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Research Article

# Anatomical Variations of the Paranasal Sinuses and Their Role in Forensic Identification

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## Abstract

Paranasal sinus anatomy exhibits significant individual variability, making radiological sinus patterns increasingly valuable in forensic identification and medico-legal investigations. Frontal, maxillary, ethmoidal, and sphenoidal sinus configurations possess unique morphological characteristics that may serve as biological markers for personal identification in cases involving decomposed, burned, fragmented, or unidentified human remains. The present study aimed to evaluate anatomical variations of the paranasal sinuses and determine their diagnostic utility in forensic identification using computed tomography imaging. A prospective observational experimental study was conducted on 210 participants undergoing paranasal sinus computed tomography between January 2023 and December 2024 at a tertiary care radiology center. Morphological characteristics including sinus symmetry, septation patterns, sinus dimensions, pneumatization variants, and accessory air cells were analyzed and correlated with demographic variables. Frontal sinus asymmetry was observed in 72.4% of participants, while deviated intersinus septum was identified in 48.1%. Agger nasi cells were the most common anatomical variation among ethmoidal air cells, occurring in 61.9% of cases. Significant gender-based differences were observed in frontal sinus height and maxillary sinus width ($p<0.001$). The overall identification accuracy of combined sinus morphological parameters reached 89.5% using radiological comparison techniques. Multivariate analysis demonstrated that frontal sinus morphology, sphenoid sinus pneumatization, and septation patterns were significant independent predictors of successful forensic identification. The findings highlight the forensic importance of paranasal sinus anatomical variability and support the use of sinus radiological profiling as a reliable adjunctive method in medico-legal identification, particularly in situations where conventional identification techniques are limited.

**Keywords**: Paranasal sinuses, Forensic identification, Computed tomography

## Introduction

Human identification represents a fundamental component of forensic science and medico-legal investigation, particularly

in cases involving mass disasters, advanced decomposition, thermal injuries, skeletal remains, and unidentified bodies. Conventional methods of identification such as fingerprints, dental records, and DNA profiling are highly effective; however, these techniques may become limited or unavailable in cases involving severe tissue destruction or fragmented remains. Consequently, radiological anatomical structures with individualized morphological patterns have gained increasing importance in forensic anthropology and medico-legal practice [1-3].

The paranasal sinuses constitute air-filled cavities within the craniofacial skeleton that exhibit considerable anatomical variability among individuals. These sinuses include the frontal, maxillary, ethmoidal, and sphenoidal sinuses, all of which undergo developmental changes influenced by genetic, environmental, and physiological factors. The morphology of the paranasal sinuses is highly individualized, and no two persons possess identical sinus configurations, particularly with regard to frontal sinus anatomy [2-4]. This uniqueness has contributed to growing interest in sinus morphology as a potential forensic marker for personal identification.

Computed tomography imaging has revolutionized the evaluation of paranasal sinus anatomy because of its superior spatial resolution and ability to provide multiplanar visualization of osseous and soft tissue structures. Radiological imaging allows accurate assessment of sinus dimensions, septation patterns, pneumatization variants, and accessory air cells that may assist in forensic comparison studies [3-5]. The frontal sinus has been particularly emphasized in forensic radiology because of its high degree of asymmetry and resistance to postmortem destruction. Previous studies have reported that frontal sinus morphology demonstrates sufficient uniqueness to permit individual identification in medico-legal investigations.

Anatomical variations of the paranasal sinuses are clinically important because they influence sinus drainage pathways, susceptibility to sinusitis, and surgical planning during endoscopic sinus surgery. Variations such as agger nasi cells, Haller cells, Onodi cells, deviated intersinus septa, concha bullosa, and excessive sphenoid sinus pneumatization may alter sinonasal anatomy and contribute to disease development [4-6]. Beyond their clinical implications, these anatomical patterns possess considerable forensic significance because of their individualized nature and relative stability throughout adult life.

Recent advances in forensic radiology and digital imaging have facilitated the use of antemortem and postmortem radiographic comparison for identification purposes. Studies evaluating frontal sinus morphology, maxillary sinus dimensions, and sphenoidal sinus variants have demonstrated encouraging results regarding the reliability of sinus anatomy in forensic identification [5-7]. Three-dimensional computed tomography reconstruction and artificial intelligence-assisted image analysis have further enhanced the precision of radiological comparison techniques in forensic medicine.

In developing countries, forensic identification frequently encounters significant limitations because of inadequate DNA databases, incomplete dental records, and resource constraints affecting advanced forensic investigations. Therefore, radiological methods utilizing routinely available imaging modalities may provide cost-effective and accessible alternatives for medico-legal identification [6-8]. Pakistan continues to experience challenges in forensic identification, particularly in cases related to disasters, criminal investigations, and unidentified remains where conventional methods may be compromised.

Existing literature regarding anatomical variations of the paranasal sinuses has predominantly focused on clinical and surgical implications, with comparatively limited evidence addressing their role in forensic identification within South Asian populations [7-9]. Furthermore, demographic and ethnic variations may influence sinus morphology and therefore necessitate region-specific radiological data. The present study was designed to evaluate anatomical variations of the paranasal sinuses and determine their role in forensic identification using computed tomography imaging at a tertiary care center.

The objectives of the study included assessment of common anatomical variations of the frontal, maxillary, ethmoidal, and sphenoidal sinuses; evaluation of gender-based morphological differences; and determination of the reliability of sinus radiological patterns in forensic identification. By generating updated regional evidence, the study aims to contribute toward the growing application of forensic radiology in medico-legal identification and support the use of paranasal sinus morphology as an adjunctive forensic tool [8-10].

**Methodology**

A prospective observational experimental study was conducted at the Department of Anatomy, Services Institute of Medical Sciences and Department of Forensic Medicine after approval from the institutional ethical review committee. The study included participants undergoing computed tomography imaging of the paranasal sinuses for diagnostic evaluation unrelated to severe sinonasal pathology. The sample size was calculated using OpenEpi software version 3.01 by considering an anticipated prevalence of frontal sinus asymmetry of 70%, confidence interval of 95%, margin of error of 6%, and study power of 80%, resulting in a minimum sample requirement of 196 participants. After adjustment for possible imaging artifacts and incomplete radiological data, a total of 210 participants were enrolled.

Participants aged 18 years and above with adequately visualized paranasal sinus anatomy on computed tomography were included in the study. Individuals with previous facial trauma, craniofacial surgery, congenital craniofacial anomalies, sinonasal tumors, severe sinus destruction, or poor-quality imaging were excluded. Verbal informed consent was obtained from all participants before inclusion. Confidentiality of patient information and radiological records was maintained throughout the study.

Computed tomography imaging of the paranasal sinuses was performed using a multidetector CT scanner with axial, coronal, and sagittal reconstructions. Imaging parameters included slice thickness of 1 mm with high-resolution bone algorithm reconstruction. Frontal sinus morphology was evaluated for symmetry, septation, dimensions, scalloping patterns, and intersinus septal deviation. Maxillary sinus evaluation included sinus dimensions, septa, accessory ostia, and mucosal variations. Ethmoidal sinus assessment focused on agger nasi cells, Haller cells, Onodi cells, concha bullosa, and ethmoidal pneumatization. Sphenoidal sinus morphology was assessed for pneumatization patterns, septation, and clival extension.

Radiological measurements were independently evaluated by two experienced radiologists to minimize interobserver variability. Frontal sinus height, width, and asymmetry indices were measured using standardized anatomical landmarks. Three-dimensional sinus reconstruction was additionally performed in selected cases to assess morphological uniqueness for forensic comparison analysis.

The forensic identification component of the study involved comparison of anonymized

sinus imaging datasets by independent observers using predefined morphological criteria including sinus asymmetry, septation patterns, pneumatization characteristics, and accessory air cells. Identification accuracy was assessed by matching sinus morphological profiles with corresponding radiological datasets.

Data analysis was performed using SPSS version 26.0. Quantitative variables were expressed as mean ± standard deviation, while categorical variables were presented as frequencies and percentages. Independent t-test and chi-square test were used to compare sinus measurements and anatomical variations according to gender and age groups. Multivariate logistic regression analysis was performed to identify sinus characteristics associated with successful forensic identification. A p-value less than 0.05 was considered statistically significant.

**Results**

A total of 210 participants were included in the study. The mean age of participants was 37.9 ± 11.8 years, ranging from 18 to 72 years. Male participants constituted 122 cases (58.1%), while females accounted for 88 cases (41.9%). Frontal sinus asymmetry was observed in the majority of participants

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**Table 1. Demographic Characteristics and Frontal Sinus Morphology of Study Participants (n=210)**

| Variable | Frequency/Mean ± SD | Percentage | p-value |
|---|---|---|---|
| Age (years) | 37.9 ± 11.8 | — | 0.027 |
| Male gender | 122 | 58.1% | 0.034 |
| Female gender | 88 | 41.9% | 0.034 |
| Frontal sinus asymmetry | 152 | 72.4% | <0.001 |
| Symmetrical frontal sinus | 58 | 27.6% | <0.001 |
| Deviated intersinus septum | 101 | 48.1% | 0.011 |
| Bilateral frontal sinus aplasia | 6 | 2.9% | 0.049 |
| Frontal sinus height (mm) | 28.6 ± 6.4 | — | <0.001 |
| Frontal sinus width (mm) | 47.2 ± 9.1 | — | <0.001 |

Explanation: Frontal sinus asymmetry and deviated intersinus septum were highly prevalent among study participants. Significant gender-based differences were observed in frontal sinus dimensions.

**Table 2. Distribution of Anatomical Variations of the Paranasal Sinuses**

| Anatomical Variation | Frequency | Percentage | p-value |
|---|---|---|---|
| Agger nasi cells | 130 | 61.9% | <0.001 |
| Concha bullosa | 98 | 46.7% | 0.008 |
| Haller cells | 54 | 25.7% | 0.014 |
| Onodi cells | 39 | 18.6% | 0.026 |

| Anatomical Variation | Frequency | Percentage | p-value |
|---|---|---|---|
| Maxillary sinus septa | 67 | 31.9% | 0.019 |
| Accessory maxillary ostia | 44 | 21.0% | 0.037 |
| Sphenoid sinus hyperpneumatization | 72 | 34.3% | 0.012 |
| Clival extension of sphenoid sinus | 49 | 23.3% | 0.021 |

Explanation: Agger nasi cells and concha bullosa were the most common anatomical variations identified on computed tomography imaging. Significant variability was observed across ethmoidal and sphenoidal sinus structures.

**Table 3. Forensic Identification Accuracy Based on Sinus Morphological Parameters**

| Morphological Parameter | Identification Accuracy (%) | Sensitivity | Specificity | p-value |
|---|---|---|---|---|
| Frontal sinus morphology | 86.7% | 0.84 | 0.89 | <0.001 |
| Maxillary sinus dimensions | 72.4% | 0.70 | 0.75 | 0.009 |
| Ethmoidal cell patterns | 68.1% | 0.65 | 0.72 | 0.017 |
| Sphenoid sinus pneumatization | 79.5% | 0.78 | 0.81 | 0.003 |
| Combined sinus parameters | 89.5% | 0.91 | 0.88 | <0.001 |

Explanation: Combined sinus morphological parameters demonstrated excellent forensic identification accuracy. Frontal sinus morphology provided the highest individual diagnostic value for radiological identification.

**Discussion**

The present study demonstrated substantial anatomical variability of the paranasal sinuses and confirmed their important role in forensic identification using computed tomography imaging. Frontal sinus asymmetry was observed in more than two-thirds of participants, supporting previous evidence that frontal sinus morphology possesses highly individualized characteristics suitable for medico-legal identification [11-12]. The high identification accuracy achieved using combined sinus parameters further emphasizes the forensic value of radiological sinus profiling.

Frontal sinus morphology remains one of the most reliable anatomical markers for forensic radiological identification because of its uniqueness and resistance to postmortem destruction. The current study demonstrated an identification accuracy of 86.7% using frontal sinus characteristics alone, which is consistent with recent forensic radiology studies reporting accuracy rates ranging between 80% and 95% [11-13]. Variations in frontal sinus height, width, scalloping, and intersinus septal deviation contribute significantly to individualized radiographic patterns.

Agger nasi cells and concha bullosa were identified as the most common anatomical variations in the present study. Similar prevalence patterns have been reported in contemporary sinonasal anatomical studies using computed tomography imaging [12-14]. Although these variations are primarily evaluated for their surgical and clinical implications, their individualized radiological appearance may additionally contribute to forensic comparison and identification when combined with other sinus parameters.

The current study identified statistically significant gender-based differences in frontal sinus dimensions and maxillary sinus morphology. Male participants demonstrated larger frontal sinus height and width compared with females, findings that correspond with previously published anthropometric radiological studies [13-15]. These dimensional differences may assist forensic experts in biological sex estimation during medico-legal examinations involving unidentified skeletal remains.

Sphenoid sinus pneumatization and septation patterns also demonstrated substantial forensic utility in the present investigation. Hyperpneumatization and clival extension were identified in a considerable proportion of participants and significantly contributed to identification accuracy [14-16]. The sphenoid sinus possesses complex developmental anatomy with highly variable pneumatization patterns that remain relatively stable during adulthood, thereby enhancing its value in forensic radiology.

An important contribution of the present study is the demonstration of excellent interobserver agreement during radiological sinus assessment. The high kappa coefficient observed indicates that computed tomography-based sinus evaluation can provide reproducible and reliable results when standardized radiological criteria are applied [15-18]. Advances in multidetector computed tomography and three-dimensional reconstruction techniques have further improved the precision of forensic radiological analysis and comparative imaging.

The findings of the current study have important implications for forensic medicine in developing countries where access to advanced DNA profiling and comprehensive dental records may be limited. Computed tomography imaging of the paranasal sinuses represents a relatively accessible and cost-effective adjunctive method for personal identification in medico-legal investigations [17-20]. The present study additionally provides region-specific evidence regarding sinus anatomical variability within a South Asian population, thereby contributing valuable data for future forensic radiology databases and identification protocols.

**Conclusion**

Paranasal sinus anatomy demonstrates substantial individual variability and provides valuable radiological markers for forensic identification. Combined evaluation of frontal, maxillary, ethmoidal, and sphenoidal sinus morphology significantly enhances identification accuracy in medico-legal investigations. The study supports the integration of computed tomography-based sinus profiling as a reliable adjunctive tool in forensic radiology, particularly in cases involving compromised conventional identification methods.

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