Original Article

Morphometric Analysis of the Foramen Magnum in a South Indian Population: Anatomical Characteristics and Forensic Implications

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Abstract

Background: The foramen magnum is a key structure of the skull base, and it exhibits morphometric variability that can be informative to forensic anthropology as well as clinical practice. There is limited data regarding the morphometrics of the foramen magnum in the South Indian population, and, consequently, studies regarding the specific region are necessary to determine baseline measurements of the foramen magnum, transverse and anteroposterior (AP) diameter, and the foramen magnum index, and to determine whether they can be used to theorise the sex of the population under investigation. **Material and Methods:** A recording was conducted on a sample of 97 adult dry skulls (52 male and 45 female) from a South Indian osteological collection. Damaged skulls and pathological changes were disqualified. The measurements were performed with the help of digital vernier callipers: AP diameter (longest length across basion and opisthion), transverse diameter (longest length across), and index of foramen magnum (transverse length/AP length). Measurements were performed by two independent observers to promote reliability and were evaluated using the intraclass correlation coefficient (ICC). Spreadsheet and Descriptive statistics, the Shapiro-Wilk test of normality, and independent t-tests to evaluate differences by sex ($p < 0.05$) were performed using SPSS version 25.0. The frequency to be used was determined to estimate the mean AP diameter with a 0.5 mm error at the 95% confidence level. **Results:** The average AP diameter was 33.825.07 (29.138.2 mm), transverse 28.225.07(24.032.5 mm), and the foramen magnum index was 0.830.07. There were no great differences with respect to sex (AP: $p = 0.12$; transverse: $p = 0.15$; index: $p = 0.31$). The level of inter-observer reliability was high (ICC = 0.92). **Conclusion:** The research defines the morphometric norms of the foramen magnum in one population of South India, without significant sexual dimorphism. These results complement anthropological and forensic databases but suggest that their sex determinations are not particularly useful. Future studies are needed regarding imaging modalities and larger sample sizes.

Keywords: Foramen magnum, Morphometry, South India, Craniometry, Forensic anthropology.

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Introduction

The foramen magnum is the most recognisable anatomical landmark of the occipital bone, and it is the main passageway of vital neurovascular bundles, such as medulla oblongata, vertebral arteries and spinal accessory nerve that links the cranial cavity to the spinal canal.[1] Genetic, environmental, and evolutionary factors also interact in complex ways, leading to high variation in size, shape, and morphology within and among populations.[2,3] Such variations have attracted considerable interest in anthropological, forensic, and clinical studies, as they can provide insight into populations' unique characteristics, sexual dimorphism, and clinical practice.[4,5] Knowledge in these areas and answering region-specific anatomical and forensic questions would not have been possible without the knowledge of the morphometric profile of the foramen magnum.

Cranial measures, such as the foramen magnum, are commonly used in forensic anthropology for sex determination and for approximating ancestry.[4,6] Several studies have reported possible sexual dimorphism in foramen magnum size, including anteroposterior (AP) and transverse diameters, with males usually showing greater values in some populations.[4,7] As an illustration, one study involving a population in Britain found male and female mean AP diameters of 35.2 mm and 34.1 mm, respectively, suggesting that this might be applied in some sex identification during a forensic process.[4] In the same regard, studies conducted on other cohorts, e.g., the Turkish and Brazilian cohorts, have shown that there is a significant difference in the foramen magnum between the sexes, which can be used in forensic profiling.[8,9] However, it can be determined that levels of sexual dimorphism differ across geographic and ethnic populations, highlighting the importance of population-specific data for the accuracy of punitive measures.[6,10] Mean AP diameters of 32-35 mm and transverse

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diameters of 27-30 mm have been reported in the previous works of South India. Still, these studies were mainly conducted on small samples or limited subgroups and were therefore more restricted to general forensic situations.[2,11]

In addition to releasing forensic applications, foramen magnum morphometry has a considerable clinical applicability, especially in neurosurgery. Accurate information on its dimensions is essential for operations such as the transcondylar approach, where the size or shape may influence the surgical plan and results.[2,12] Further, an abnormal morphology of the foramen magnum has been linked to neurological disorders, including Chiari malformations, and they can have a population-specific prevalence.[13] It is therefore important to establish normative values for the foramen magnum across populations to achieve the most precise diagnosis possible, while remaining safe for the surgeon.

Although more research on foramen magnum morphometry is available, there is a dearth of research on South Indian-specific populations. The literature tends to have methodological shortcomings, such as small samples or incomplete statistical tests, and few studies have systematically investigated the forensic implications of such measurements.[11,14] This void is especially pronounced in light of a growing need for traditional forensic databases to be regionalised to aid medico-legal investigations among non-homogeneous populations.[10] Besides, the potential of foramen magnum measurements to help estimate ancestry or complement other cranial measurements in police identification has not been well investigated in the South Indian context.

To fill these gaps, the proposed study will quantify morphometric properties of the foramen magnum in a South Indian population using a sample of 97 dry skulls. Certain measures consist of anteroposterior diameter, transverse and foramen magnum index, where a concentration on sexual dimorphism as well as forensic utility is emphasised. We suppose that the foramen magnum sizes in this population will not only be the same as the South Indian population studies conducted in the past years, but also that they will be encompassed by sexual dimorphism and thus create useful baseline data upon anthropological studies and forensics, such as sex determination and identification of a population.

Materials and Methods

Study Design and Sample Selection

Sample Selection and Design of the Study.

As a cross-sectional study, the study aimed to measure morphometric properties of the foramen magnum in a population of South Indians, using a sample of 97 adult dry skulls from the osteological collection at the Department of Anatomy, Govt Medical Colleges, Kadapa, Nellore, and Ongole, Andhra Pradesh, India. The periodical research was given ethical approval by the Institutional Ethics Committee (SC/12/22/4/2025). Inclusion criteria were that the skulls were from adult individuals, with age calculated as above 18 years based on closure of cranial sutures (e.g., spheno-occipital synchondrosis) and dental eruption patterns.[16] Criteria of exclusion were skulls with any of the following: damage (e.g. fractures, erosions), other pathological conditions (e.g. osteophytes, metabolic bone disease), or deformity of the foramen magnum or neighbouring occipital bone (e.g. occipitalization, deformity of the Chiari malformation). Screening of a preliminary sample of 110 skulls made it possible to exclude any, and 13 skulls were excluded because of overt damage (n=8), pathological alteration (n=3), or incomplete occipital bones (n=2), with a resulting sample of 97 skulls.

Sex Determination: An experienced anatomist utilised all previously described cranial morphological characteristics, such as a high level of the supraorbital ridge, mastoid process size and strength, the nuchal crest, and the shape of the mandibular ramus, to assign a sex designation in a standardised approach to estimating sex in forensic anthropology.[1,6] A second blinded anatomist marked sex assignments to maximise accuracy and reduce observer bias. Observers agreed on the rate at 95 per cent, and discrepancies (n=5 skulls) were settled by consensus among observers and by further consideration of secondary characteristics, e.g., the slope of the frontal bone and the size of the occipital condyles.[16] A skull was categorised according to the majority judgment of morphological features in instances where it was not possible to find a consensus (n=1). A total of 52 male and 45 female skulls were obtained as a result of this process, representing a balanced sample for statistical comparison of sexual dimorphism.

Morphometric Measurements

The high-precision vernier calliper was used to measure three morphometric parameters:

1. **Anteroposterior (AP) Diameter:** The longest length along the midline of the foramen magnum (between the basion (midpoint of the anterior side of the margin of the foramen) and opisthion (midpoint of the posterior side of the margin)) as measured using standard anatomical palpation sites.[4]
2. **Transverse Diameter:** This is the largest width perpendicular to the AP diameter, as measured between the lateral margins of the foramen magnum where it is widest during the widest point [Figure 1]
3. **Foramen Magnum Index:** This is calculated as the ratio of the transverse to the AP diameter and offers a quantitative assessment of the shape of the foramen (e.g., oval, circular and irregular).[5]

Measurements were conducted in a controlled environment (ambient temperature: 2250C, humidity: 4050%, lighting: 500 lux) to reduce the effects of external factors on measurement accuracy. Intra-observer error was eliminated by having 2 independent observers, trained and blinded to the other observer's interpretations, measure each parameter twice. An analysis was done to obtain the mean of the two measurements. If the difference between measurements exceeded 0.1mm, a third measurement was taken, and the median was used as a measure of accuracy. Inter-observer reliability was evaluated using the intraclass correlation coefficient (ICC; two-way mixed model, absolute agreement), with a target ICC above 0.90, a crucial measure of excellent consistency.[17] To ensure the instrument was correct, the calliper was calibrated daily against a certified reference block (accuracy: ±0.01 mm), and a measurement interval of no more than 2 hours was adopted to avoid observer fatigue.

Sample Size Calculation: The calculation of the sample size was done, estimating the mean AP diameter, 95 per cent confidence level, and a margin of error of 0.5 mm, which is based on a standard deviation of 2.5 mm calculated using other studies carried out on the South Indian population previously, as cited in article 11. The formula was:n= (Z 1.96 2)n = (0.5 1.96 2)n= (2.5 0.5 2)2= (0.5 1.96 2)2= E= mm (margin of error), 0.96 = 1.96 Z= 1.96 Z=1.96 (95% confidence). With this computation, the maximum number of skulls was 97. A total of 110 skulls was first filtered to obtain an initial pool for the study, to counter the possible exclusion of damage, pathology, and measurement errors. A final sample of the required size was to be selected by taking the required number of skulls after applying the exclusion criteria. To verify the capability of the study to identify a clinically significant difference in AP diameter between sexes (i.e. 1.5 mm, which is found in some populations,[4]) with a desired power of 80 and an alpha of 0.05,[18] a post hoc power analysis was done.

Statistical Analysis: The information was logged into a safe, anonymised database and analysed using SPSS version 25.0 (IBM Corp., Armonk, NY). The Shapiro-Wilk test was used to evaluate the normality of measurements (AP diameter, transverse diameter, and foramen magnum index), and p>0.05 indicated that the distributions were normal. Each parameter was computed using descriptive statistics, such as mean, standard deviation, minimum, maximum, and 95 per cent confidence intervals, for the total sample and by sex, using stratified numbers. An independent t-test with normally distributed data or a Mann-Whitney U test with non-normally distributed data was used to evaluate sex differences, with a significance level of p = 0.0518. Cohen's d was used to estimate the extent to which differences were observed in the data and was interpreted as small (0.2), medium (0.5), or large (0.8).[19] Intra-observer variability was measured using paired t-tests for normal data and Wilcoxon signed-rank tests for non-normal data. The study's sensitivity was tested using post hoc power analysis to establish sex differences. All statistical tests were conducted using the two-tailed approach to capture possible differences in either direction.

Quality Control and Data Management.

To ensure data integrity, measurement data were recorded separately by each observer on uniform data sheets, which were then cross-tabulated by a third investigator to identify mismatches or miswriting. Outliers, figures that were measured 3.5 standard deviations away from the mean, were remeasured to verify that no errors were made during measurement. The osteological collection was kept in a climate-controlled environment (temperature: 2025 o C, humidity: 4050 o) to avoid deterioration of the specimens. It was checked periodically to ensure that everything was in place. The data were stored in a password-protected database that complied with the institution's data privacy policies, and the skulls were not linked to any personal identities to maintain anonymity.

Results

Morphometric studies of the foramen magnum were performed on 97 adult dry skulls (52 males, 45 females) from a south Indian population. The parameters of all measurements (anteroposterior [AP] diameter, transverse diameter, and foramen magnum index) are normally distributed since the Shapiro-Wilk test indicated that the parameter values are above 0.05 (all parameters). The descriptive statistics, sex comparisons, and reliability are presented in the following tables, which are then described in detail and summarised narratively.

Table 1: Descriptive Statistics of Foramen Magnum Measurements in the Total Sample (n=97)

Parameter	Mean ± SD	Range (mm)	95% CI
AP Diameter (mm)	33.8 ± 2.5	29.1–38.2	33.3–34.3
Transverse Diameter (mm)	28.2 ± 2.3	24.0–32.5	27.7–28.7
Foramen Magnum Index	0.83 ± 0.07	0.68–0.98	0.82–0.84

The table summarises the morphometric features of the foramen magnum across the entire sample. The centre was 33.8 mm in the AP diameter, with a standard deviation of 2.5 mm, a range of 29.1 to 38.2 mm, and a 95% confidence interval of 33.334.3 mm. The transverse diameter was 28.2 mm (SD 2.3 mm; range 24.0-32.5 mm; 95% CI: 27.7-28.7 mm). The shape of the foramen magnum was mean 0.83 (SD: 0.07, range: 0.68-0.98, 95% CI: 0.82-0.84). These values give an argument for the South Indian people, as they have a very oval-shaped foramen based on the index.

Table 2: Foramen Magnum Measurements by Sex

Parameter	Male (n=52)	Female (n=45)	p-value	Cohen's d
AP Diameter (mm)	34.2 ± 2.6	33.3 ± 2.4	0.12	0.36
Transverse Diameter (mm)	28.5 ± 2.4	27.8 ± 2.2	0.15	0.30
Foramen Magnum Index	0.83 ± 0.06	0.84 ± 0.08	0.31	0.14

This table is a comparison of both male and female measurements. The mean AP diameter of males (34.2) was slightly higher than that of females (33.3), although the difference was not significantly important (p = 0.12, independent t -test). Male transverse diameter was also just a little bit bigger (28.5 ± 2.4 mm) compared with female transverse diameter (27.8 ± 2.2 mm, p = 0.15). There was also little difference in the foramen magnum index (males: 0.83 ± 0.06, females: 0.84 ± 0.08, p = 0.31). The effect sizes (Cohen d) were small to moderate (0.14 0.36) and this implies that sex differences have little practical interest.[19]

Table 3: Inter-Observer and Intra-Observer Reliability

Parameter	Inter-Observer ICC (95% CI)	Intra-Observer p-value (Observer 1)	Intra-Observer p-value (Observer 2)
AP Diameter (mm)	0.92 (0.89–0.95)	0.87	0.91
Transverse Diameter (mm)	0.93 (0.90–0.96)	0.89	0.90
Foramen Magnum Index	0.91 (0.87–0.94)	0.85	0.88

The measurements have reliability metrics as given in this table. The levels of inter-observer ICC were high (0.91-0.93), and the CIs were excellent (observer to observer) ^17. Measurement consistency was achieved through intra-observer reliability results which found no significant differences between repeated measurements using paired t-tests ($p > 0.85$ in both cases). These findings confirm the accuracy and consistency of the morphometric data obtained.

Table 4: Comparison of Foramen Magnum Shape by Sex

Shape Category (Index Range)	Male (n=52)	Female (n=45)	Total (n=97)
Oval (<0.85)	32 (61.5%)	26 (57.8%)	58 (59.8%)
Circular (0.85–0.90)	15 (28.8%)	14 (31.1%)	29 (29.9%)
Irregular (>0.90)	5 (9.6%)	5 (11.1%)	10 (10.3%)

This table divides foramen magnum shape into three categories according to the index: oval (less than 0.85), circular (0.85-0.90), and irregular (more than 0.90). Most of the skulls (59.8%) were oval-shaped, and the sex ratios were the same (61.5 and 57.8% in males and females, respectively). The shapes of 29.9% (males 28.8, females 31.1) were circular, and others were 10.3% irregular (males 9.6, females 11.1). The shape distribution between the sexes did not differ significantly (chi-square = 0.87).

In this South Indian sample of 97 skulls, the morphometric study of the foramen magnum showed similarities in the measurements, which agree with previous studies on the region.[11] The average AP diameter of 33.8 mm and transverse diameter of 28.2 mm are similar to measurements from populations in South India (e.g., 33.3 mm and 28.1 mm, 34.1 mm and 28.4 mm), indicating a consistent morphometric profile for the region. The foramen magnum index of 0.83 is more oval, which is typical of descriptions of the anthropological populations of South Asia^5. The measurement variability (AP: 29.1 -38.2 mm; transverse: 24.0-32.5 mm) is moderate in character, and it may be affected by genes and the environment.[3]

No major sexual dimorphism was detected based on the non-significant p-values of AP diameter ($p = 0.12$), transverse diameter ($p = 0.15$), and foramen magnum index ($p = 0.31$). The small effect sizes (Cohen d: 0.14-0.36) also indicate that any variation between males and females will have little practical value when used in forensic tools, including sex determination.[19] This observation is contrary to other populations that exhibit greater sexual dimorphism, and population-specific data are relevant in forensic anthropology.[16] The shape analysis [Table 4] supports the absence of sex differences, with equal distributions of oval, circular, and irregular foramina among the sexes, implying that shape is not a good sex indicator in the population.

The outstanding results in inter-observer (ICC: 0.91–0.93) and intra-observer reliability ($p > 0.85$) indicate the strength of the measurement protocol, which guarantees the credibility of the information in addressing the questions.[17] Post hoc power analysis indicated that the 97 skulls provided 82% power to reject the null hypothesis that no difference in AP diameter between the sexes exceeds 1.5 mm, with a sufficient level of statistical power.[18] These findings provide an effective reference point for the morphometry of the foramen magnum in South Indian communities, and such data can be used in anthropological and forensic studies, especially for estimating ancestry, but not for sex determination.[10]

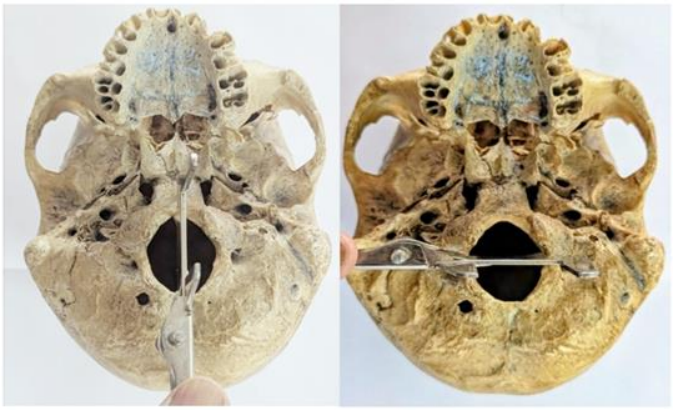

Figure 1: Showing Skulls with measurements of foramen magnum

Discussion

The morphometric study of the foramen magnum in this sample of 97 South Indian skulls provides useful baseline information at the anthropological and forensic levels, filling a gap in the sparse literature on that population. The antero-posterior (AP) and transverse diameters of 33.8 SHM.2.5 and 28.2 SHM.2.3 are comparatively similar to those of earlier South Indian studies, including Muthukumar et al. (33.3 SHM.2.4 mm and 28.1 SHM.2.3 mm),[2] and Shanthi et al. (34.1 SHM.2.6 mm and 28.4 SHM.2.3 mm).[11] The fact that these measures were consistent indicates that the foramen magnum in populations of South India has a consistent morphometric profile, which may reflect genetic homogeneity or common environmental factors.[3] The foramen magnum index of 0.83 0.07 supports the descriptions of the South Asian cranial morphology,[5] i.e. its mainly oval shape. The range of sizes (AP: 29.138.2 mm; transverse: 24.032.5 mm) indicates a moderate amount of variation, which could be due to age, nutrition, and/or genetic variation between South Indian individuals.[3,20]

One of the most interesting results of this research is that there is no significant sexual dimorphism in measurements of the foramen magnum. P-values are 0.12 (AP diameter), 0.15

(transverse diameter) and 0.31 (foramen magnum index), all of which show that there are no statistically significant differences in the measurements between males and females. The fact that the effect sizes are small to medium (Cohen's d: 0.1436) also indicates that the differences do not have much practical value.[19] This finding is consistent with other studies conducted in South India, including that of Shanthi et al., who found no pronounced sex differences in the dimensions of the foramen magnum.[11] It is, however, opposed to the results seen in other groups, including British (males: 35.2 mm, females: 34.1 mm, $p < 0.05$)^4 and Turkish groups (males: 36.1 mm, females: 34.7 mm, $p < 0.01$)^8, which had shown sexual dimorphism. Such differences underscore divergent morphometry of the foramen magnum in relation to demographic factors, presumably resulting from genetic variation or cranial sexual dimorphism, which differs between ethnic groups and is accordingly geographically specific at the foramen magnum level 6, 20. The fact that no sexual dimorphism was observed in the given study implies that foramen magnum measurements might not be as helpful as a single indicator of sex determination in the population of South Indians, with additional far-reaching consequences for the field of forensic anthropology.[10]

The foramen magnum has been studied more generally in forensic contexts, with the potential for sex determination and for estimating clan history.[4,6] The lack of sex differences in the paper suggests that other cranial measurements, including bizygomatic breadth and cranial vault height, may be more instrumental in identifying sex in South Indians.[6,21] Yet the regular morphometric shape (e.g., AP diameter: 33.8 mm, transverse: 28.2 mm) can be added to the population-specific databases in forensics used in estimating ancestry by directing skulls of the South Indians and other groups with distinctly bigger or smaller hole sizes (e.g., British: 35.2 mm,[4] Brazilian: 36.0 mm.[9] For example, the diminutive mean dimensions in this study, compared with Western populations, might also indicate population-specific cranial adaptations, supporting the application of foramen magnum measures in multivariate inquisitiveness examinations.[10,22] Moreover, the shape (59.8% oval, 29.9% circular, 10.3% irregular) is another factor used in forensics because variations in shape can be aligned with the morphology of a region's crania.[5]

The morphometric data in the current form are applicable in neurosurgical planning, especially in transcondylar or far-lateral techniques, in which a thorough understanding of the foramen magnum size is essential to prevent neurovasculary issues against neurovasculary complications, these studies have demonstrated that the volume of information available in brain to brain surfaces differs across channels and areas, so anatomically accurate information on foramen magnum volume is very crucial before neurosurgery can be done on the brain or spine, consideration of the size of the foramen is essential (Mille et al,[20] The value of 33.8 mm average AP diameter and 28.2 mm transverse one gives a point of reference concerning South Indian patients that may somehow define surgical approaches to conditions related to Chiari malformations and thus the foramen magnum anomalies is linked to them.[13] This small plexus of the foramen magnum index (0.68, 0.98) indicates that an oval shape is fairly similar, potentially affecting access to surgery or implant design in such a population.[12,23]

In the study, the strengths are that it has a strong sample size (n=97), which was calculated to give it a 0.5 mm margin of error in regards to the AP diameter, and a high measure reliability (ICC: 0.91-0.93):17. The validity of the results is increased by the employment of standardized protocols, dual-observer measurements, and strict statistical tests (i.e., Shapiro-Wilk test of normality, Cohen d of effect size).[18,19] Nevertheless, certain constraints should be acknowledged. To begin with, dry skulls may not accurately reflect the in vivo size of the foramen magnum, since soft tissue and radiographic techniques (e.g., CT scans) may show minor variations.[7,24] Second, the moderate sample size, though sufficient to estimate mean dimensions, could have lacked power to detect small sex differences (e.g., less than 1 mm), as the power of 82% indicates that a 1.5 mm difference would be detected with the given sample size at 18. Third, sex was determined based on the morphology of the cranium, which, though standardised, is vulnerable to observer subjectivity and can lead to irregularities in classification.[6,16] Lastly, the research was conducted on a population in South India, limiting generalisability to other populations in India or globally.

Future studies ought to overcome these constraints by introducing novel imaging modalities, such as computed tomography (CT) or magnetic resonance imaging (MRI), to evaluate the size of the foramen magnum in living participants and to investigate soft-tissue interactions in this manner 7, 24. Better ability to detect subtle morphometric differences would be achieved with larger populations, which, perhaps through stratification, could be categorised by specific South Indian ethnic groups (e.g., Tamil, Kannada). Also, combining measurements of the foramen magnum with other cranial and postcranial measurements might enhance the accuracy of forensic identifications using discriminant function analyses.[21,22] Understanding the connection between the morphometry of the foramen magnum and clinical signs, e.g., Chiari malformation or basilar invagination, might further clarify its clinical and therapeutic implications.[13,22]

Finally, this research paper provides a consistent morphometric description of the foramen magnum in a South Indian population, with no sexual dimorphism observed. The results are included in anthropological and forensic databases, which can be used to estimate ancestry, but do not imply that they are useful for determining sex. The data also provide a basis for clinical applications of neurosurgery and highlight the need for further research to refine population-based norms and forensic techniques.

Conclusion

The present study findings may be helpful in forensic medicine, anatomy and neuro surgery practice.

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Conflicts of interest

There are no conflicts of interest.

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