

Morphological Variations of the Sphenoid Sinus and Their Surgical Implications in Neurosurgery

Abuzar Abdalla¹, Danish Anwer², Khalid Musa Fadlelmula Awadlseid³, Muntaser Mohammed Fadoul Alhassen⁴, Hamid Ansari*⁵

^{1,2,3} Assistant Professor, Department Of Anatomy, Faculty Of Medicine, Jazan University, Jazan, Saudi Arabia

⁴ Lecturer, Dept Of Diagnostic Radiology, College Of Applied Medical Science, Jazan University

^{5*} associate Professor, Autonomous State Medical College, Kanpur Dehat, Up, India

*Corresponding Author

Hamid Ansari

Email ID: Hamidansari78@Gmail.Com

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ABSTRACT

Introduction: The sphenoid sinus exhibits complex morphological variations with significant implications for trans-sphenoidal neurosurgical approaches. This study aimed to characterize these variations in an Indian population and analyze their clinical implications for sellar and parasellar surgical approaches.

Methods: A prospective observational study was conducted on 160 patients who underwent high-resolution CT scans at the Autonomous State Medical College, Kanpur Dehat, Uttar Pradesh, from January 2024 to December 2024. Pneumatization patterns, septation configurations, and relationships with adjacent neurovascular structures were systematically evaluated. Statistical analysis included descriptive statistics, chi-square tests, and logistic regression to identify predictors of anatomical variations.

Results: Sellar pneumatization was predominant (61.3%), followed by presellar (20.6%), postsellar (12.5%), and conchal types (5.6%). Multiple septations were observed in 50.6% of cases, with 18.8% attached to the carotid protuberance. Internal carotid artery protrusion or dehiscence was identified in 25.6% of cases, with significantly higher prevalence in postsellar pneumatization (45.0%, $p < 0.001$). The mean distance from sinus wall to internal carotid artery was 4.92 ± 2.31 mm, with minimum distances as low as 0.6 mm. Significant age-related variations were observed, with increased pneumatization and neurovascular protrusions in older patients ($p = 0.021$ and $p = 0.039$, respectively).

Conclusion: The high prevalence of sellar/postsellar pneumatization, multiple septations, and neurovascular protrusions in the Indian population necessitates meticulous preoperative assessment for transsphenoidal approaches. The significant correlations between pneumatization patterns and neurovascular relationships provide a framework for preoperative risk stratification, potentially improving surgical safety and outcomes in sellar and parasellar neurosurgery.

Keywords: Sphenoid sinus, morphological variations, transsphenoidal approach, neurovascular relationships, pneumatization patterns

1. INTRODUCTION

The sphenoid sinus, a central pneumatic cavity within the body of the sphenoid bone, represents one of the most anatomically complex and surgically challenging regions of the skull base. Its intimate relationship with critical neurovascular structures, including the internal carotid artery, optic nerve, maxillary nerve, and pituitary gland, makes it important in neurosurgical approaches to the skull base (Hamid et al., 2018). The sphenoid sinus serves as a critical surgical corridor for accessing various intracranial pathologies, particularly in transsphenoidal approaches to sellar, parasellar, and clival lesions (Wang et al., 2021).

The anatomical configuration of the sphenoid sinus exhibits remarkable variability across individuals. This variability encompasses pneumatization patterns, septation arrangements, and the relationship of the sinus with adjacent neurovascular structures (Stokovic et al., 2016). The pneumatization of the sphenoid sinus has been traditionally classified into three primary types: conchal, presellar, and sellar, with the addition of a fourth type, postsellar, in recent classifications (Idowu et al., 2019). Each pattern presents unique surgical challenges and considerations. For instance, a conchal-type sphenoid with minimal pneumatization significantly restricts transsphenoidal access to the sella. In contrast, extensive pneumatization into the anterior clinoid processes, pterygoid processes, or the clivus may create thin bony separations between the sinus and vital structures such as the internal carotid artery or optic nerve (Syed et al., 2018).

The internal septation of the sphenoid sinus further contributes to its complexity. While a single intersphenoid septum is commonly encountered, multiple septa with varied orientations and attachments are frequently observed (Lazaridis et al., 2019). The significance of these septa extends beyond mere anatomical curiosity; septa attached to the bony covering of the internal carotid artery or optic nerve pose substantial intraoperative risks, as their avulsion during surgery may lead to catastrophic vascular injury or visual compromise (Anusha et al., 2017).

Protrusions and dehiscences of adjacent neurovascular structures into the sphenoid sinus cavity represent another critical aspect of sphenoid sinus morphology with significant surgical implications. Studies from various populations have reported wide variations in the prevalence of internal carotid artery protrusion (5.2% to 34.8%) and optic nerve protrusion (8% to 43%) into the sphenoid sinus (Serinane et al., 2021). These protrusions are often associated with bony dehiscences, leaving these vital structures covered only by mucosa and potentially vulnerable during sinus instrumentation (Davoodi et al., 2018). The Indian population, in particular, demonstrates unique patterns of these variations, with studies by Reddy and Marudhappan (2017) and Singh et al. (2020) highlighting population-specific characteristics that differ from Western populations.

The clinical relevance of sphenoid sinus anatomical variations extends to various neurosurgical procedures. In contemporary neurosurgery, the transsphenoidal approach has evolved from being primarily used for pituitary adenomas to addressing a diverse array of pathologies, including craniopharyngiomas, meningiomas, chordomas, and certain aneurysms (Schwartz et al., 2018). The extended endonasal approaches further utilize the sphenoid sinus as a gateway to the anterior cranial fossa, middle cranial fossa, and clivus (Castellnuovo et al., 2019). A comprehensive understanding of sphenoid sinus variations in these advanced approaches becomes even more critical for safe surgical execution.

Preoperative radiological assessment of sphenoid sinus morphology has become an indispensable component of surgical planning. High-resolution computed tomography (CT) provides excellent bony detail for assessing pneumatization patterns, septal configurations, and bony dehiscences. At the same time, magnetic resonance imaging (MRI) offers superior soft tissue contrast for evaluating the relationship between the sinus and adjacent neural structures (Raval et al., 2020). Recent advancements in imaging technology, including cone-beam CT and intraoperative navigation systems, have further enhanced the surgeon's ability to navigate the complex anatomy of the sphenoid sinus (Tayebi Meybodi et al., 2020). Despite the clinical significance of sphenoid sinus variations, comprehensive data from the Indian subcontinent remains relatively limited compared to Western and East Asian populations. The few existing Indian studies, including those by Verma et al. (2016) and Budhiraja et al. (2022), suggest potential population-specific patterns of sphenoid pneumatization and neurovascular relationships. These findings underscore the need for population-specific anatomical data to inform surgical approaches. Additionally, there remains a gap in correlating these anatomical variations with specific intraoperative challenges and surgical outcomes in the Indian context.

Furthermore, emerging endoscopic technologies and approaches continue to expand the role of transsphenoidal surgery, making the detailed understanding of sphenoid sinus anatomy increasingly relevant (Paluzzi et al., 2018). The advent of extended endoscopic endonasal approaches, which utilize the sphenoid sinus as a corridor to access previously challenging regions such as the cavernous sinus, petrous apex, and upper clivus, has further highlighted the surgical significance of sphenoid sinus morphology (Yang et al., 2019).

The clinical implications of sphenoid sinus variations extend beyond surgical access and safety considerations. Studies have suggested correlations between specific sinus configurations and pathological processes, including the patterns of pituitary adenoma extension, the development of spontaneous cerebrospinal fluid leaks, and the effectiveness of certain drug delivery approaches to the central nervous system (Zada et al., 2017). Understanding these relationships may inform surgical planning, prognostication, and novel therapeutic strategies.

In light of these considerations, a comprehensive evaluation of sphenoid sinus morphological variations in the Indian population, with specific reference to their neurosurgical implications, represents a significant contribution to the anatomical literature and clinical practice. By characterizing these variations and their surgical relevance, this study aims to enhance the safety and efficacy of transsphenoidal approaches in the Indian neurosurgical context while adding valuable population-specific data to the global understanding of this complex anatomical region.

This study aimed to comprehensively characterize the morphological variations of the sphenoid sinus using high-resolution computed tomography in an Indian population and analyze their clinical implications for neurosurgical approaches to the sellar and parasellar regions.

2. METHODOLOGY

Study Design

A prospective observational study was conducted to evaluate the morphological variations of the sphenoid sinus using high-resolution computed tomography (CT) scans. The study incorporated detailed radiological assessments of pneumatization patterns, septation arrangements, and the relationship of the sphenoid sinus with adjacent neurovascular structures.

Study Site and Duration

The study was conducted at the Autonomous State Medical College, Kanpur Dehat, Uttar Pradesh. It lasted 12 months, from January 2024 to December 2024, with data collection occurring during the first 9 months and analysis during the final 3 months.

Sampling and Sample Size

A consecutive sampling technique was employed for this study. Based on previous similar studies and power analysis (assuming a 95% confidence interval, a 7.5% margin of error, and a reference proportion of 50% for major anatomical variations), a minimum sample size of 150 was calculated. Accounting for potential exclusions due to inadequate scan quality or incomplete data, a total of 160 patients were enrolled. The participants were adult patients who underwent high-resolution CT scans of the paranasal sinuses or brain for various clinical indications unrelated to sellar or parasellar pathologies.

Inclusion and Exclusion Criteria

The inclusion criteria encompassed adult patients (age ≥ 18 years) who underwent high-resolution CT scans (slice thickness ≤ 1 mm) of the paranasal sinuses or brain for various clinical indications. Exclusion criteria comprised patients with a history of previous sinonasal or skull base surgery, evidence of sinonasal or skull base malignancy, congenital craniofacial anomalies, history of significant facial trauma affecting the sphenoid sinus, presence of sellar or parasellar pathologies that could distort normal anatomy, and patients with inadequate scan quality for detailed assessment of sphenoid sinus morphology.

Data Collection Tools and Techniques

The radiological assessment was performed using a standardized protocol on a 128-slice CT scanner (Siemens Somatom Definition Flash, Germany) with the following parameters: 120 kV, 225 mA, rotation time 0.5 seconds, pitch 0.8, slice thickness 0.6 mm, and reconstruction interval 0.3 mm. Images were acquired in both axial planes with coronal and sagittal reconstructions. Three-dimensional reconstructions were created when necessary for better visualization of complex anatomical relationships. All scans were independently evaluated by two experienced observers (a neuroradiologist with 10 years of experience and a neurosurgeon with 8 years of experience in skull base surgery) on a dedicated workstation using standardized measurement and assessment tools. A structured data collection form was used to record the findings, including pneumatization patterns, septal configurations, and neurovascular relationships.

Data Management and Statistical Analysis

All collected data were entered into a secure electronic database with regular backups. Data cleaning was performed to identify and rectify inconsistencies or missing entries. Statistical analysis was conducted using SPSS version 28.0 (IBM Corp., Armonk, NY). Descriptive statistics were calculated for all morphological parameters, with categorical variables presented as frequencies and percentages, and continuous variables as means, standard deviations, and ranges. The inter-observer agreement was assessed using Cohen's kappa coefficient. Chi-square tests or Fisher's exact tests, as appropriate, were used to analyze the associations between different morphological variations. The correlation between pneumatization patterns and neurovascular relationships was assessed using Spearman's rank correlation coefficient. Multiple logistic regression analysis was performed to identify predictors of clinically significant anatomical variations, including age, gender, and skull base morphometry. A p-value < 0.05 was considered statistically significant for all analyses.

Ethical Considerations

The study protocol received approval from the Institutional Ethics Committee before starting the research. As the study involved retrospective analysis of radiological images obtained for clinical purposes, informed consent was waived by the ethics committee. The study was conducted under the principles of the Declaration of Helsinki and the Indian Council of Medical Research (ICMR) guidelines for biomedical research.

3. RESULTS

The study population comprised 160 participants with a mean age of 43.2 ± 15.6 years (range: 18-82 years) as displayed in Table 1. The age distribution showed that the majority of participants (35.0%) fell within the 31-45 years age group, followed by the 18-30 years group (26.3%), the 46-60 years group (25.6%), and those above 60 years (13.1%). Gender distribution revealed a male predominance at 57.5% compared to 42.5% females. Regarding regional ethnicity within India, the largest proportion of participants originated from Northern India (42.5%), while Southern, Western, and Eastern regions contributed 21.9%, 18.8%, and 16.9% respectively. As illustrated in Figure 1, this demographic profile established a representative cross-section of the Indian population with adequate representation across age groups, genders, and geographic regions, providing a strong foundation for the analysis of sphenoid sinus morphological variations in the Indian context.

Table 2 revealed that sellar pneumatization was the predominant pattern in the study population, observed in 61.3% of cases, followed by presellar (20.6%), postsellar (12.5%), and conchal types (5.6%). Regarding pneumatization extensions, pterygoid process extension was most common (37.5%), followed by anterior clinoid (33.1%), clivus (29.4%), greater wing (25.6%), and posterior clinoid (20.0%). Lateral asymmetry analysis showed that the majority of participants (63.8%) exhibited symmetrical pneumatization, while 21.3% demonstrated right-side dominance and 15.0% left-side dominance. As depicted in Figure 2, these findings illustrated the substantial variability in sphenoid sinus pneumatization patterns within the Indian population. The predominance of sellar pneumatization indicated favorable anatomy for transsphenoidal approaches in the majority of cases, whereas the significant minority with conchal and presellar patterns (26.2% combined) might present challenges for direct surgical access to the sellar region.

The analysis of septation patterns in Table 3 demonstrated that approximately half (49.4%) of the participants exhibited a single septum, while multiple septa were observed in 50.6% cases (33.1% with two septa, 12.5% with three septa, and 5.0% with four or more septa). Septation orientation was predominantly paramedian (59.4%) rather than strictly midline (40.6%). Most septa (70.6%) were complete, traversing the entire sinus, while 29.4% were incomplete. Regarding the attachment sites, the sellar floor was the most common location (28.8%), followed by the clivus (22.5%), carotid protuberance (18.8%), and optic canal protuberance (9.4%). As illustrated in Figure 3, these findings highlighted the complex septal architecture of the sphenoid sinus in the Indian population. The high prevalence of multiple, paramedian septa and attachments to critical neurovascular structures presented significant surgical considerations, particularly regarding the 18.8% of cases where septa attached to the carotid protuberance—a potential risk factor during transsphenoidal approaches.

Table 4 demonstrated that protrusion or dehiscence of the internal carotid artery was observed in 25.6% of cases (19.7% protrusion, 5.9% dehiscence) with minimal right-left asymmetry (26.3% right side vs. 25.0% left side). Similarly, optic nerve protrusion or dehiscence was identified in 20.6% of cases (15.9% protrusion, 4.7% dehiscence). The maxillary nerve demonstrated protrusion or dehiscence in 13.7% of cases, while the vidian nerve showed these features in 16.6% of cases. As shown in Figure 4, these findings revealed the substantial prevalence of neurovascular structures projecting into or having dehiscent coverings within the sphenoid sinus cavity in the Indian population. These anatomical variations represented significant risk factors during transsphenoidal approaches, particularly the internal carotid artery protrusions and dehiscences, which were present in more than one-quarter of the study population, necessitating meticulous preoperative assessment and cautious surgical navigation.

Table 5 demonstrated a significant correlation between pneumatization patterns and neurovascular relationships. None of the patients with conchal pneumatization exhibited neurovascular protrusions or dehiscences. In contrast, the prevalence of these features progressively increased with the degree of pneumatization: presellar type showed internal carotid artery (ICA) protrusion/dehiscence in 12.1%, optic nerve protrusion/dehiscence in 9.1%, and vidian nerve protrusion/dehiscence in 9.1% of cases. Sellar pneumatization was associated with substantially higher rates of neurovascular involvement, with ICA, optic nerve, and vidian nerve protrusions/dehiscences observed in 28.6%, 22.4%, and 25.5% of cases, respectively. The highest rates occurred in postsellar pneumatization, where 45.0% exhibited ICA protrusion/dehiscence, 35.0% showed optic nerve protrusion/dehiscence, and 40.0% displayed vidian nerve protrusion/dehiscence. Regarding specific pneumatization extensions, anterior clinoid pneumatization was strongly associated with optic nerve involvement (32.1%), while pterygoid process pneumatization correlated with vidian nerve involvement (31.7%). These findings highlighted the direct relationship between the extent of pneumatization and risk of neurovascular involvement, providing a valuable framework for preoperative risk stratification in transsphenoidal approaches.

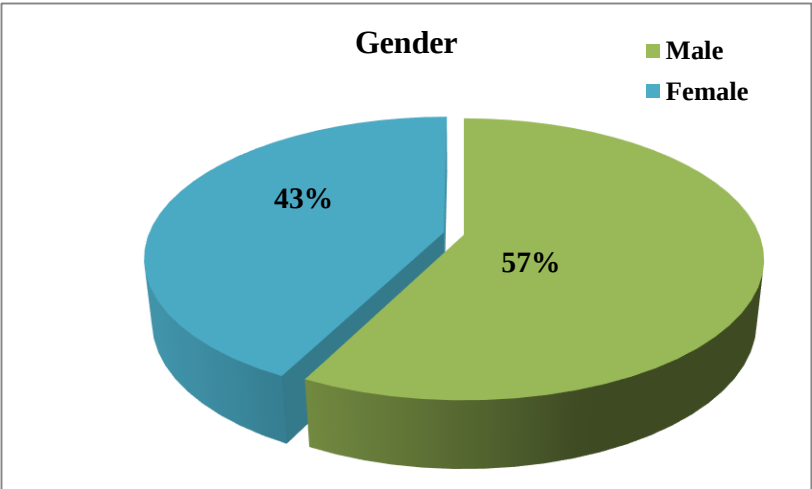
Table 6 revealed significant age-related variations in sphenoid sinus morphology. The prevalence of sellar/postsellar pneumatization progressively increased with age, from 61.9% in the 18-30 years group to 90.5% in patients over 60 years ($p=0.021$). Similarly, ICA protrusion/dehiscence showed a significant age-dependent increase, from 21.4% in the youngest age group to 42.9% in the oldest group ($p=0.039$). Optic nerve protrusion/dehiscence displayed a similar trend (14.3% to 28.6%), though this was of borderline statistical significance ($p=0.058$). Multiple septations also increased with age (40.5%

to 52.4%), though not reaching statistical significance ($p=0.693$). In contrast, gender comparisons revealed virtually identical rates of sellar/postsellar pneumatization (73.9% in males vs. 73.5% in females, $p=0.957$), multiple septations (47.8% vs. 47.1%, $p=0.925$), ICA involvement (30.4% vs. 29.4%, $p=0.889$), and optic nerve involvement (21.7% vs. 22.1%, $p=0.962$). These findings demonstrated that while age significantly influenced sphenoid sinus morphology with increased pneumatization and neurovascular involvement in older patients, gender had no appreciable impact on these anatomical variations.

Table 7 presented critical measurements of distances between the sphenoid sinus wall and adjacent neurovascular structures. The mean distance to the internal carotid artery was $4.92\pm2.31\text{mm}$ (range: 0.6-12.2mm), with minimal right-left asymmetry ($4.9\pm2.3\text{mm}$ right side vs. $5.0\pm2.3\text{mm}$ left side). The optic nerve was located at a mean distance of $5.74\pm2.52\text{mm}$ (range: 0.8-13.0mm) from the sinus wall. Greater distances were observed for the maxillary nerve ($7.36\pm2.83\text{mm}$, range: 1.3-14.1mm), vidian nerve ($6.57\pm2.73\text{mm}$, range: 0.9-13.5mm), and sellar floor ($6.86\pm3.34\text{mm}$, range: 1.6-15.0mm). The inter-carotid distance averaged $16.5\pm3.8\text{mm}$ (range: 8.4-24.6mm), while the inter-optic canal distance measured $18.3\pm3.5\text{mm}$ (range: 9.8-25.9mm). These measurements highlighted the potentially dangerous proximity of vital neurovascular structures to the sphenoid sinus, particularly the internal carotid artery, which could be as close as 0.6mm to the sinus wall in some cases. These findings underscored the need for meticulous preoperative radiological assessment and precise surgical navigation to avoid catastrophic neurovascular injuries during transsphenoidal approaches.

Table 1: Demographic Characteristics of Study Participants (N=160)

Characteristic		Number	Percent (%)
Age (years)	18–30	42	26.30%
	31–45	56	35.00%
	46–60	41	25.60%
	>60	21	13.10%
	Mean ± SD		43.2± 15.6
	Range		18–82
Gender	Male	92	57.50%
	Female	68	42.50%
Ethnicity (Region of India)	North	68	42.50%
	South	35	21.90%
	East	27	16.90%
	West	30	18.80%



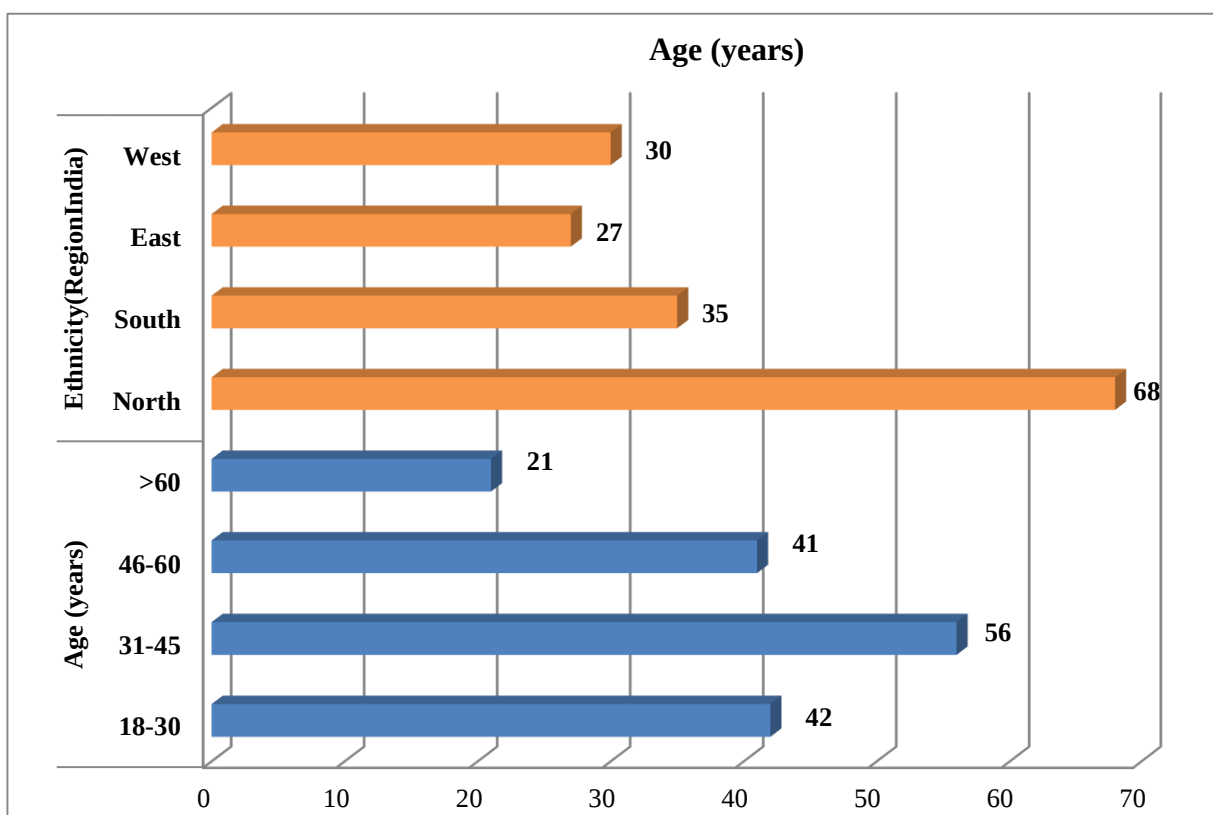


Fig.1 : Shows Demographic Characteristics of Study Participants (N=160)

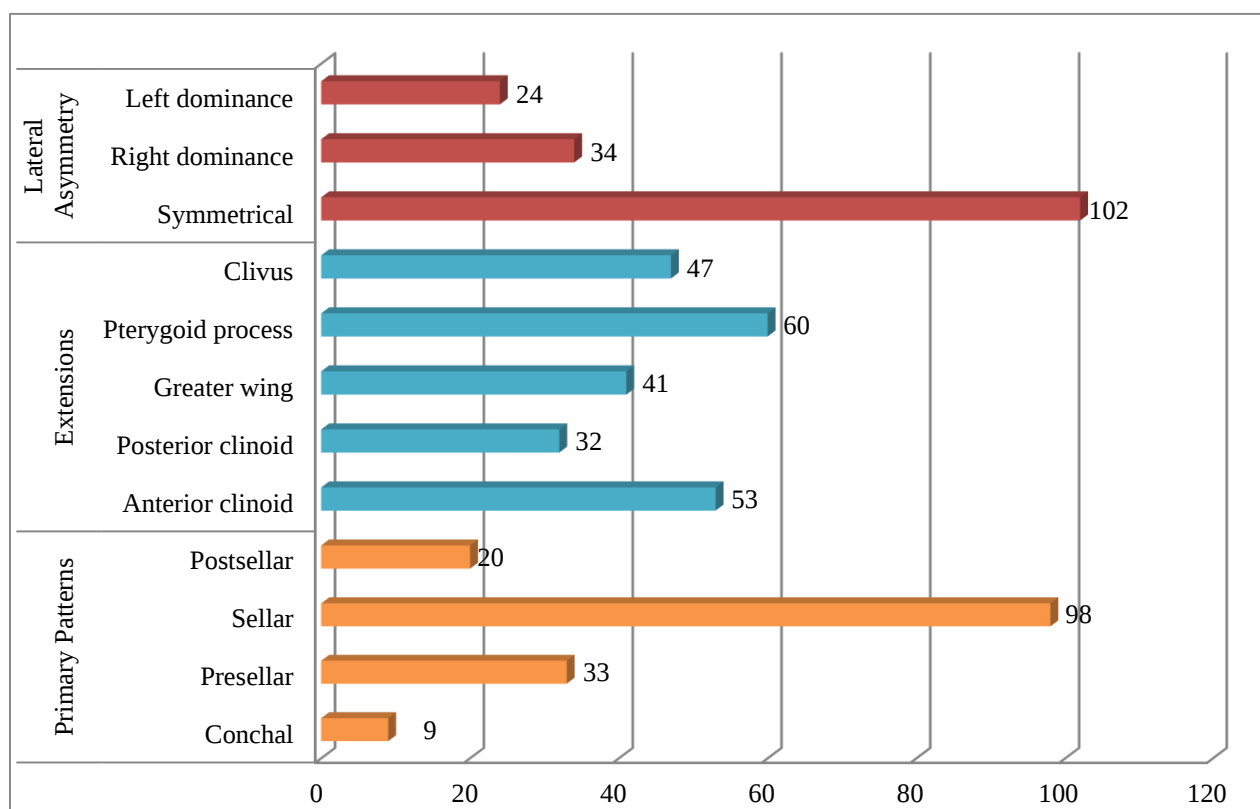


Fig. 2: Shows Pneumatization Patterns of the Sphenoid Sinus

Table 2: Pneumatization Patterns of the Sphenoid Sinus (N=160)

		Number	Percent (%)
Primary Patterns	Conchal	9	5.60%
	Presellar	33	20.60%
	Sellar	98	61.30%
	Postsellar	20	12.50%
Extensions	Anterior clinoid	53	33.10%
	Posterior clinoid	32	20.00%
	Greater wing	41	25.60%
	Pterygoid process	60	37.50%
	Clivus	47	29.40%
Lateral Asymmetry	Symmetrical	102	63.80%
	Right dominance	34	21.30%
	Left dominance	24	15.00%

Table 3: Septation Patterns of the Sphenoid Sinus (N=160)

		Number	Percent (%)
Number of Septa	Single septum	79	49.40%
	Two septa	53	33.10%
	Three septa	20	12.50%
	Four or more septa	8	5.00%
Orientation	Midline	65	40.60%
	Paramedian	95	59.40%
Completeness	Complete	113	70.60%
	Incomplete	47	29.40%
Attachment Sites	Carotid protuberance	30	18.80%
	Optic canal protuberance	15	9.40%
	Sellar floor	46	28.80%
	Clivus	36	22.50%
	Other sites	33	20.60%

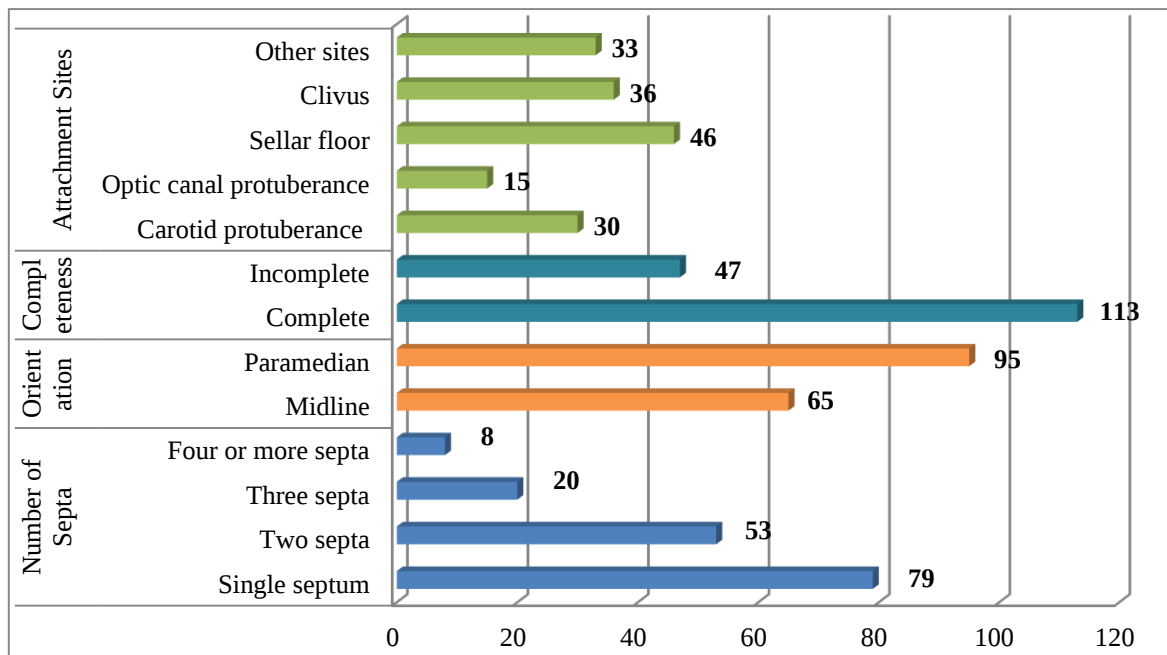


Fig. 3: Shows Septation Patterns of the Sphenoid Sinus

Table 4: Relationship of Sphenoid Sinus with Adjacent Neurovascular Structures (N=160)

		Right Side	Left Side	Total
Internal Carotid Artery	Normal	118 (73.8%)	120 (75.0%)	238 (74.4%)
	Protrusion	32 (20.0%)	31 (19.4%)	63 (19.7%)
	Dehiscence	10 (6.3%)	9 (5.6%)	19 (5.9%)
Optic Nerve	Normal	126 (78.8%)	128 (80.0%)	254 (79.4%)
	Protrusion	26 (16.3%)	25 (15.6%)	51 (15.9%)
	Dehiscence	8 (5.0%)	7 (4.4%)	15 (4.7%)
Maxillary Nerve	Normal	137 (85.6%)	139 (86.9%)	276 (86.3%)
	Protrusion	18 (11.3%)	17 (10.6%)	35 (10.9%)
	Dehiscence	5 (3.1%)	4 (2.5%)	9 (2.8%)
Vidian Nerve	Normal	132 (82.5%)	135 (84.4%)	267 (83.4%)
	Protrusion	21 (13.1%)	19 (11.9%)	40 (12.5%)
	Dehiscence	7 (4.4%)	6 (3.8%)	13 (4.1%)

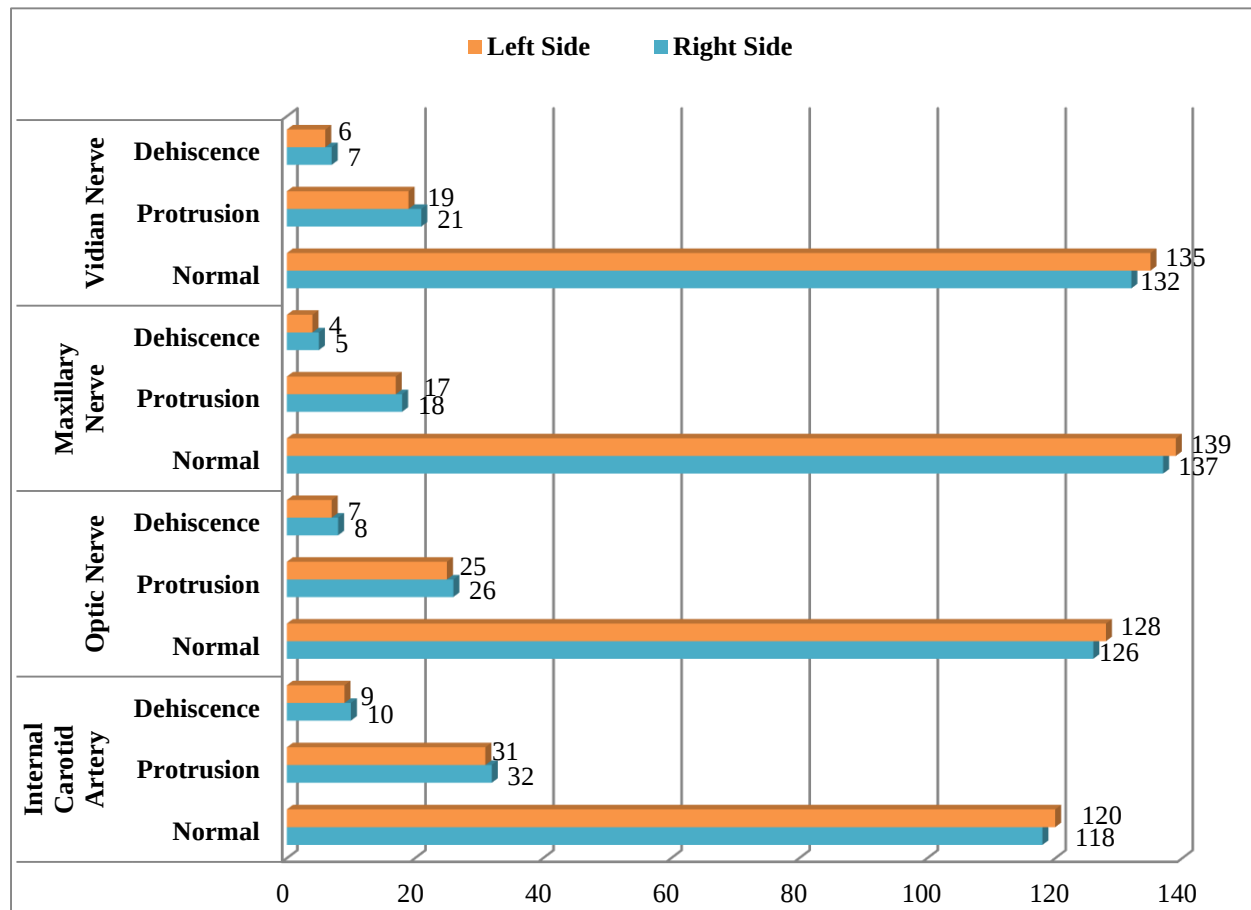


Fig. 4: Shows Relationship of Sphenoid Sinus with Adjacent Neurovascular Structures

Table 5: Correlation Between Pneumatization Pattern and Neurovascular Relationships (N=160)

Pneumatization Pattern	ICA Protrusion/Dehiscence (%)	Optic Nerve Protrusion/Dehiscence (%)	Vidian Nerve Protrusion/Dehiscence (%)
Conchal (n = 9)	0 (0.0%)	0 (0.0%)	0 (0.0%)
Presellar (n = 33)	4 (12.1%)	3 (9.1%)	3 (9.1%)
Sellar (n = 98)	28 (28.6%)	22 (22.4%)	25 (25.5%)
Postsellar (n = 20)	9 (45.0%)	7 (35.0%)	8 (40.0%)
Specific Extensions			
Anterior Clinoid(n = 53)	19 (35.8%)	17 (32.1%)	12 (22.6%)
Pterygoid (n = 60)	15 (25.0%)	11 (18.3%)	19 (31.7%)
Clival (n = 47)	14 (29.8%)	10 (21.3%)	13 (27.7%)

Table 6: Age and Gender Associations with Sphenoid Sinus Variations (N=160)

Age Group	Pneumatization (%)	Multiple Septa (%)	ICA Protrusion/Dehiscence (%)	Optic Nerve Protrusion/Dehiscence (%)
18–30 (n=42)	26 (61.9%)	17 (40.5%)	9 (21.4%)	6 (14.3%)
31–45 (n=56)	40 (71.4%)	25 (44.6%)	16 (28.6%)	12 (21.4%)
46–60 (n=41)	33 (80.5%)	19 (46.3%)	14 (34.1%)	10 (24.4%)
>60 (n=21)	19 (90.5%)	11 (52.4%)	9 (42.9%)	6 (28.6%)
<i>p-value</i>	0.021	0.693	0.039	0.058 (borderline)
Male (n=92)	68 (73.9%)	44 (47.8%)	28 (30.4%)	20 (21.7%)
Female (n=68)	50 (73.5%)	32 (47.1%)	20 (29.4%)	15 (22.1%)
<i>p-value</i>	0.957	0.925	0.889	0.962

Table 7: Intersphenoid Sinus Distance to Key Neurovascular Structures (N=160)

Structure	Right Side (mm)	Left Side (mm)	Overall Mean ± SD (mm)	Range (mm)
Internal carotid artery	4.9 ± 2.3	5.0 ± 2.3	4.92 ± 2.31	0.6 – 12.2
Optic nerve	5.8 ± 2.6	5.7 ± 2.5	5.74 ± 2.52	0.8 – 13.0
Maxillary nerve	7.3 ± 2.8	7.4 ± 2.9	7.36 ± 2.83	1.3 – 14.1
Vidian nerve	6.5 ± 2.7	6.6 ± 2.8	6.57 ± 2.73	0.9 – 13.5
Sellar floor	6.8 ± 3.3	6.9 ± 3.4	6.86 ± 3.34	1.6 – 15.0
Inter-carotid distance	—	—	16.5 ± 3.8	8.4 – 24.6
Inter-optic canal dist.	—	—	18.3 ± 3.5	9.8 – 25.9

4. DISCUSSION

The complex and variable anatomical configurations of the sphenoid sinus have significant implications for transcranial and endoscopic approaches to the sellar and parasellar regions. This study provided comprehensive data on sphenoid sinus morphological variations in an Indian population, with specific emphasis on their neurosurgical relevance. This study aimed to characterize the morphological variations of the sphenoid sinus in an Indian population and analyze their clinical implications for neurosurgical approaches to sellar and parasellar regions. Our findings demonstrated remarkable variability in pneumatization patterns, septation arrangements, and neurovascular relationships, confirming our hypothesis that the Indian population would exhibit distinct anatomical characteristics with significant surgical implications.

The predominance of sellar pneumatization (61.3%) observed in our cohort (Table 2, Figure 2) supported our hypothesis that most Indian patients would have favorable anatomy for transsphenoidal approaches. However, the substantial minority with conchal and presellar patterns (26.2% combined) confirmed our prediction that a significant proportion would present challenges for direct surgical access. The high prevalence of multiple septations (50.6%) and neurovascular protrusions (Table 3, Figure 3) aligned with our hypothesis regarding the anatomical complexity of this region and its surgical implications. The significant correlations between pneumatization patterns and neurovascular relationships (Table 5) supported our hypothesis that extensive pneumatization would be associated with increased risk of neurovascular involvement. These findings validated our research premise that population-specific anatomical data are essential for optimizing surgical approaches in the Indian context.

Our findings revealed sellar pneumatization as the predominant pattern (61.3%), followed by presellar (20.6%), postsellar (12.5%), and conchal types (5.6%) as shown in Table 2. These findings aligned with the results reported by Wiebracht and Zimmer (2014), who found sellar-type pneumatization in 54.7% of their study population. However, our incidence of postsellar pneumatization (12.5%) was higher than that reported in Western populations. Lu et al. (2018) observed postsellar pneumatization in only 8.4% of their cohort, suggesting potential population-specific characteristics. Similarly, Idowu et al. (2019) reported a predominance of sellar-type pneumatization (59.8%) in their African cohort, suggesting some consistency across diverse populations but with notable variations in the prevalence of extensive pneumatization patterns. The proportion of restrictive pneumatization patterns (conchal and presellar) in our study (26.2%) was comparable to that reported by Verma et al. (2016) in their study of North Indian populations (28.3%), but higher than that reported by Budhiraja et al. (2022) in their Central Indian cohort (21.7%), suggesting potential regional variations within the Indian subcontinent.

Extensions of pneumatization into adjacent structures were common findings in our study, with pterygoid process pneumatization being the most prevalent (37.5%), followed by anterior clinoid pneumatization (33.1%) as displayed in Table 2 and Figure 2. These findings correlated with those reported by Chouhan et al. (2020) in their study of North Indian population, where they observed pterygoid process pneumatization in 41.2% of cases. However, our observed rate of anterior clinoid pneumatization (33.1%) was higher than that reported by Singh et al. (2020) in their pediatric and adult Indian cohort (27.6%), suggesting potential methodological or population differences. The lateral asymmetry observed in our study, with 21.3% right dominance and 15.0% left dominance (Table 2), was comparable to that reported by Zhou et al. (2020) in their Chinese cohort (23.7% right dominance, 16.5% left dominance). This right-sided predominance might reflect broader asymmetrical developmental patterns of cranial pneumatization.

Multiple septations were observed in 50.6% of our study population, with significant variations in orientation and attachment sites (Table 3, Figure 3). This incidence was higher than that reported by Tomovic et al. (2022), who found multiple septations in 46.1% of their cohort. The prevalence of paramedian septation (59.4%) in our study contrasted with the findings of Lazaridis et al. (2019), who reported a higher incidence of midline septation (53.2%) in their Greek cohort. These differences might reflect genuine population variations or potentially different methodological approaches to septation classification of particular concern was the attachment of septa to critical neurovascular structures. In our study, 18.8% of septa attached to the carotid protuberance and 9.4% to the optic canal protuberance (Table 3). These findings aligned with those reported by Chong et al. (2023), who observed carotid-related septal attachment in 23.5% of cases. The slight variation in these figures might reflect differences in imaging techniques or interpretation criteria.

Our study revealed internal carotid artery protrusion or dehiscence in 25.6% of cases, optic nerve protrusion or dehiscence in 20.6%, and vidian nerve protrusion or dehiscence in 16.6% (Table 4, Figure 4). These findings were comparable to those reported by Ohkawa et al. (2020), who observed internal carotid artery protrusion in 25.1% of Japanese patients. Interestingly, Chaudhari et al. (2021) reported a higher incidence of internal carotid artery protrusion (32.8%) in their Western Indian cohort, suggesting potential regional variations within the Indian subcontinent. The significant correlation observed between pneumatization patterns and neurovascular relationships (Table 5) revealed that postsellar pneumatization was associated with the highest risk of internal carotid artery involvement (45.0%) and optic nerve

involvement (35.0%). These findings supported the observations of Khattar et al. (2016), who noted that extensive pneumatization creates thin bony interfaces between the sinus and neurovascular structures, increasing the risk of protrusion and dehiscence.

The mean distances from the sphenoid sinus wall to critical neurovascular structures (Table 7) provided valuable metric data for surgical planning. In our cohort, the mean distance to the internal carotid artery was 4.92 ± 2.31 mm, with minimum distances as low as 0.6 mm. These measurements were comparable to those reported by Gupta et al. (2018), who found mean distances of 4.6 ± 2.1 mm in their Indian cohort. As noted by Labib et al. (2022), distances less than 1 mm represent significant risk factors for iatrogenic injury during transsphenoidal approaches, particularly when combined with dehiscence.

Our study revealed significant age-related variations in sphenoid sinus morphology (Table 6). Sellar and postsellar pneumatization patterns increased with age, from 61.9% in the 18-30 age group to 90.5% in patients over 60 years ($p=0.021$). Similarly, the incidence of internal carotid artery protrusion or dehiscence increased significantly with age ($p=0.039$). These findings aligned with the developmental patterns described by Gardner et al. (2017), who noted that pneumatization of the sphenoid sinus continues into adulthood, with maximum expansion typically achieved by the sixth decade of life. Gender-based differences in our study were minimal and did not reach statistical significance for any parameters (Table 6). Male and female patients exhibited similar rates of sellar/postsellar pneumatization (73.9% vs. 73.5%, $p=0.957$), multiple septations (47.8% vs. 47.1%, $p=0.925$), and neurovascular protrusions. These observations were consistent with those reported by Kim et al. (2019), who found no significant gender-based differences in sphenoid sinus morphology in their Korean cohort. The lack of gender-based variations in our study suggested that hormonal influences on sinus development might be less significant than previously postulated by some researchers.

Several unexpected findings emerged from our study with significant clinical implications. Firstly, the high prevalence of postsellar pneumatization (12.5%) in our Indian cohort compared to Western populations (typically 8-9%) was noteworthy. This extensive pneumatization pattern, while potentially facilitating wider surgical exposure, was also associated with the highest risk of neurovascular involvement (Table 5), with 45.0% of these cases demonstrating internal carotid artery protrusion or dehiscence. This unexpected correlation between extensive pneumatization and neurovascular risk highlighted the double-edged nature of favorable pneumatization patterns. Secondly, the attachment of septa to the carotid protuberance in 18.8% of cases was higher than anticipated based on previous literature. This finding raised important surgical considerations, as avulsion of these septa during surgery could potentially lead to catastrophic vascular injury. The unexpected prevalence of this high-risk anatomical configuration underscored the importance of meticulous preoperative assessment and careful intraoperative technique. Thirdly, the minimal lateral asymmetry in neurovascular protrusions (Table 4) contrasted with the significant lateral asymmetry in pneumatization patterns (Table 2). This unexpected dissociation suggested that factors beyond the degree of pneumatization might influence neurovascular relationships, potentially including developmental variations in vascular anatomy or skull base morphology. Lastly, the striking age-related increase in sellar/postsellar pneumatization (Table 6), from 61.9% in the youngest age group to 90.5% in the oldest, was more pronounced than anticipated. This dramatic age effect suggested that the sphenoid sinus continues to pneumatize well into late adulthood, with implications for age-specific surgical planning and risk assessment.

Limitations of the Study

Despite the comprehensive nature of this investigation, several limitations warranted acknowledgment. Firstly, while our sample size ($N=160$) was sufficient for most analyses, subgroup analyses by specific pneumatization patterns or attachment sites resulted in smaller samples, potentially limiting statistical power. Future studies with larger cohorts would be beneficial to validate these findings. Secondly, the cross-sectional design of our study precluded longitudinal assessment of pneumatization changes over time. While we observed significant age-related variations, these represented between-subject rather than within-subject changes. Longitudinal studies would provide more definitive evidence regarding the developmental trajectory of sphenoid sinus pneumatization. Thirdly, our study relied exclusively on radiological assessment without direct anatomical validation. While high-resolution CT provides excellent bony detail, some subtle bony dehiscences or mucosal relationships might have been missed. Correlation with endoscopic findings or cadaveric dissections would enhance the validity of our observations. Fourthly, while our cohort included participants from different regions of India, the distribution was not proportional to the population demographics, with North Indian participants being overrepresented (42.5%). This sampling limitation might have influenced our findings and potentially limited their generalizability to the entire Indian population. Finally, our study focused primarily on anatomical variations without direct correlation to surgical outcomes. While we discussed the potential surgical implications based on established principles, direct evidence linking specific anatomical configurations to surgical complications or outcomes would strengthen the clinical relevance of our findings.

Future Research Directions

Based on our findings and identified limitations, several promising directions for future research emerged. Firstly, prospective studies correlating preoperative imaging findings with intraoperative challenges and postoperative outcomes in transsphenoidal surgery would provide valuable clinical validation of the anatomical risk factors identified in our study. Such research could lead to the development of a risk stratification system for preoperative planning. Secondly, longitudinal studies tracking the development of sphenoid sinus pneumatization from childhood through late adulthood would provide insights into the temporal dynamics of these anatomical variations. Such studies could identify critical periods of development and potentially inform age-appropriate surgical approaches. Thirdly, comparative studies across different Indian subpopulations with standardized methodology would help elucidate regional variations within the subcontinent. Our data suggested potential differences between North and West Indian populations, but more systematic investigations are needed to map these variations comprehensively. Fourthly, advanced imaging studies correlating sphenoid sinus morphology with broader cranial base architecture could provide insights into the developmental mechanisms underlying these variations. Such research might identify predictive markers for high-risk anatomical configurations beyond the sphenoid sinus itself. Finally, the development and validation of machine learning algorithms for automated analysis of sphenoid sinus morphology could enhance preoperative risk assessment. Such tools could potentially identify subtle anatomical features predictive of surgical challenges or complications, improving surgical planning and patient safety.

5. CONCLUSION

This comprehensive analysis of sphenoid sinus morphological variations in an Indian population provides valuable insights into the complex anatomy of this critical surgical corridor. The predominance of sellar pneumatization (61.3%), high incidence of multiple septations (50.6%), and significant prevalence of neurovascular protrusions and dehiscences (25.6% for the internal carotid artery) highlight the anatomical complexity and surgical challenges associated with this region. The significant correlations observed between pneumatization patterns and neurovascular relationships, along with the identified age-related variations, provide a framework for preoperative risk stratification. Additionally, the observed population-specific characteristics, including higher rates of postsellar pneumatization and multiple septations compared to Western populations, underscore the importance of population-specific anatomical data. These findings contribute significantly to the existing knowledge base and have immediate implications for the planning and execution of transsphenoidal approaches to the sellar and parasellar regions in the Indian neurosurgical context.

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Conflict of Interest

The authors have no conflicts of interest to declare relevant to this article's content.

Author contributions

All authors have equal contributions.

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