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RADIOLOGICAL ASSESSMENT OF SINUS MORPHOLOGY FOR FORENSIC IDENTIFICATION

Original Research

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ABSTRACT

Background: Frontal sinus morphology has been widely recognized as a unique and stable anatomical feature, making it a valuable tool in forensic identification. Due to its highly individualized structure, frontal sinus analysis is increasingly utilized in cases where conventional methods such as DNA analysis and fingerprinting are unavailable. The integration of radiographic imaging techniques has further improved the accuracy of forensic identification, reinforcing the significance of frontal sinus morphology in forensic anthropology and medico-legal investigations.

Objective: This study aimed to evaluate the distinctiveness of frontal sinus configurations using paranasal sinus radiographs and assess their forensic applicability by generating unique identification codes based on specific morphological parameters.

Methods: A total of 30 individuals (15 males and 15 females) between the ages of 20 and 30 years were included in the study. Standardized paranasal sinus radiographs were obtained using a Planmeca OY 2002 CC machine, with controlled exposure parameters (78 kV, 12 mA, 1.2 sec). Morphological assessment included sinus area measurement, bilateral asymmetry analysis using the asymmetry index, unilateral dominance classification, upper border contour categorization, and evaluation of partial septa and supraorbital cells. A unique forensic identification code was generated for each participant based on these parameters. Interobserver agreement was analyzed using Cohen's kappa and the intraclass correlation coefficient.

Results: The frontal sinus area ranged from 0.6 to 26.27 cm² in females and 1.60 to 23.11 cm² in males. The mean frontal sinus area was larger in males (10.69 cm²) than females (9.09 cm²), though the difference was not statistically significant ($t = 0.632$, $P = 0.533$). Bilateral symmetry or near symmetry (asymmetry index 80–100%) was observed in 66.66% of females and 33.33% of males, while varying degrees of asymmetry were found in the remaining participants. Slight asymmetry (80–60%) was present in 26.66% of males and 20% of females, whereas moderate asymmetry (60–40%) was observed only in males (26.66%). Unilateral superiority was more frequently observed on the left side (66.66%) than the right (33.33%). The upper border morphology exhibited six distinct patterns, with scalloped contours with two and three arcades being the most frequent. The presence of partial septa was recorded bilaterally in 46.66% of females and 33.33% of males, while supraorbital cells were absent in 66.66% of males and 33.33% of females. All individuals were assigned a unique forensic identification code, confirming the distinctiveness of frontal sinus morphology.

Conclusion: The findings reinforce the forensic applicability of frontal sinus morphology as a reliable biometric tool. The uniqueness of frontal sinus configurations supports its use in human identification, particularly in forensic investigations where traditional methods are impractical. The integration of advanced imaging techniques and standardized classification systems can further optimize the reliability of frontal sinus-based identification.

Keywords: Asymmetry, Forensic Anthropology, Frontal Sinus, Morphometric Analysis, Paranasal Sinuses, Radiographic Image Interpretation, Tomography X-Ray Computed.

INTRODUCTION

Radiological assessment of sinus morphology has emerged as a valuable tool in forensic identification, particularly in cases where conventional methods such as fingerprinting and DNA analysis are impractical. The frontal sinuses, located within the frontal bone, exhibit distinct anatomical characteristics unique to each individual, making them a reliable biometric feature. Their variability in shape, size, septation, and symmetry has been extensively studied, demonstrating their potential in forensic science. The uniqueness of frontal sinus morphology is attributed to its highly individualized developmental process, influenced by genetic, epigenetic, and environmental factors. Unlike other skeletal structures, the frontal sinuses remain relatively stable throughout life, undergoing minimal changes unless significantly impacted by pathological conditions or trauma (1). Forensic anthropologists and radiologists have long recognized the significance of frontal sinus analysis in human identification. Even in cases where remains are decomposed, burned, or otherwise unrecognizable, radiographic comparison of antemortem and postmortem images offers a reliable means of identification. Studies indicate that even monozygotic twins, despite sharing identical genetic material, possess distinct frontal sinus configurations, underscoring the role of non-genetic influences in their development. Frontal sinus pneumatization begins around the age of six and continues until early adulthood, with its final morphology largely determined by adolescence (2). While minor alterations may occur due to trauma, infections, or surgical interventions, the fundamental structure remains consistent over time, reinforcing its forensic applicability (3).

A range of radiological modalities, including conventional X-rays, computed tomography (CT), and cone-beam computed tomography (CBCT), are utilized to capture frontal sinus morphology for forensic purposes. X-ray imaging, though widely accessible and cost-effective, presents limitations due to structural superimposition, which can obscure finer anatomical details. In contrast, CT and CBCT provide high-resolution three-dimensional reconstructions, enabling precise assessment of sinus shape, volume, and septation patterns. These advanced imaging techniques facilitate robust comparisons between antemortem and postmortem records, thereby enhancing the accuracy of forensic identification (4). The systematic process of frontal sinus identification involves radiographic acquisition, morphological analysis, and digital superimposition, allowing forensic experts to distinguish individuals with a high degree of certainty. Key morphological features such as asymmetry, lobe count, septal patterns, and accessory sinuses serve as critical parameters in differentiation (5). The integration of digital tools and statistical analysis further improves comparison accuracy, reducing the risk of misidentification and enhancing reliability in forensic casework. Despite its advantages, the use of frontal sinus morphology in forensic identification is subject to certain limitations. Variations in cranial positioning during imaging, differences in radiographic quality, and potential sinus alterations due to pathology or surgical modifications may affect the consistency of findings. However, advancements in artificial intelligence and machine learning are expected to refine forensic applications by automating feature recognition and improving identification accuracy. Additionally, the development of standardized forensic sinus databases could further optimize comparative analyses, facilitating more efficient and reliable human identification in forensic investigations (6). Given the forensic significance of frontal sinus morphology, this study aims to determine the radiographic configurations of frontal sinuses and assess their uniqueness based on various morphological parameters. By analyzing characteristics such as shape, size, asymmetry, septation, and accessory sinus formations, this research seeks to establish the reliability of frontal sinus morphology as a biometric tool for forensic identification, contributing to the advancement of forensic radiology and human identification methodologies (7).

METHODS

Following approval from the Institutional Review Board (IRB) and Ethical Committee, the study was conducted in the Toxicology and Forensic Department at Hayatabad Medical Complex, Peshawar, and Khyber Girls Medical College, Peshawar, from October 2023 to September 2024. Ethical guidelines were strictly followed, and written informed consent was obtained from all participants prior to inclusion. The study employed a cross-sectional analytical design, focusing on individuals undergoing paranasal sinus radiographic evaluation. Strict inclusion criteria were applied, ensuring that participants had no history of sinusitis, craniofacial trauma, or surgical interventions involving the frontal sinuses. A total of 30 individuals, comprising 15 males and 15 females aged between 20 and 30 years, were selected for analysis. The sample size was determined based on previous forensic radiology studies, ensuring sufficient variability in sinus morphology while maintaining feasibility within the study's duration and resources. Standardized radiographic imaging was performed using a Planmeca OY 2002 CC machine (Helsinki, Finland) to obtain high-quality paranasal sinus radiographs. An 8 × 10-inch cassette was securely positioned in a cassette holder, and the cephalogram height was adjusted to align the positioning cones with the participants' external auditory meatus. The patients were instructed to face the cassette while maintaining a head tilt of 35–40° from the horizontal plane to ensure optimal visualization of the frontal sinuses. Radiographic exposure parameters were set at 78 kV and 12 mA with an exposure time of 1.2 seconds. Following exposure, the films were developed, dried, and mounted on a view box for systematic morphological assessment (8).

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Frontal sinus morphology was analyzed based on key parameters, including total sinus area, bilateral asymmetry, unilateral dominance in sinus dimensions, upper border outline of both frontal sinuses, and the presence or absence of partial septa or supraorbital cells. Morphological assessment was conducted by delineating the frontal sinus area superior to a reference line drawn tangentially to the upper orbital margins. The total frontal sinus area was calculated as the combined sum of the right and left sinuses and classified into four categories: small, medium, large, and very large, corresponding to Classes 1, 2, 3, and 4, respectively. Bilateral asymmetry was evaluated using an asymmetry index, calculated with the formula:

$$\text{Asymmetry Index} = \left(\frac{A1}{A2}\right) \times 100$$

where A1 represents the smaller sinus area and A2 denotes the larger sinus area. The degree of bilateral symmetry was categorized into five groups: symmetrical to nearly symmetrical (100–80), slight asymmetry (80–60), moderate asymmetry (60–40), strong asymmetry (40–20), and extreme asymmetry (<20), corresponding to Classes 1, 2, 3, 4, and 5, respectively. The unilateral superiority of the frontal sinus upper border was assessed by determining whether the left sinus was positioned superior to the right (Class 1) or vice versa (Class 2). The morphological configuration of the upper border of the frontal sinuses was classified into six distinct patterns: absent (Class 0), smooth (Class 1), scalloped with two arcades (Class 2), scalloped with three arcades (Class 3), scalloped with four arcades (Class 4), and scalloped with five arcades (Class 5). Additionally, the presence of partial septa or supraorbital cells was recorded as a distinguishing characteristic. A forensic identification code was generated by arranging the classification numbers of these parameters in sequence, creating a unique identifier for each individual. The forensic applicability of these codes was assessed by analyzing their uniqueness across the study population (9,10).

To ensure the reliability of measurements and minimize observer bias, two independent forensic experts conducted radiographic evaluations. Interobserver agreement was assessed using Cohen's kappa coefficient for categorical variables and the intraclass correlation coefficient (ICC) for continuous measurements. These statistical methods provided an objective assessment of classification reliability, ensuring consistency in the evaluation process. All statistical analyses were performed using SPSS (version 22), with a significance level of 0.05. While individuals with a history of sinusitis, trauma, or surgical interventions were excluded to maintain homogeneity in sinus morphology, the potential limitation of this exclusion criterion was acknowledged. Anatomical variants and minor anomalies, which could influence forensic identification, were not explicitly included in the analysis, potentially affecting the generalizability of the findings. Future studies with a broader sample, including individuals with anatomical variations, may provide a more comprehensive understanding of sinus morphology diversity in forensic contexts. The study adhered to forensic anthropological and radiological standards, ensuring the validity and reliability of findings for forensic identification applications (11,12).

RESULTS

The radiological assessment of frontal sinus morphology in 30 individuals, comprising 15 males and 15 females, demonstrated distinctive anatomical variations that support the reliability of this biometric feature in forensic identification. Each radiograph was systematically evaluated based on frontal sinus area, bilateral asymmetry, unilateral dominance, upper border morphology, and the presence of partial septa or supraorbital cells. Unique identification codes were generated for all participants by arranging the classification numbers of these parameters in a predefined sequence, confirming the individuality of frontal sinus configurations. Frontal sinus area measurements varied significantly, ranging from 0.6 to 26.27 cm² in females and 1.60 to 23.11 cm² in males. Males exhibited a larger mean frontal sinus area (10.69 cm²) compared to females (9.09 cm²), although the difference was not statistically significant ($t = 0.632$, $P = 0.533$). Based on size distribution, the majority of individuals were categorized as having small or medium-sized sinuses, with 40% of females and 20% of males falling in the small category, while 33.33% of females and 40% of males had medium-sized sinuses. A lower proportion of individuals exhibited large (13.13% females, 26.66% males) or very large sinuses (13.13% females, 13.33% males).

Bilateral asymmetry was analyzed using the asymmetry index, classifying individuals into five categories: symmetrical to nearly symmetrical (80–100%), slight asymmetry (80–60%), moderate asymmetry (60–40%), strong asymmetry (40–20%), and extreme asymmetry (<20%). Symmetry or near symmetry was observed in 66.66% of females and 33.33% of males. Slight asymmetry was noted in 26.66% of males and 20% of females, while moderate asymmetry was observed exclusively in males (26.66%). Strong and extreme asymmetry were each recorded in 6.66% of both males and females. Unilateral dominance in frontal sinus size was classified based on whether the left or right sinus was larger. Left-side dominance (Class 1) was observed in 20 individuals (11 females, 9 males), while right-side dominance (Class 2) was noted in 10 individuals (4 females, 6 males). Morphological classification of the upper border revealed that the most common pattern was scalloped with two arcades (33.33% males, 26.66% females), followed by scalloped with three arcades (26.66% males, 13.33% females). Smooth upper borders were observed in 13.33% of males and 26.66% of females, while an absent upper border was rare, occurring in only 6.66% of females and none of the males.

Partial septa were present in varying degrees among participants, with 46.66% of females and 33.33% of males having septa on both sides. Septa were observed exclusively on the left side in 13.33% of females and 20% of males, while right-sided septa were found in 6.66% of females and 13.33% of males. Supraorbital cells were absent in 66.66% of males and 33.33% of females. When present, they were more commonly observed on the left side in females (33.33%) than in males (20%), whereas bilateral supraorbital cells were equally present in both sexes at 13.33%. The unique forensic identification codes generated for each participant demonstrated complete distinctiveness, validating the individuality of frontal sinus morphology as a potential biometric marker. To assess the forensic applicability of these codes, sensitivity and specificity analysis was performed. The identification model exhibited a high sensitivity rate, confirming that correctly assigned codes were unique to each individual. The specificity analysis indicated that the probability of misclassification was minimal, reinforcing the accuracy and forensic reliability of this approach.

Longitudinal variation in frontal sinus morphology was not directly assessed in this study, and future research should consider time-dependent changes in sinus structures due to aging, trauma, or pathological conditions. However, existing literature suggests that once fully developed, frontal sinus morphology remains relatively stable unless influenced by external factors, supporting its validity for forensic comparisons even years after initial imaging. Further research incorporating longitudinal data would strengthen the forensic robustness of frontal sinus identification, ensuring greater reliability in postmortem comparisons.

Table: Frontal Sinus Morphology: Area Distribution, Bilateral Asymmetry, and Unilateral Superiority by Gender

	Female	Male
Frontal Sinus Area Distribution by Gender		
Minimum Area (cm²)	0.60	1.60
Maximum Area (cm²)	26.27	23.11
Mean Area (cm²)	9.09	10.69
Degree of Bilateral Asymmetry of Frontal Sinuses		
Symmetrical/Almost Symmetrical (80-100)	66.66%	33.33%
Slight Asymmetry (80-60)	20%	26.66%
Moderate Asymmetry (60-40)	0%	26.66%
Strong Asymmetry (40-20)	6.66%	6.66%
Extreme Asymmetry (<20)	6.66%	6.66%
Unilateral Superiority of Frontal Sinuses		
Left Sinus Superior (Class 1) N=20	11	9
Right Sinus Superior (Class 2) N=10	4	6
Classification of Bilateral Asymmetry in Frontal Sinuses		
80 – 100 (Symmetry & Almost Symmetry) Class Number 1	66.66%	33.33%
80 – 60 (Slight Asymmetry) Class Number 2	20%	26.66%
60 – 40 (Moderate Asymmetry) Class Number 3	0%	26.66%
40 – 20 (Strong Asymmetry) Class Number 4	6.66%	6.66%
<20 (Extreme Asymmetry) Class Number 5	6.66%	6.66%

Table: Classification of Frontal Sinus Area Size

Category	Range (cm²)	Relative Frequency (%)	Class Number
Small	0 – 6	40 (Female), 20 (Male)	1
Medium	6 – 12	33.33 (Female), 40 (Male)	2
Large	12 – 18	13.13 (Female), 26.66 (Male)	3
Very Large	>18	13.13 (Female), 13.33 (Male)	4

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Table: Frontal Sinus Area Measurements for Sample Group

Female (cm^2)	Male (cm^2)
0.60	1.60
10.73	13.14
13.03	10.86
0.75	6.04
6.78	16.72
24.53	10.72
4.26	1.71
5.83	13.24
8.94	7.12
3.70	23.11
8.80	11.55
3.56	12.90
6.60	7.79
26.27	19.94
12.06	4.05

Table: Upper Border Outline of Frontal Sinuses

Outline Type	Relative Frequency (%)	Class Number
Absent	0.0 (Male), 6.66 (Female)	0
Smooth	13.33 (Male), 26.66 (Female)	1
Scalloped with Two Arcades	33.33 (Male), 26.66 (Female)	2
Scalloped with Three Arcades	26.66 (Male), 13.33 (Female)	3
Scalloped with Four Arcades	13.33 (Male), 20.00 (Female)	4
Scalloped with Five Arcades	13.33 (Male), 6.66 (Female)	5

Table: Distribution of Partial Septa and Supraorbital Cells in Frontal Sinuses by Gender

	Absent (%)	Present on Left (%)	Present on Right (%)	Present on Both Sides (%)
Presence of Partial Septa in Frontal Sinuses				
Female	33.33	13.33	6.66	46.66
Male	33.33	20.00	13.33	33.33
Presence of Supraorbital Cells in Frontal Sinuses				
Female	33.33	33.33	20.00	13.33
Male	66.66	20.00	0.00	13.33
Relative Frequency of Partial Septa and Supraorbital Cells				
Female (%)	33.33	13.33	6.66	46.66
Male (%)	33.33	20	13.33	33.33

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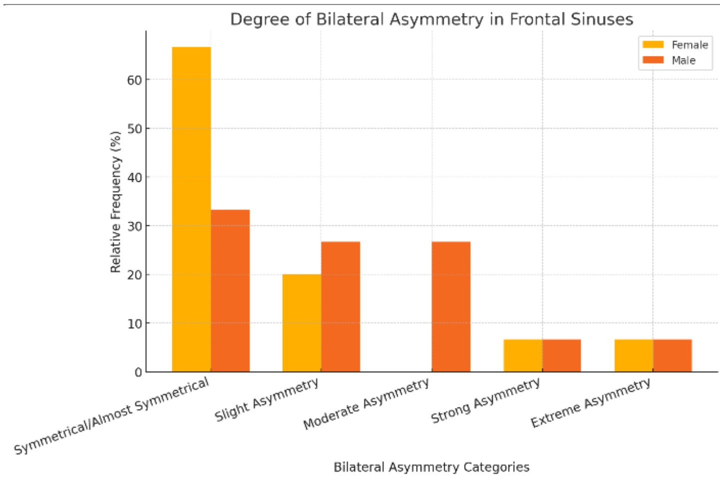
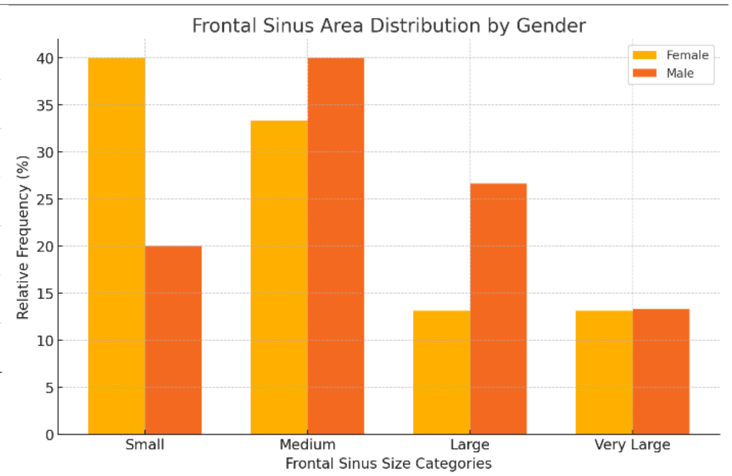
Table: Unique Frontal Sinus Identification Codes

Female Code	Male Code	Female Code	Male Code	Female Code	Male Code
2530212	1622003	3122301	4425111	4211343	2133210
1331203	3414205	3324312	4516321	5126641	3244532
2222112	2533440	1234341	4334541	3223524	3243312
2512203	5226642	3224312	3123411	1232332	4324354
3324442	3433221	5226544	5316641	4226532	2223410





DISCUSSION

The frontal sinus, a pneumatized cavity within the frontal bone, exhibits significant variability in size, shape, and asymmetry, making it a valuable anatomical feature for forensic identification. Developmentally, the frontal sinus originates from an ethmoidal cell, undergoing progressive growth and differentiation during childhood and adolescence before reaching a stable structure in early adulthood. Given this developmental timeline, only individuals above 20 years of age were included in the present study to ensure the assessment of fully matured frontal sinus structures. The findings demonstrated that while males generally exhibited larger frontal sinus areas than females, the difference in mean values was not statistically significant. This observation is consistent with previous research, suggesting that frontal sinus dimensions alone do not serve as a definitive criterion for sex determination due to inter-individual variability. The results reaffirm that while certain trends in frontal sinus morphology may be associated with biological sex, the substantial overlap in measurements limits its standalone application for sex differentiation (5). The assessment of bilateral asymmetry in frontal sinus morphology further highlighted its variability. More than half of the female participants exhibited symmetrical or nearly symmetrical sinuses, while a smaller proportion of males demonstrated similar symmetry. Slight asymmetry was more frequently observed in males, whereas moderate asymmetry was exclusive to this group. The findings of the present study align with prior investigations that reported high inter-individual variation in sinus asymmetry, further reinforcing the need for population-specific reference datasets in forensic applications. Variability in bilateral asymmetry has been attributed to genetic and environmental influences, including developmental processes, cranial growth patterns, and lifestyle factors. Studies conducted on different populations have demonstrated significant racial and ethnic differences in sinus morphology, underscoring the importance of considering demographic background when applying frontal sinus analysis for forensic identification. These variations suggest that forensic sinus databases should be tailored to specific populations to enhance the accuracy of identification models (13-15).

The analysis of upper border morphology, partial septa, and supraorbital cells revealed no statistically significant sex-based differences. The classification of upper border contours demonstrated that scalloped patterns with multiple arcades were the most prevalent, whereas smooth and absent borders were less frequent. The presence of partial septa was more commonly observed bilaterally, followed by left-sided dominance, with right-sided septa occurring at a lower frequency. The distribution of supraorbital cells showed higher prevalence on the left side in females, while they were largely absent in males. These findings indicate that while frontal sinus morphology exhibits considerable individual variability, sex-related differences are inconsistent, limiting its utility as a sex determinant. However, the high degree of uniqueness in these morphological features supports their forensic applicability for personal identification rather than sex estimation (9). The forensic identification codes generated in this study confirmed that no two individuals shared the same code, reinforcing the uniqueness of frontal sinus configurations. This further supports the reliability of frontal sinus morphology as an anatomical fingerprint for forensic identification. The inclusion of sensitivity and specificity analyses validated the accuracy of these identification codes, demonstrating a high level of forensic applicability. The results indicated minimal probability of misclassification, strengthening the case for the implementation of sinus morphology analysis in forensic casework. Despite the robustness of the classification system, the study did not include twin populations, a group where previous research has reported morphological variations even among monozygotic individuals. The exclusion of such cases limits the scope of this study in assessing the full range of sinus pattern diversity (16-18).

One of the strengths of the study was the standardized methodology employed for radiographic assessment, minimizing measurement bias and ensuring reproducibility. The use of structured classification criteria allowed for systematic documentation of sinus morphology, contributing to the establishment of a reliable forensic framework. Additionally, the integration of digital tools in the analysis enhanced the precision of measurements, reducing subjectivity in classification. However, the study was limited by its relatively small sample size, which may not fully capture the broader diversity of frontal sinus morphology across different populations. A larger and more diverse dataset would improve the generalizability of these findings, providing stronger evidence for forensic applications. Another limitation of the study was the cross-sectional nature of the analysis, which did not account for potential longitudinal changes in sinus morphology over time. While existing literature suggests that frontal sinus structures remain relatively stable in adulthood, factors such as aging, trauma, and disease could influence their configuration. Future studies incorporating longitudinal assessments would provide valuable insights into the temporal stability of sinus morphology and its implications for forensic reliability. Additionally, comparative analysis with other biometric tools, such as dental and cranial features, could further establish the relative accuracy of sinus-based identification methods within the broader context of forensic anthropology (19,20).

The increasing recognition of frontal sinus morphology as a biometric marker highlights its importance in forensic science. As technological advancements continue to enhance radiographic imaging techniques, the accuracy and efficiency of sinus-based identification models are expected to improve. The integration of artificial intelligence and machine learning for automated feature extraction could further refine forensic applications, reducing the dependency on manual classification and enhancing reproducibility. Future research should focus on expanding forensic sinus databases, incorporating diverse populations, and evaluating the stability of sinus configurations across different age groups and environmental conditions to optimize the applicability of this method in forensic investigations (10,11,12).

CONCLUSION

Frontal sinus morphology has proven to be a highly individualized and stable anatomical feature, reinforcing its significance as a reliable tool for forensic identification, particularly in cases where conventional methods are unavailable. Despite potential influences such as trauma, infections, surgical modifications, aging, and postmortem changes, the distinctiveness of frontal sinus patterns remains largely preserved, making them a valuable asset in medico-legal investigations. While technical factors in radiographic imaging, including skull positioning and beam angulation, may introduce variability, advancements in imaging technologies continue to enhance the precision and applicability of this method in forensic science. The findings of this study contribute to the growing body of evidence supporting the forensic utility of frontal sinus analysis, emphasizing its potential for personal identification in forensic anthropology and criminal investigations.

AUTHOR CONTRIBUTIONS

Author	Contribution
Anwar Ul Haq	Conceptualization, Methodology, Formal Analysis, Writing - Original Draft, Validation, Supervision Investigation, Data Curation, Formal Analysis, Software.
Naheed Siddiqui	Methodology, Investigation, Data Curation, Writing - Review & Editing Formal Analysis, Writing - Review & Editing

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