



## FORENSIC RELEVANCE OF CRANIAL SUTURE UNION AND SUTURE LENGTH FOR ESTIMATION OF AGE, SEX, AND STATURE IN A CENTRAL INDIAN POPULATION: A CADAVER-BASED STUDY

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### Abstract

**Background:** Identification of unknown human remains is a fundamental responsibility in forensic practice. Estimation of age, sex, and stature becomes challenging when bodies are decomposed, mutilated, or skeletonised. The skull is often preserved in such conditions, and cranial sutures have been widely studied as potential forensic markers. However, population-specific variations limit the applicability of existing standards, particularly in the Indian context.

**Objectives:** To evaluate the relationship of sagittal, coronal, and lambdoid cranial sutures with age, sex, and stature in cadavers from Central India.

**Materials and Methods:** This cadaver-based cross-sectional observational study was conducted in the Department of Forensic Medicine and Toxicology at a tertiary care centre in Central India. A total of 500 cadavers of known age and sex, aged 20 years and above, were included. Degree of ectocranial and endocranial suture union and lengths of sagittal, coronal, and lambdoid sutures were assessed during routine postmortem examinations. Stature was measured prior to autopsy. Statistical analysis included correlation analysis, linear regression for stature estimation, and discriminant function analysis for sex determination using Stata version 17.0.

**Results:** Progressive suture union was observed with advancing age, with endocranial fusion preceding ectocranial fusion. Sagittal and coronal suture lengths showed statistically significant positive correlations with stature, with coronal sutures demonstrating the strongest association. Lambdoid suture length did not show a significant correlation with stature. Discriminant function analysis using all three sutures achieved an overall sex classification accuracy of 66.6%, with higher accuracy for males than females.

**Conclusion:** Cranial sutures provide supportive forensic evidence for age assessment and can aid in estimation of stature and sex when other skeletal elements are unavailable. Population-specific standards are essential, and cranial suture analysis should be used in conjunction with other forensic parameters.

**Keywords:** Cranial sutures; forensic anthropology; age estimation; sex determination; stature estimation; Central India

## Introduction

Identification of unknown human remains is a core task in forensic medicine. Age, sex, and stature are the key biological parameters used for this purpose(1). These parameters become difficult to assess when bodies are decomposed, burnt, mutilated, or skeletonised. In such situations, the skull plays a crucial role because of its durability and distinct anatomical features(1). Cranial sutures, especially the sagittal, coronal, and lambdoid sutures, show progressive changes with advancing age(2). The pattern and degree of suture union have long been studied as indicators of age, while the length of these sutures may help in estimating sex and stature(3). However, previous studies have shown wide variation in suture closure due to population, sex, and biological factors. Most available standards are derived from Western populations and may not be directly applicable to Indian populations.

India lacks adequate region-specific forensic standards for age, sex, and stature estimation using cranial sutures. Central India, in particular, is under-represented in published literature. Variations in genetics, nutrition, and environmental factors can influence suture closure and cranial dimensions. Applying data from other populations may lead to inaccurate conclusions in medico-legal cases. A systematic evaluation of cranial suture union patterns and suture length in a Central Indian population is therefore necessary. This study aims to generate locally relevant forensic data that can support age estimation, sex determination, and stature assessment in unidentified cadavers.

## Aim

To assess the relationship of sagittal, coronal, and lambdoid cranial sutures with age, sex, and stature in cadavers from Central India.

## Material and Methods

This study was designed as a cadaver-based cross-sectional observational postmortem study. This approach was suitable for examining the association between cranial sutures and age, sex, and stature under controlled conditions, without influencing the biological parameters under observation. The study was conducted in the Department of Forensic Medicine and Toxicology, Gandhi Medical College and Associated Hamidia Hospital, Bhopal, Madhya Pradesh. Postmortem examinations of medicolegal cases from urban and rural areas were routinely performed at this centre, providing an appropriate study population. Ethical approval was obtained prior to initiation of the study. The complete study protocol, data collection proforma, and consent-related documents were submitted for review. This study was conducted over a span of 18 months. The primary outcomes were the degree and pattern of union of the sagittal, coronal, and lambdoid cranial sutures in relation to chronological age and sex. The secondary outcomes included estimation of stature and sex using measurements of cranial suture length. All observations were recorded at the time of postmortem examination using predefined scoring and measurement criteria. The exposure of interest was the morphological status of cranial sutures, assessed by direct visual and manual examination of the skull during autopsy. This included evaluation of ectocranial and endocranial suture union stages and measurement of suture lengths. No comparator or control group was involved. Study participants consisted of deceased individuals of known age and sex subjected to routine medicolegal autopsy. The sample included adult cadavers suitable for detailed cranial examination and anthropometric assessment, aligning with the objectives of age, sex, and stature estimation.

## Inclusion criteria

- Cadavers of known age and sex
- Age  $\geq 20$  years
- Intact skull without gross damage

### ***Exclusion criteria***

- Unknown age or sex
- Gross cranial trauma, fractures, or deformities
- Pathological conditions affecting cranial sutures

**Sample Size:** 500 cadavers. A non-random convenience sampling method was used. This approach was appropriate as the study relied on the availability of eligible medicolegal autopsy cases during the study period. Potential participants were screened at the mortuary by the Principal Investigator. Eligibility was assessed using predefined selection criteria. Final inclusion was confirmed after verification of age, sex, and suitability of the skull for examination. Written informed consent was obtained from the legally authorised representatives using pre-approved consent forms in the preferred language. No financial incentives or compensation were provided. Consent was obtained in the presence of a witness. Standard autopsy instruments, measuring boards, measuring tapes, and calibrated scales were used. Statistical analysis was performed using computer-based software as specified in the protocol. Data accuracy was ensured through direct supervision by the study supervisor. Periodic cross-verification of entries and random checks were performed to minimise recording errors.

### **Study Variables**

- **Dependent variables:** Age estimation, sex determination, stature estimation
- **Independent variables:** Degree of suture union, suture length
- **Confounding variables:** Sex, age group

**Statistical Analysis:** The primary hypothesis was that cranial suture union and length were significantly associated with age, sex, and stature. Categorical variables were summarised using frequencies and percentages. Continuous variables were expressed as means and standard deviations. Correlation analysis was performed to assess associations between suture union stages and age. Regression analysis was used to derive equations for stature estimation. Comparative analyses between sexes were conducted using appropriate inferential tests. Statistical significance was assessed at a predefined level. Both statistical and graphical analyses were conducted using Stata version 17.0.

**Data Collection Procedure:** All medicolegal cases received for postmortem examination in the department during the study period were screened on the day of autopsy. Relevant medico-legal documents and inquest papers were reviewed to confirm the identity, age, and sex of the deceased. Cases were assessed for eligibility based on the predefined inclusion and exclusion criteria, and only cadavers with known age and sex and an intact skull were included. Each enrolled case was assigned a unique study identification number to maintain anonymity.

Stature was measured before autopsy in the supine position using a standard measuring board, ensuring correct anatomical alignment. During routine autopsy, the scalp was reflected and the skull vault exposed using standard postmortem techniques. The sagittal, coronal, and lambdoid sutures were identified on both ectocranial and endocranial surfaces. The degree of suture union was assessed visually and manually by the Principal Investigator using the predefined staging system and recorded separately for each suture. Where applicable, segmental assessment was performed. The lengths of the sagittal, coronal, and lambdoid sutures were measured along their anatomical course using a flexible measuring tape.

All observations and measurements were recorded immediately in the structured data collection proforma. At the end of each examination, entries were checked for completeness and consistency. The completed proformas were reviewed periodically by the Study Supervisor. Data were then entered into a secure digital database, with random cross-verification against source records to ensure accuracy.

## Results

Table 1 shows the age and gender distribution of the study population. Of the 500 cadavers examined, 307 (61.4%) were male and 193 (38.6%) were female. The largest proportion of cases belonged to the 20–29-year age group, followed by the 30–39-year group. Together, individuals below 40 years accounted for more than half of the study population. Male predominance was observed across most age groups, particularly in the 40–59-year range, whereas females were relatively more represented in the younger age groups.

| Table 1. Age and gender distribution of the study population (N = 500) |                  |                  |                  |
|------------------------------------------------------------------------|------------------|------------------|------------------|
| Age group (years)                                                      | Total, n (%)     | Male, n (%)      | Female, n (%)    |
| 20–29                                                                  | 155 (31.0)       | 72 (23.4)        | 83 (43.0)        |
| 30–39                                                                  | 141 (28.2)       | 80 (26.0)        | 61 (31.6)        |
| 40–49                                                                  | 98 (19.6)        | 73 (23.7)        | 25 (12.9)        |
| 50–59                                                                  | 58 (11.6)        | 46 (14.9)        | 12 (6.2)         |
| 60–69                                                                  | 31 (6.2)         | 24 (7.8)         | 7 (3.6)          |
| ≥70                                                                    | 17 (3.4)         | 12 (3.9)         | 5 (2.5)          |
| <b>Total</b>                                                           | <b>500 (100)</b> | <b>307 (100)</b> | <b>193 (100)</b> |

Table 2 presents the gender-wise comparison of mean stages of ectocranial and endocranial sagittal suture union across age groups. In both sexes, a progressive increase in mean suture union stage was noted with advancing age. Endocranial fusion consistently preceded ectocranial fusion across all age groups. Minor differences were observed between males and females within the same age categories, but the overall pattern of age-related progression remained similar in both sexes.

| Table 2. Gender-wise comparison of mean stage of union of ectocranial and endocranial sagittal sutures across age groups |                                       |                                         |                                       |                                         |
|--------------------------------------------------------------------------------------------------------------------------|---------------------------------------|-----------------------------------------|---------------------------------------|-----------------------------------------|
| Age group (years)                                                                                                        | Ectocranial sagittal (Male) Mean ± SD | Ectocranial sagittal (Female) Mean ± SD | Endocranial sagittal (Male) Mean ± SD | Endocranial sagittal (Female) Mean ± SD |
| 20–29                                                                                                                    | 0.96 ± 0.53                           | 0.93 ± 0.45                             | 1.20 ± 0.56                           | 1.11 ± 0.65                             |
| 30–39                                                                                                                    | 2.22 ± 0.59                           | 2.29 ± 0.40                             | 2.92 ± 0.27                           | 2.92 ± 0.19                             |
| 40–49                                                                                                                    | 3.43 ± 0.48                           | 3.34 ± 0.31                             | 3.69 ± 0.56                           | 3.68 ± 0.24                             |
| 50–59                                                                                                                    | 3.50 ± 0.35                           | 3.31 ± 0.22                             | 3.66 ± 0.25                           | 3.56 ± 0.22                             |
| 60–69                                                                                                                    | 3.51 ± 0.58                           | 3.25 ± 0.72                             | 3.78 ± 0.26                           | 3.78 ± 0.30                             |
| ≥70                                                                                                                      | 3.22 ± 0.76                           | 3.35 ± 0.63                             | 3.58 ± 0.62                           | 3.80 ± 0.21                             |

Table 3 summarises the linear regression analysis for estimation of stature using cranial suture lengths. Sagittal and coronal suture lengths showed statistically significant positive correlations with stature in the total population as well as when analysed separately by sex. The strongest association was observed with coronal suture length. Regression equations derived for sagittal and coronal sutures were statistically significant, whereas lambdoid suture length did not show a significant correlation with stature and failed to yield a reliable regression model.

| Table 3. Linear regression analysis for estimation of stature using cranial suture lengths |            |                                     |                             |                                 |         |
|--------------------------------------------------------------------------------------------|------------|-------------------------------------|-----------------------------|---------------------------------|---------|
| Suture                                                                                     | Gender     | Regression equation (Stature in mm) | Correlation coefficient (r) | Standard error of estimate (mm) | p-value |
| Sagittal                                                                                   | Both sexes | 1579.10 + (0.019 × L)               | 0.251                       | ±63.439                         | 0.000   |
|                                                                                            | Male       | 1618.25 + (0.009 × L)               | 0.135                       | ±46.940                         | 0.018   |
|                                                                                            | Female     | 1519.66 + (0.013 × L)               | 0.153                       | ±40.016                         | 0.033   |

|                 |            |                              |       |              |       |
|-----------------|------------|------------------------------|-------|--------------|-------|
| <b>Coronal</b>  | Both sexes | $1578.14 + (0.015 \times L)$ | 0.416 | $\pm 59.586$ | 0.000 |
|                 | Male       | $1605.37 + (0.061 \times L)$ | 0.379 | $\pm 43.832$ | 0.000 |
|                 | Female     | $1504.57 + (0.074 \times L)$ | 0.362 | $\pm 37.750$ | 0.000 |
| <b>Lambdoid</b> | Both sexes | Not significant              | —     | $\pm 65.305$ | 0.065 |

Table 4 shows the results of discriminant function analysis for sex determination using cranial suture lengths. The overall classification accuracy was 66.6%. Correct classification was higher for males than females. A substantial proportion of female cases were misclassified as male, indicating moderate discriminatory power. These findings suggest that cranial suture length demonstrates sexual dimorphism but provides limited accuracy when used as a sole parameter.

| Table 4. Discriminant function analysis for sex determination using cranial suture lengths |                |                  |       |
|--------------------------------------------------------------------------------------------|----------------|------------------|-------|
| Sex (actual)                                                                               | Predicted male | Predicted female | Total |
| <b>Male (n = 307)</b>                                                                      | 263 (85.7%)    | 44 (14.3%)       | 307   |
| <b>Female (n = 193)</b>                                                                    | 123 (63.7%)    | 70 (36.3%)       | 193   |

## Discussion

The present study examined the utility of cranial suture characteristics for forensic identification, with particular emphasis on age-related changes, stature estimation, and sex determination in a Central Indian population. The findings demonstrate that the length of sagittal and coronal sutures shows a statistically significant association with stature, while lambdoid suture length does not provide reliable predictive value. In addition, discriminant function analysis based on the combined lengths of sagittal, coronal, and lambdoid sutures achieved moderate accuracy in sex determination. These results highlight both the potential and the limitations of cranial sutures as forensic markers. Importantly, the observed patterns reflect population-specific variations, reinforcing the need for regionally derived standards rather than reliance on data from non-Indian populations. This section discusses the findings in relation to existing literature and explores their practical relevance in medico-legal practice.

In the present study, an overall classification accuracy of 66.6% was achieved, with better prediction observed for males than females. This indicates that cranial suture length demonstrates measurable sexual dimorphism, although the accuracy remains moderate rather than definitive(4). Among the three sutures, the coronal suture contributed most strongly to sex discrimination, followed by the sagittal suture, while the lambdoid suture showed the least contribution. These findings suggest that cranial vault dimensions are influenced by sex-related differences in skull growth patterns, with males generally exhibiting greater cranial robustness and suture length(5).

The results are broadly consistent with earlier studies cited in the thesis, which have reported moderate success rates for sex determination using cranial measurements. Several authors have documented higher accuracy when multiple cranial variables are combined rather than relying on a single parameter, a finding supported by the present discriminant model(6–8). Subsequent Indian studies referenced in the thesis, have emphasised that male skulls tend to show greater linear dimensions, particularly in the coronal and sagittal regions, which improves discriminatory power(6–8). However, similar to the present findings, these studies also caution against using cranial sutures alone for definitive sex identification. Variations in accuracy across studies may be explained by differences in sample size, population composition, measurement techniques, and statistical models used. The relatively lower contribution of the lambdoid suture in the present study has also been noted by previous authors, who reported inconsistent sexual dimorphism in the posterior cranial vault(6,9,10). The present findings support the use of cranial sutures as *adjunct* forensic markers, but they also confirm the well-known limitation that suture-based methods are population-sensitive and only moderately precise(11). In this Central Indian cadaver series, suture obliteration showed a clear age-

related progression, with endocranial union preceding ectocranial union, and with earlier commencement and completion in males than females. This general pattern aligns with broader forensic and anthropological observations that endocranial fusion tends to be more uniform than ectocranial fusion, and that ectocranial assessment is prone to “lapsed union” and irregular serration, which reduces precision when used alone(12). Recent reviews and regional studies similarly conclude that cranial suture closure can help to place an individual into broad adult age ranges, but it performs poorly for exact age estimation, and lambdoid closure often shows weaker or inconsistent associations with chronological age(6).

With respect to stature estimation, the present study found statistically significant positive associations between stature and the lengths of the **coronal** and **sagittal** sutures, whereas the **lambdoid** suture length was not a useful predictor. The correlation was strongest for coronal length in both sexes combined ( $r \approx 0.416$ ), while sagittal length showed a weaker relationship ( $r \approx 0.251$ ). This pattern closely matches the South Indian male study by Rao and colleagues, which reported that coronal length correlated better with height than sagittal length and yielded more practical regression performance for identification when only the skull is available(13). At the same time, international evidence indicates that this relationship is not universal: Kolencherry and colleagues (Central European sample) reported no statistically significant regression between stature and either sagittal or coronal suture length, underscoring that cranial suture–stature equations should not be transferred across populations without validation(13). Taken together, the current results add to the Indian literature suggesting that coronal suture length may offer a modest, usable signal for stature estimation locally, while sagittal length provides a weaker contribution and lambdoid length may be unreliable. For sex estimation, discriminant function analysis using combined suture lengths achieved **moderate** overall accuracy (66.6%), with notably better correct classification among males than females. This level of performance is in line with the thesis-cited work of Sahoo et al. from Odisha, who reported significant sexual dimorphism in coronal suture length and relatively higher accuracy when using cranial suture measurements for sex determination. The present result is also broadly comparable to other cadaver-based approaches that use suture length or vault metrics as predictors and typically achieve accuracies in the mid-range rather than near-complete separation. For example, Sobh et al. (Egyptian cadavers) reported that coronal and sagittal suture lengths differed by sex and showed reasonable discrimination, though accuracy remained imperfect even with combined predictors(13). In this context, the present discriminant findings support the practical view that suture length can contribute to sex estimation when the skull vault is available, but it should be treated as supportive evidence rather than a stand-alone determinant—particularly because misclassification was more frequent among females.

Methodologically, the present work has strengths relevant to real-world forensic practice: it used direct postmortem assessment on a sizeable sample of adults ( $n=500$ ), included both ectocranial and endocranial evaluations, and analysed sex-specific models where appropriate. The study also highlights limitations that are consistent with prior literature. First, suture closure and suture length are influenced by ancestry, nutrition, cranial shape variation, and measurement technique, which is why the literature warns against applying discriminant or regression functions outside the population in which they were derived. Second, because the sample had unequal sex and age-group distributions, sampling structure could affect model stability and classification performance, and this should be considered when interpreting predictive accuracy. Finally, as emphasised in modern reviews of suture-based age estimation, wide inter-individual variability (especially in ectocranial appearance) limits precision and supports using sutures as part of a multi-parameter biological profile rather than as a single decisive criterion(6).

## Conclusion

This study demonstrates that cranial sutures can provide useful supportive information for forensic identification in adult cadavers from Central India. Progressive union of cranial sutures showed a clear relationship with advancing age, with endocranial fusion occurring earlier than ectocranial

fusion, confirming their value for broad age categorisation rather than precise age estimation. Stature showed a statistically significant positive association with the length of sagittal and coronal sutures, with the coronal suture demonstrating the strongest predictive value. In contrast, lambdoid suture length did not show a reliable correlation with stature. Sex determination based on combined cranial suture lengths achieved moderate accuracy, with better classification among males than females, indicating limited but practical sexual dimorphism.

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