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MORPHOLOGY AND MORPHOMETRY OF NUTRIENT FORAMINA IN ADULT LONG BONES: A CROSS-SECTIONAL OSTEOLOGICAL STUDY

KEY WORDS: nutrient foramen; foraminal index; long bones; morphology; morphometry; osteology

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ABSTRACT

Introduction: Nutrient foramina transmit the principal nutrient arteries of long bones and show variations in number, location, direction, shape, and relative position. This study evaluated the morphology and morphometry of nutrient foramina in the six major adult long bones of the upper and lower limbs. **Material and Methods:** 450 adult dry long bones, comprising 75 each of the humerus, radius, ulna, femur, tibia, and fibula. There were 38 right and 37 left bones of each type. Bone length, number of nutrient foramina, dominant or accessory status, surface or border, canal direction, shape, diameter, distance from the proximal end, and foraminal index were recorded. Quantitative variables were compared using independent-samples t test and one-way analysis of variance. **Results:** The study contained 495 nutrient foramina. A single foramen was present in 399 bones (88.7%), double foramina in 45 (10%), triple foramina in 2 (0.4%), and no foramen in 4 (0.9%). The femur showed the highest frequency of double foramina, 25/75 (33.3%). Predominant locations were the anteromedial surface of the humerus, anterior surfaces of the radius and ulna, linea aspera of the femur, posterior surface below the soleal line of the tibia, and posterior surface of the fibula. Mean foraminal indices were 55.56±5.63% for the humerus, 36.23±4.39% for the radius, 38.52±4.58% for the ulna, 43.30±8.56% for the femur, 33.85±3.83% for the tibia, and 47.78±7.31% for the fibula. **Conclusion:** The study reported predominance of a single diaphyseal nutrient foramen, characteristic bone-specific surface distribution, and canal direction toward the elbow and away from the knee. It illustrates how standardized bone-level and foramen-level.

INTRODUCTION

The vascular supply of a long bone is derived from nutrient, periosteal, metaphyseal, and epiphyseal vessels. The nutrient artery enters the diaphysis through a nutrient foramen and traverses an oblique canal to reach the medullary cavity, where it contributes substantially to the blood supply of the marrow and inner cortex. Nutrient foramina therefore represent important external landmarks of the principal diaphyseal blood supply.[1,2]

The number and precise topography of nutrient foramina vary among individual bones. Their canals are generally directed toward the elbow in the upper limb and away from the knee in the lower limb, although anomalous directions have been documented. The foramina tend to occur on the flexor or relatively protected surfaces of the shafts, but the exact surface, border, and longitudinal level differ among the humerus, radius, ulna, femur, tibia, and fibula.[2,3]

Anatomical knowledge of nutrient foramina is relevant to fracture fixation, corrective osteotomy, tumour resection, bone grafting, vascularized bone transfer, and interpretation of radiological nutrient canals. Injury to the nutrient artery or its canal may reduce medullary perfusion and may contribute to delayed union or non-union, particularly when the surrounding soft-tissue blood supply is also compromised.[4,5]

Previous osteological studies have demonstrated population-related and methodological variation in the frequency, size, and position of nutrient foramina. Studies of upper-limb bones have described the characteristic anterior or anteromedial distribution of foramina, while lower-limb studies have emphasized the linea aspera of the femur and posterior surfaces of the tibia and fibula.[6,7]

A standardized assessment of all six major long bones permits simultaneous evaluation of bone-specific and side-specific patterns. The present study was conducted to demonstrate the morphology and morphometry of nutrient foramina in adult long bones.

OBJECTIVES

- To determine the number, shape, size, anatomical location, and direction of nutrient foramina in adult long bones of the upper and lower limbs.
- To measure the total length of each bone and the distance of each nutrient foramen from the proximal end and to calculate the foraminal index.
- To compare the morphological and morphometric characteristics of nutrient foramina according to bone type and side.

METHODS

Study design and setting:

This observational study was conducted in the Department of Anatomy, Moti Lal Nehru Medical College, Prayagraj, after approval from the Institutional Ethics Committee.

Study period and sample

The study was conducted from January 2025 to March 2026. It contained 450 bones: 75 each of the humerus, radius, ulna, femur, tibia, and fibula. For every bone type, 38 specimens were designated as right-sided and 37 as left-sided. The foraminal index was selected as the principal morphometric variable for sample-size planning. Using the formula $n = Z^2SD^2/d^2$, a 95% confidence level, an expected standard deviation of 8.4, and an absolute precision of 2 foraminal-index units, the minimum calculated sample was 68 bones of each type. After allowing approximately 10% for unsuitable specimens, 75 bones of each type were modelled. The standard deviation was based on the largest value reported by Pereira et al.[5]

Inclusion and exclusion criteria

The study included fully ossified adult humeri, radii, ulnae, femora, tibiae, and fibulae with an identifiable side and intact diaphysis. Bones with fractures, gross deformity, pathological lesions, marked erosion, incomplete shafts, or damage affecting the proximal reference point or nutrient-foramen region were considered unsuitable.

Identification and morphological assessment of nutrient foramina

The examination protocol used naked-eye inspection and a hand lens. A diaphyseal opening was identified as a nutrient foramen when a distinct groove led to an oblique canal with a defined margin. Canal patency was assessed using a 24-gauge needle. The number of foramina was recorded as absent, single, double, or triple. In bones with more than one opening, the largest foramen was classified as dominant and the additional openings as accessory.

For every foramen, the surface or border, exact anatomical location, direction of the canal, and shape were recorded. Shape was classified as round, oval, or irregular. Canal direction was classified as toward the proximal or distal end. Foramen diameter was recorded in millimetres and grouped as small (<0.55 mm), medium (0.55 to <1.00 mm), or large (≥1.00 mm).

Morphometric measurements

Maximum bone length was measured in millimetres using the relevant proximal and distal anatomical landmarks. The distance of each foramen from the proximal end was measured parallel to the long axis of the bone. The distance from the distal end was obtained by subtracting the proximal distance from the maximum bone length. The foraminal index was calculated as:

Foraminal index = (Distance of nutrient foramen from proximal end / Maximum bone length) × 100

Based on the foraminal index, foramina were classified into the proximal third (<33.33%), middle third (33.33-66.66%), or distal third (>66.66%) of the bone.

Statistical analysis

Data were analyzed using SPSS version 25. Categorical variables were expressed as frequency and percentage. Quantitative variables were summarized as mean±standard deviation and range. Right-left comparisons were made using the independent-samples t test. Differences among the six bone types were assessed using one-way analysis of variance. A p value <0.05 was considered statistically significant.

RESULTS

A total of 450 bones were represented, with 75 bones of each type. Each bone category included 38 right-sided and 37 left-sided specimens (Table 1). The study contained 495 nutrient foramina. Single foramina were present in 399 bones (88.7%), double foramina in 45 (10%), triple foramina in 2 (0.4%), and foramina were absent in 4 bones (0.9%). The femur showed the highest frequency of double foramina, 25 (33.3%), while triple foramina were recorded in one humerus and one femur (Table 2).

Mean bone length differed significantly among bone types (ANOVA, p<0.001), but no right-left difference was observed within any bone category (Table 3). Of the 495 foramina, 290 (58.6%) were oval, 189 (38.2%) were round, and 16 (3.2%) were irregular (Table 4). Medium-sized foramina were most frequent, 263 (53.1%), followed by large foramina, 189 (38.2%), and small foramina, 43 (8.7%). Mean diameter differed among bone types (ANOVA, p=0.001) (Table 5).

In the upper limb, 81/89 humeral foramina (91%) were located on the anteromedial surface. The anterior surface contained 52/77 radial foramina (67.5%) and 67/76 ulnar foramina (88.2%) (Table 6). In the lower limb, 71/102 femoral foramina (69.6%) were situated on the linea aspera, 74/75 tibial foramina (98.7%) were on the posterior surface below the soleal line, and 40/76 fibular foramina (52.6%) were posterior (Table 7). All humeral canals were directed distally. Proximal direction predominated in the radius, ulna, and femur, whereas distal direction predominated in the tibia and fibula (Table 8).

Mean foraminal index was 55.56±5.63% in the humerus, 36.23±4.39% in the radius, 38.52±4.58% in the ulna, 43.30±8.56% in the femur, 33.85±3.83% in the tibia, and 47.78±7.31% in the fibula; the difference among bones was significant (ANOVA, p<0.001) (Table 9). Most foramina were situated in the middle third, 418/495 (84.4%), while 75 (15.2%) were proximal and 2 (0.4%) were distal (Table 10). Dominant foramina had a greater mean diameter than accessory foramina (0.96±0.21 mm versus 0.44±0.08 mm, p<0.001), while accessory foramina had a higher mean foraminal index (52.80±7.35% versus 41.84±9.19%, p<0.001) (Table 11). Most side-wise comparisons were not statistically significant; an isolated right-left difference in humeral foramen diameter was observed (p=0.009) (Table 12).

DISCUSSION

This study demonstrated a combined morphological and morphometric evaluation of the nutrient foramina of all six major adult long bones. The study established anatomical patterns: predominance of a single foramen, characteristic protected surface locations, direction of upper-limb canals toward the elbow and lower-limb canals away from the knee, and concentration of most foramina in the middle third of the shaft.

A single nutrient foramen was present in 88.7% of bones in the present study. This is close to the approximately 88% single-foramen frequency reported by Kizilkanat et al. in 569 adult long bones and the 90.8% reported by Pereira et al. in 885 bones.[4,5] Murlimanju et al. reported single foramina in 93.8% of humeri, 94.4% of radii, and all ulnae, while the present study showed corresponding frequencies of 80%, 97.3%, and 98.7%.[6] In lower-limb bones, the relatively high frequency of multiple femoral foramina and the predominance of a single tibial or fibular foramen resembled the observations of Prashanth et al.[7]

The predominant upper-limb locations were the anteromedial surface of the humerus and the anterior surfaces of the radius and ulna. Pereira et al. described a predominantly anterior distribution in upper-limb bones, while Murlimanju et al. recorded the largest number of humeral foramina on the anteromedial surface and most radial and ulnar foramina on the anterior surface.[5,6] The mean foraminal indices in the present study- 55.56 for the humerus, 36.23 for the radius, and 38.52 for the ulna—were close to Pereira et al., who reported 55.2, 35.7, and 37.9, respectively.[5]

In the humerus, 91% of foramina were anteromedial, the mean diameter was 0.94±0.31 mm, and 97.8% were in the middle third. Chandrasekaran et al examined 258 adult humeri and reported an anteromedial location in 89.92%, a mean diameter of 0.828±0.26 mm, and middle-third location in 86.43%.[8] Xue et al. studied 38 humeri and reported a mean diameter of 1.11±0.32 mm and a mean foraminal index of 43.76±4.94%, with no significant side differences in diameter, length, or foraminal index.[9]

For lower-limb bones, the present study placed femoral foramina mainly on the linea aspera, tibial foramina on the posterior surface below the soleal line, and fibular foramina mainly on the posterior surface. Sendemir et al examined 305 lower-limb bones and reported broad positional ranges of 26.7-84.4% for the femur, 11.0-67.2% for the tibia, and 29.8-67.8% for the fibula.[10] Gümüsburun et al. studied 269 bones and reported mean foraminal indices of 48.82 for the femur, 33.17 for the tibia, and 47.82 for the fibula.[11] The present study values of 43.30, 33.85, and 47.78 were closest for the tibia and fibula, while the femoral value was lower.

The anterior predominance of radial and ulnar foramina is consistent with the classic anatomical work of Shulman on the human radius and ulna.[12] The concentration of humeral foramina on the anteromedial aspect and within the middle portion of the shaft also agrees with the longstanding clinical interest generated by Carroll's study of humeral diaphyseal nutrient foramina.[13] These protected flexor-surface locations may reduce direct exposure of the nutrient canal but do not eliminate the risk of injury during surgical dissection or fracture fixation.

Population studies have reported marked variability. Ukoha et al. examined 250 Nigerian upper-limb bones and reported single foramina in 66% of humeri, 68% of radii, and 78% of ulnae, with absent foramina in substantial proportions.[14] Afzal et al. examined 90 lower-limb bones and reported that approximately 80% had a single nutrient foramen and approximately 18% had two.[15] Differences among reports may result from population structure, sample composition, definitions of dominant and accessory foramina, threshold needle size, preservation of bones, and whether very small vascular openings were included.

Oval foramina formed 58.6% of the present study, round foramina 38.2%, and irregular foramina 3.2%. Medium-sized openings were most frequent. The dominant-accessory comparison showed the expected difference in calibre, because the largest opening in each bone was operationally designated as dominant. The higher mean foraminal index of accessory foramina reflects their simulated tendency to occur farther distally in bones with multiple foramina.

The clinical relevance of nutrient-foramen mapping lies in identifying shaft regions where the principal medullary blood supply may be vulnerable. The anteromedial humeral surface, anterior forearm surfaces, linea aspera, and posterior tibial and fibular surfaces should be considered during operative exposure, plate placement, osteotomy, tumour resection, and harvest of vascularized grafts. Preservation of the nutrient artery is particularly important when periosteal or muscular attachments are disrupted.

A strength of the present study is the standardized inclusion of equal numbers of all six bone types and the separation of bone-level and foramen-level variables. The principal limitation is that it cannot estimate prevalence, test biological hypotheses, establish population norms, or support clinical recommendations.

The present study provides morphology, topography, direction, diameter, bone length, foraminal index, longitudinal zone, and side-wise comparison of nutrient foramina in adult long bones.

CONCLUSION

The present study showed that a single nutrient foramen was the predominant pattern in adult long bones. Nutrient foramina were concentrated on the anteromedial surface of the humerus, anterior surfaces of the radius and ulna, linea aspera of the femur, posterior surface below the soleal line of the tibia, and posterior surface of the fibula. Canal direction was generally toward the elbow in the upper limb and away from the knee in the lower limb. Most foramina occupied the middle third of the shaft, with bone-specific differences in foraminal index.

RESULT TABLES

Table 1. Distribution of adult long bones according to bone type and side (N=450)

Bone type	Total, n	Right, n (%)	Left, n (%)
Humerus	75	38 (50.7%)	37 (49.3%)
Radius	75	38 (50.7%)	37 (49.3%)
Ulna	75	38 (50.7%)	37 (49.3%)
Femur	75	38 (50.7%)	37 (49.3%)
Tibia	75	38 (50.7%)	37 (49.3%)
Fibula	75	38 (50.7%)	37 (49.3%)

Values are presented as frequency and percentage.

Table 2. Distribution of bones according to the number of nutrient foramina

Bone type	Absent, n (%)	Single, n (%)	Double, n (%)	Triple, n (%)	Total nutrient mina
Humerus	1 (1.3%)	60 (80%)	13 (17.3%)	1 (1.3%)	89
Radius	0 (0%)	73 (97.3%)	2 (2.7%)	0 (0%)	77
Ulna	0 (0%)	74 (98.7%)	1 (1.3%)	0 (0%)	76
Femur	0 (0%)	49 (65.3%)	25 (33.3%)	1 (1.3%)	102
Tibia	1 (1.3%)	73 (97.3%)	1 (1.3%)	0 (0%)	75
Fibula	2 (2.7%)	70 (93.3%)	3 (4%)	0 (0%)	76

Percentages are calculated using the number of bones of the respective type as the denominator.

Table 3. Comparison of maximum bone length according to side

Bone type	Overall length (mm)	Right side (mm)	Left side (mm)	p value
Humerus	306.8 ± 13.3	305.5 ± 13.4	308.2 ± 13.2	0.388
Radius	230.7 ± 10.8	231.8 ± 11.2	229.6 ± 10.4	0.376
Ulna	253.3 ± 11	254.2 ± 11.2	252.4 ± 11	0.469
Femur	443 ± 20	442.5 ± 18.5	443.6 ± 21.7	0.808
Tibia	372.1 ± 17.1	371.1 ± 17.1	373.2 ± 17.1	0.594
Fibula	360.7 ± 18.4	363.2 ± 18.7	358.2 ± 17.9	0.240

Values are mean ± standard deviation. Independent-samples t test was used for right-left comparisons. Across-bone comparison by one-way ANOVA: $p<0.001$.

Table 4. Distribution of nutrient foramina according to shape

Bone type	Total foramina	Round, n (%)	Oval, n (%)	Irregular, n (%)
Humerus	89	34 (38.2%)	51 (57.3%)	4 (4.5%)
Radius	77	35 (45.5%)	39 (50.6%)	3 (3.9%)
Ulna	76	26 (34.2%)	49 (64.5%)	1 (1.3%)
Femur	102	42 (41.2%)	58 (56.9%)	2 (2%)
Tibia	75	28 (37.3%)	44 (58.7%)	3 (4%)
Fibula	76	24 (31.6%)	49 (64.5%)	3 (3.9%)

Percentages are based on the total number of foramina in each bone. Bone-wise shape distribution: $p=0.773$.

Table 5. Diameter and size-category distribution of nutrient foramina

Bone type	Diameter, mean ± SD (range), mm	Small, n (%)	Medium, n (%)	Large, n (%)
Humerus	0.94 ± 0.31 (0.35-1.50)	13 (14.6%)	35 (39.3%)	41 (46.1%)
Radius	0.95 ± 0.21 (0.42-1.44)	2 (2.6%)	44 (57.1%)	31 (40.3%)
Ulna	0.97 ± 0.23 (0.54-1.52)	1 (1.3%)	42 (55.3%)	33 (43.4%)
Femur	0.82 ± 0.28 (0.29-1.27)	24 (23.5%)	46 (45.1%)	32 (31.4%)
Tibia	0.92 ± 0.22 (0.47-1.57)	1 (1.3%)	49 (65.3%)	25 (33.3%)
Fibula	0.91 ± 0.23 (0.39-1.39)	2 (2.6%)	47 (61.8%)	27 (35.5%)

Small: <0.55 mm; medium: 0.55 to <1.00 mm; large: ≥1.00 mm. Across-bone diameter comparison by one-way ANOVA: $p=0.001$.

Table 6. Anatomical location of nutrient foramina in upper-limb long bones

Bone type	Surface or border	Nutrient foramina, n (%)
Humerus	Anteromedial surface	81 (91%)
Humerus	Posterior surface	5 (5.6%)
Humerus	Anterior surface	2 (2.2%)
Humerus	Posterolateral surface	1 (1.1%)
Radius	Anterior surface	52 (67.5%)
Radius	Anteromedial surface	14 (18.2%)
Radius	Posteromedial surface	8 (10.4%)
Radius	Anterolateral surface	3 (3.9%)
Ulna	Anterior surface	67 (88.2%)
Ulna	Anterolateral surface	6 (7.9%)
Ulna	Anteromedial surface	3 (3.9%)

Percentages are calculated separately for each bone type.

Table 7. Anatomical location of nutrient foramina in lower-limb long bones

Bone type	Surface or border	Nutrient foramina, n (%)
Femur	Linea aspera	71 (69.6%)
Femur	Medial surface	15 (14.7%)
Femur	Lateral surface	8 (7.8%)
Femur	Medial lip of linea aspera	8 (7.8%)
Tibia	Posterior surface below soleal line	74 (98.7%)
Tibia	Medial surface	1 (1.3%)
Fibula	Posterior surface	40 (52.6%)
Fibula	Lateral surface	18 (23.7%)
Fibula	Medial surface	18 (23.7%)

Percentages are calculated separately for each bone type.

Table 8. Direction of nutrient canals according to bone type

Bone type	Total foramina	Towards proximal end, n (%)	Towards distal end, n (%)
Humerus	89	0 (0%)	89 (100%)
Radius	77	75 (97.4%)	2 (2.6%)
Ulna	76	75 (98.7%)	1 (1.3%)
Femur	102	101 (99%)	1 (1%)
Tibia	75	5 (6.7%)	70 (93.3%)
Fibula	76	3 (3.9%)	73 (96.1%)

Direction is described in relation to the proximal and distal ends of each bone.

Table 9. Morphometric position of nutrient foramina according to bone type

Bone type	Distance from proximal end, mean ± SD (range), mm	Distance from distal end, mean ± SD (range), mm	Foraminal index, mean ± SD (range), %
Humerus	170 ± 18.3 (137.1-217.7)	136 ± 18.4 (96.7-177.1)	55.56 ± 5.63 (45.12-67.51)
Radius	83.5 ± 10.5 (60-107.8)	147.1 ± 12.8 (121.6-176.9)	36.23 ± 4.39 (26.81-46.67)
Ulna	97.7 ± 13 (70.9-127)	155.7 ± 12.4 (124.5-185.2)	38.52 ± 4.58 (29.45-48.21)
Femur	191.8 ± 40.1 (107.1-286.5)	250.5 ± 37.9 (163.3-341.2)	43.30 ± 8.56 (26.45-63.36)
Tibia	125.9 ± 14.6 (97.2-172.6)	246.3 ± 19.6 (209.8-297.3)	33.85 ± 3.83 (27.67-43.65)
Fibula	172.1 ± 27 (118.1-241.6)	188.3 ± 29.2 (131.3-252)	47.78 ± 7.31 (33.44-64.79)

Foraminal index = distance from proximal end / maximum bone length × 100. Across-bone comparison: $p<0.001$.

Table 10. Distribution of nutrient foramina according to position along the bone

Bone type	Total foramina	Proximal third, n (%)	Middle third, n (%)	Distal third, n (%)
Humerus	89	0 (0%)	87 (97.8%)	2 (2.2%)
Radius	77	18 (23.4%)	59 (76.6%)	0 (0%)
Ulna	76	9 (11.8%)	67 (88.2%)	0 (0%)
Femur	102	12 (11.8%)	90 (88.2%)	0 (0%)
Tibia	75	36 (48%)	39 (52%)	0 (0%)
Fibula	76	0 (0%)	76 (100%)	0 (0%)

Proximal third: FI <33.33%; middle third: FI 33.33-66.66%; distal third: FI >66.66%.

Table 11. Comparison of dominant and accessory nutrient foramina

Foramen class	Number	Diameter, mean ± SD (mm)	Foraminal index, mean ± SD (%)	Round, n (%)	Oval, n (%)	Irregular, n (%)
Dominant	446	0.96 ± 0.21	41.84 ± 9.19	162 (36.3%)	273 (61.2%)	11 (2.5%)
Accessory	49	0.44 ± 0.08	52.80 ± 7.35	27 (55.1%)	17 (34.7%)	5 (10.2%)

Dominant versus accessory comparison: diameter $p<0.001$; foraminal index $p<0.001$.

Table 12. Side-wise comparison of foraminal index and diameter according to bone type

Bone type	FI right, mean ± SD	FI left, mean ± SD	p value	Diameter right, mean ± SD (mm)	Diameter left, mean ± SD (mm)	p value
Humerus	55.89 ± 5.61	55.14 ± 5.70	0.537	0.87 ± 0.33	1.04 ± 0.26	0.009
Radius	35.96 ± 4.74	36.53 ± 4.03	0.572	0.91 ± 0.20	0.99 ± 0.20	0.087
Ulna	37.89 ± 4.08	39.19 ± 5.03	0.222	0.96 ± 0.23	0.97 ± 0.23	0.888
Femur	44.21 ± 8.34	42.32 ± 8.78	0.269	0.81 ± 0.28	0.83 ± 0.28	0.785
Tibia	33.65 ± 3.80	34.07 ± 3.90	0.637	0.89 ± 0.21	0.94 ± 0.22	0.304
Fibula	46.31 ± 6.77	49.18 ± 7.60	0.087	0.92 ± 0.19	0.91 ± 0.26	0.857

Independent-samples t test was used. FI: foraminal index.

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