 2.7– 55	34.18 (26.29) 3.9–152	29.9 (14.5) 2.7–67.54
F. rotundum	9.56 (5.03) 2.6–18.93	7.32 (4.37) 3–19.53	7.49 (5.22) 1.67–24.83	10.75 (5.19) 2.6–19.61	8.61 (5.15) 1.67–24.83	8.82 (4.98) 2.68–19.6
F. spinosum	5.77 (3.56) 0.85–15.82	4.15 (2.09) 1–9.4 (n = 26)*	4.60 (2.75) 0.54–10.8	3.71 (2.23) 0.5–9.91 (n = 18)*	5.27 (3.22) 0.54–15.82	3.89 (2.2) 0.5–9.91 (n = 44)*
F. lacerum	41.97 (14.93) 11.46–70.15	39.68 (14.16) 19.08–68.73	40.75 (16.38) 17.93–70.58	36.24 (13.81) 15.92–66.71	41.46 (15.4) 11.46–70.58	38.23 (13.98) 15.92–68.73

All measurements are in mm^2. Mean values with standard deviations (in parentheses) and ranges (given below) are set out in the appropriate columns.
* Area measurements could not be accurately computed for the partially damaged right foramen spinosum in 3 male and 3 female skulls.

and structurally dense region, where critically vital entities take intriguingly circuitous routes to be literally and figuratively bow-tied to the brain. The variations in the MCF foramina as also their clinical consequences are not well known. Morphometric data pertaining to this region is therefore extremely scarce and hence surgical guidelines are at best sketchy.

An extensive and detailed review of available literature revealed the selective nature of the morphometric studies attempted in this region, usually pertaining to the specific surgical approach for the practice of which the respective study was designed.[6–8] Verifiable data is available for only a few bony structures within the MCF. Most of the earlier studies that were attempted from a neuro-surgical perspective, have been conducted on dissected specimens rather than on dry macerated skulls.[9,10] Dry bones are better resource material for collecting morphometric data, although cadaveric specimens offer more realistic and skill-based training possibilities for surgeons.

The skulls selected for this study (most likely of Indian origin), represent human groups of mixed ethnicity[11] as also indigenous tribes,[12,13] embracing tremendous intra-population diversity.[14,15] There are reports on differences in skull capacity among various ethnic groups, and their influence on our data cannot be denied.[16–18] All the measurements on MCF foramina in the current study, can therefore be considered as reference data for a population representing an admixture of various races.

4.1. Non-metric features of MCF foramina

The consistent presence of the major foramina in the floor of the MCF noted in all the specimens currently studied, was found to be in complete agreement with similar reports in existing literature.[19,20] The findings about the *foramen ovale* in this study are also in tandem with those of Reymond et al. who reported a wide diversity in the shape of this foramen as well as subdivision into 2–3 smaller foramina in 4.5% of their cases.[19] Some variations like a bipartite *foramen rotundum* have not been reported earlier, to the best of our knowledge.

Foramen spinosum was found bilaterally in all our specimens, although its absence has been reported in some studies: the foramen was found absent in 0.4% cases through an X-ray study by Lindblom[21] it was absent in 3.2% cases in a CT study reported by Ginsberg et al.[20] This foramen can easily be missed in a casual survey due to its small size: we found maximum diameters as small as 0.38 mm. Its shape is also difficult to define due to its small size. A confluence of foramen spinosum with foramen ovale, separated from it by an incomplete curved spur has also been reported earlier.[20] Small details of the foramen spinosum and other minor foramina of the MCF may require further exploration.

Our findings regarding presence of the *emissary sphenoidal foramen of Vesalius* unilaterally in 17% cases and bilaterally in 6 skull specimens, exactly corresponds to the frequency reported by Reymond et al. in 17% of their cases.[19] However Ginsberg et al. reported it in 80% of their cases in their CT study on temporal bones.[20] It can be reasonably argued that despite the comparatively large sample size (123 CT studies) studied by Ginsberg et al., examination through a direct eye-view of dry macerated skulls is relatively more authentic for such bony details. The disparity in observations may also have arisen due to differences in observational criteria or the ethnicity of the studied population. No special feature was found associated with this foramen either in this study or on literature survey.

Cannaliculus innominatus or the *petrosal foramen of Arnold* was found unilaterally in 5% of our cases as against 16.3% reported by Ginsberg et al. in their CT study of temporal bones.[20] The little information about this foramen in literature mandates further studies on various representative populations before a reasonable comment on its occurrence may be attempted.

4.2. Morphometry of MCF foramina

The data on **maximum diameters** of the major MCF foramina was collected using image analyzer and found largely consistent with the values reported by Berlis et al. in their direct and CT-based morphometric studies.[22] The minor disparity in values maybe understood in the context of differences in the type of sample, its size and the methodology used for measurement and analysis.

The maximum diameter of the *foramen ovale* reported by this study (mean 8.14 mm ± SD 1.7–2.7, range 2.4–16.9 mm) mirrors the findings reported by both Berge et al. (mean 7.11 mm, range 2–8 mm)[23] and those of Berlis et al. by direct measurement (mean 7.41 mm ± SD 1.31, range 4.61–11.29 mm) and using CT scans (mean 7.67 mm ± SD 1.43, range 5–12 mm).[22] The mean values recorded in our study were however slightly greater than those reported by both these groups.

The maximum diameter of the *foramen rotundum* reported by Berge et al. (mean 3.26 mm, range 2–4.5 mm)[23] and by Berlis et al. on direct measurement (mean 3.29 mm ± SD 0.63, range 2.05–5.14 mm) as well as CT scans (mean 3.11 mm ± SD 0.78, range 2–5 mm)[22] are quite close in values to those observed in the present study using digital images (mean 3.09 mm ± SD 0.82–1.05, range 0.62–5.09 mm).

The maximum diameter of the *foramen spinosum* reported by Berge et al. on direct measurement (mean 2.39 mm, range 1–4 mm)[23] and that by Berlis et al. on direct measurement (mean 2.60 mm $\pm$ SD 0.52, range 1.53–4.35)[22] as well as from CT scans (mean 2.42 mm $\pm$ SD 0.71, range 1–4 mm) are very close to the values measured in this study on digital images (2.25 mm $\pm$ SD 0.8–0.93, range 0.38–4.7 mm).

The **mean area** of *foramen ovale* reported in the present study (value derived by averaging left & right mean values) is 32 mm^2 which is quite close to the average values reported in literature (28.8 mm^2) as calculated from the formula of an ellipse using linear dimensions.[22,24,25] The mean values for female skulls and the right sided foramina were found significantly lower in the present study than those for male skulls and the left sided foramina. In the current study, values range from as low as 2.7 mm^2 to as high as 152.07 mm^2. The reported overall range calculated from linear dimensions by other workers was 25.24–115.31 mm^2.[22,24,25]

The present study similarly computed the mean area for *foramen rotundum* as 8.72 mm^2 (range 1.67–24.83 mm^2). On the other hand, mean area of this foramen computed by using the formula of an ellipse from the values provided by Berge et al. average 5.78 mm^2 (range 3.14–12.36 mm^2).[23]

Since these other mentioned authors derived their values of area indirectly by calculation from length and width using the formula of an ellipse,[a] the values computed in this study maybe considered more accurate. The area was computed as a whole in the present study, using the ImageJ software and taking into account the curves and irregularities in the margin of each foramen.

The area of *foramen spinosum* reported in literature[19,22] approximates 3.65 mm^2 in contrast to an overall average of 4.5 $mm^2 \pm$ SD 2.09–3.56 as reported in the present study. The difference in values may be due to a different methodology used: a small difference in the measured length can lead to a much greater change in the value of area calculated from the formula of an ellipse.

A thorough literature survey did not reveal any data on diameters or area of *foramen lacerum*, probably because this is not regarded as a true foramen.[1]

Comparison of mean values of maximum diameters for all the major foramina as well as area computed for foramen rotundum, revealed no significant differences between the values recorded for each sex and body side. However the mean areas computed for the foramina ovale, spinosum and lacerum were found significantly greater on the left side in both sexes and in male skulls. We did not find any data on literature survey that was specific to gender and laterality based differences in foramen size.

Conflict of interest

The authors have no conflicts of interest to declare.

[a] Area of an ellipse = πab, where a = vertex, b = co-vertex of an ellipse, Constant π = 3.14159 (approx.).

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