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INCIDENCE AND CHARACTER OF SUBJECTIVE SLEEP DISORDERS IN THE GEORGIAN POPULATION OF CHILDREN AND ADOLESCENTS WITH AUTISM SPECTRUM DISORDER (ASD)……………………6-11

Vu Nguyen, Tan Minh Hoang.
SPINAL CANAL SIZE IMPROVEMENT AFTER XLIF FOR LUMBAR SPINAL STENOSIS……………12-17

Bi-Yun Sun, Wei Peng.
APPLICATION OF SHELL TECHNIQUE IN C-TIRADS COMBINED WITH STE IN DIAGNOSIS OF C-TIRADS GRADE 4-5 NODULES……………18-22

Talgar Abilov, Irina Ismailova, Zhangeldy Shaimbetov, Nauryzbay Imanbayev, Yerbolat Iztleuov.
IMPACT OF VITAMIN D METABOLISM DISORDERS ON THE DEVELOPMENT OF AUTOIMMUNE KIDNEY DISEASES: A SYSTEMATICREVIEW……………23-30

Abdullayev Anar Sardar.
COMPARISON OF AGE-RELATED CHARACTERISTICS OF CEPHALOMETRIC INDICATORS: BIORBITAL BREADTH (EC–EC) AND INTERORBITAL BREADTH (D–D) IN ARTIFICIALLY DEFORMED AND NORMAL SKULLS……………31-36

Olena Babkina, Svitlana Danylchenko, Ihor Korobko, Oleksandr Yanchevskyi, Artem Kravchenko.
FEATURES OF DIAGNOSTICS OF FATAL KIDNEY INJURY IN MEDICAL PRACTICE……………37-45

Uday Mahajan, MERAJ AKHTAR, Arnab Sain, Ariz Raza, Mohammad Yousaf, Asif Afridi, Bilal Ahmad, Mohamed Kabary, Ahmed Sham Nasir, Musab Mohamed, Hoosai Manyar, Holly Hathaway, Vivek Deshmukh.
INTRA-OPERATIVE ASSESSMENT OF TIBIAL PLATEAU FRACTURE REDUCTION IN LOW-RESOURCE SETTINGS……………46-48

Ardiana Dragobuzhda Ismaili, Adelina Ismaili Murati.
THE ASSOCIATION BETWEEN QUALITY OF TEACHING AND STUDENT'S SUCCESS AT THE FACULTY OF MEDICINE IN KOSOVO……………49-53

Yurevych N, Pokotylo P, Podoliuk M, Seleznova R, Voinytska O, Vdovichenko V, Sukhonosov R, Alekseeva V.
ANATOMICAL VARIABILITY OF THE ETHMOID AND SPHENOID SINUSES……………54-58

Premtim Rashiti, Bujar Shabani, Jeton Shatri, Leotrim Berisha, Ardita Kafexholli, Dijon Musliu.
TYPE A INTERCONDYLAR FOSSA CONFIGURATION SIGNIFICANTLY INCREASES ACL RUPTURE RISK: A MORPHOMETRIC MRI STUDY……………59-64

Amrit Goyal, Vivek Mittal, K.S. Dinkar, Mayur Gupta, Amit Agarwal, Hari Singh.
FEMOROACETABULAR IMPINGEMENT: PREVALENCE OF RADIOGRAPHIC MORPHOLOGY IN INDIAN POPULATION, ETIOLOGY AND CLINICAL MANAGEMENT……………65-75

Nino Totadze.
THE IMPORTANCE OF PROMOTING BREASTFEEDING-MATERNAL NUTRITION DURING LACTATION……………76-83

Asmaa Yousuf Thanoon Al-Nuaimy, Faehaa Azher Al-Mashhadane.
THE IMPACT OF HYALURONIC ACID ON GINGIVITIS AND PERIODONTAL HEALTH……………84-88

Gulnara Svyatova, Galina Berezina, Alexandra Murtazaliyeva, Yergali Miyerbekov, Ualikhan Imammyrzayev.
GENETIC ASPECTS OF WARFARIN DOSING ALGORITHMS IN CARDIAC SURGERY PATIENTS WHO HAVE UNDERGONE HEART SURGERY: SYSTEMATIC REVIEW……………89-104

Dauren Zhumatayev, Abylai Baimakhanov, Aidar Raimkhanov, Danyiar Toksanbayev, Alibek Smagulov, Giedrius Barauskas, Nazarbek Omarov.
ONE-STEP TACTICS OF SURGICAL TREATMENT OF ACUTE CHOLECYSTITIS IN COMBINATION WITH CHOLEDOCHOLITHIASIS……………105-111

Manana Machitidze, Nato Durglishvili, Maia Gogashvili, Vazha Nebieridze, Jaana Sepp.
EFFECTIVENESS OF EDUCATIONAL INTERVENTIONS TO DEVELOP PATIENT SAFETY KNOWLEDGE, SKILLS, BEHAVIORS, AND ATTITUDES IN NURSING STUDENTS – INTERNATIONAL STUDY……………112-117

Zahraa Alkhafaje, Ahmed Mohamed Kmkm, Rawnaq Jamal Madhloom, Nuha Mohammed Abdulkhaleq, Doaa Mohsin Farhan, Sura Sagban Abid Ali, Hany Akeel Al-hussaniy, Abdul-Salam Harfash, Abdulwahhab Hameed Rashid, Usama S. Altimari.
CORRELATION OF FETAL MEASUREMENTS WITH GESTATIONAL AGE IN 144 ABORTED FETUSES: A CROSS-SECTIONAL HOSPITAL-BASED OBSERVATIONAL STUDY……………118-124

Tchernev G, Broshtilova V, Tchernev KG Jr, Krastev DS, Krastev NS, Kordeva S.
POSTTRAUMATIC SUBUNGUAL ACRAL NODULAR MELANOMA WITH BONE INFILTRATION TREATED VIA AMPUTATION OF THE DISTAL AND MIDDLE PHALANX: DESCRIPTION OF A CASE AND UPDATE ON THE TOPIC……………125-130

Madina Khalmirzaeva, Almagul Kurmanova, Damilya Salimbayeva, Gulfairuz Urazbayeva, Gaukhar Kurmanova, Zhanar Kypshakbayeva, Gaukhar Koshkimbayeva.
MOLECULAR MECHANISMS OF OBSTETRIC APS……………131-144

Huseynov Fuad Rafig Ogli.
COMPARISON QUALITY OF LIFE BETWEEN THORACOSCOPIC SURGERY AND TRADITIONAL SURGERY IN THE TREATMENT OF CONGENITAL DIPHRAGMAL HERNIA IN NEWBORNS………..........................................................................…………………145-149

Diyas Myrzakozha, Tolkyn Issabekova, Nurgali Rakhymbayev, Elmira Karlova, Elena Nechepurenko.
COMPARATIVE STUDY OF ANTIBACTERIAL EFFECTS OF MODIFIED PREPARATIONS CONTAINING METAL NANOPARTICLES…………………………………………………………………………………….......................…………………150-157

Chekhovska G.S, Pustova N.O, Chaplyk-Chyzho I.O, Kachailo I.A, Sypalo A.O, Gradil G.I, Lytvynenko M.V, Lobashova K.G, Piriatinska N.E, Kudriavtseva T.O, Gargin V.V.
CONCEPTUAL AND THEORETICAL EXPLORATION OF TREATMENT OF PATIENTS WITH ONYCHOMYCOSIS…….………158-166

Yesset Muratov, Ruslan Irmekbayev, Yerbolat Iztleuov, Nauryzbay Imanbayev, Nurgul Kereyeva, Maiya Taushanova.
TOXIC EFFECTS OF CHEMOTHERAPY ON THE VISUAL ORGAN IN MALIGNANT NEOPLASMS: A SYSTEMATIC REVIEW……………………………………………………………………………………………………….......................................167-174

Niyazi Burhan Aldin Mohammad, Omeed Darweesh, Marwan M. Merkhan.
THE IMPACT OF DISEASE-MODIFYING MEDICATIONS ON THE LIPID PROFILE OF PATIENTS WITH ISCHEMIC HEART DISEASE……………………………………..............................................…………………………………………………….…175-178

Arta Veseli, Dashnor Alidema, Kaltrina Veseli, Edona Breznica, Enis Veseli, Denis Behluli, Argjira Veseli, Agon Hoti.
THE IMPACT OF SYSTEMIC DRUGS ON THE ORAL AND GUT MICROBIOME: A NARRATIVE REVIEW………..……………179-183

Altynay Dosbayeva, Askar Serikbayev, Alua Sharapiyeva, Kuralay Amrenova, Ainur Krykpayeva, Ynkar Kairkhanova, Altay Dyussupov, Assanali Seitkabylov, Zhanar Zhumanbayeva.
POST-COVID-19 SYNDROME: INCIDENCE, BIOMARKERS, AND CLINICAL PATTERNS IN KAZAKHSTAN…………..………184-192

Aisha Ibrayeva, Botagoz Turdaliyeva, Gulshara Aimbetova, Darina Menlayakova, Dalal Gizat, Alfiya Shamsutdinova, Ildar Fakhradiyev.
POST-TRAUMATIC STRESS DISORDER AMONG EMERGENCY RESPONDERS AND VICTIMS OF DISASTERS IN KAZAKHSTAN: PREVALENCE, RISK FACTORS, AND REHABILITATION NEEDS……...............................................................................................…193-197

Samal Myktybayeva, Kuralbay Kurakbayev, Zhanar Buribayeva, Madamin Karataev, Aizhan Turekhanova, Zhanar Kypshakbayeva, Madina Khalmirzaeva.
REPRODUCTIVE HEALTH OF WOMEN IN PENITENTIARY INSTITUTIONS: A CASE STUDY IN KAZAKHSTAN…..…………198-204

Adil Khalaf Altwairgi, Faisal Awadh Al-Harbi, Abdullah S. Alayed, Albaraa Nasser Almoshigeh, Emad Khalid Aloadah, Raghad Alkhalifah, Badr Alharbi.
KNOWLEDGE, ATTITUDE, AND PRACTICE TOWARD PROSTATE CANCER AND ITS SCREENING METHODS IN QASSIM REGION……………………………………………...........................................................……………………………………………205-211

Olena Haidai, Inha Samborska, Oleksandr Maievskyi.
FEATURES OF THE EFFECT OF SCORPION VENOM ON THE IMMUNE DEFENSE SYSTEM OF THE MAMMALIAN LIVER (REVIEW)…………………………………..........................................................……………………………………………………212-220

# ANATOMICAL VARIABILITY OF THE ETHMOID AND SPHENOID SINUSES

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## Abstract.

**Background:** The ethmoid and sphenoid sinuses exhibit marked anatomical variability that can impact surgical approaches and predispose individuals to complications during sinus and skull base procedures.

**Objective:** To characterize the morphometric patterns and anatomical variants of the ethmoid and sphenoid sinuses based on high-resolution CT data and to analyze their surgical and clinical significance.

**Methods:** A total of 400 CT scans were analyzed. Sinuses were classified by pneumatization type, dimensions, and presence of anatomical variants. 3D reconstructions were performed to assess spatial orientation and proximity to neurovascular structures.

**Results:** Ethmoid sinus complexity was classified into three distinct types, with higher complexity correlating with narrower surgical corridors and increased risk of incomplete ethmoidectomy. Sphenoid pneumatization showed significant variability, including presellar, sellar, and postsellar types. Onodi cells were identified in 13% of cases, closely related to the optic canal. Septated sphenoids were present in 21%, often traversing the internal carotid artery canal.

**Conclusion:** Detailed anatomical understanding of posterior sinus morphology and variation is essential for safe and effective sinus and skull base surgery. This study provides a morphometric atlas to support individualized surgical planning.

**Key words.** Computer tomography, paranasal sinusis, anatomy, sphenoid sinus, ethmoid sinus.

## Introduction.

The human paranasal sinuses exhibit remarkable anatomical variability, both in their external morphology and internal architecture [1,2]. Among them, the ethmoid and sphenoid sinuses are particularly notable for their complex, variable pneumatization patterns and their proximity to critical neurovascular structures such as the optic nerve, internal carotid artery (ICA), anterior skull base, and orbit [3,4]. For otolaryngologists, neurosurgeons, and radiologists alike, detailed anatomical understanding of these posterior sinuses is essential, not only for safe and effective surgical access but also for the accurate diagnosis of sinus disease and planning of endoscopic procedures [5,6].

The ethmoid sinus comprises a labyrinth of air cells between the nasal cavity and the orbit. Its architecture ranges from a few large, simple cells to dozens of small, interwoven compartments. This complexity impacts surgical visibility and the risk of residual disease after endoscopic ethmoidectomy. Additionally, the presence of anatomical variants, such as Onodi cells (posterior ethmoid cells that encroach on the optic canal), can dramatically increase the risk of intraoperative complications if not preoperatively identified [7-9].

The sphenoid sinus, which lies deeper and more posteriorly in the skull base, also shows wide variability in size, septal configuration, and pneumatization extent. It may be presellar, sellar, or postsellar, depending on how far posteriorly it extends relative to the sella turcica [10-11]. The sphenoid septum is often asymmetric and may deviate toward the ICA or optic nerve, increasing the risk of catastrophic injury during sphenoidotomy or transsphenoidal pituitary surgery. Moreover, bony dehiscence of the optic canal or carotid canal may leave these structures exposed directly to the sinus lumen.

Although the surgical and diagnostic importance of ethmoid and sphenoid anatomy is well established, large-scale quantitative studies describing their variability and prevalence of critical variants remain limited [12,13]. Many anatomical atlases and surgical guides rely on single-case illustrations or small cadaveric series that may not capture the full spectrum of variation encountered in clinical practice [14,15].

The present study aims to address this gap by providing a comprehensive morphometric analysis of the ethmoid and sphenoid sinuses using high-resolution CT data from 400 adult individuals. We assess the prevalence of key anatomical patterns including ethmoid morphotypes, sphenoid pneumatization types, and high-risk variants such as Onodi cells and sphenoid septations - and discuss their clinical significance. By establishing normative data and identifying high-risk configurations, we hope to support improved surgical safety, anatomical education, and radiologic reporting in sinonasal and skull base procedures.

## Materials and Methods.

This descriptive anatomical study was based on retrospective analysis of 400 anonymized high-resolution craniofacial CT scans obtained for diagnostic purposes (non-surgical) from adult patients aged 18 to 75 years. All scans were evaluated for inclusion based on the following criteria:

1. **Inclusion:** Full visualization of paranasal sinuses; absence of acute sinusitis, tumors, fractures, or surgical alterations.
2. **Exclusion:** Prior sinus surgery, craniofacial trauma, congenital cranial deformities, or radiologic artifacts.

The sample included a balanced distribution of cranial types (brachy-, meso-, and dolichocranic skulls) and both sexes, ensuring representative anatomical diversity.

CT scans were acquired using a 64-slice multidetector CT scanner with a slice thickness of 0.6–1.0 mm. Images were reconstructed in both axial and coronal planes and saved in DICOM format.

Image processing and segmentation were performed using 3D Slicer (v5.2). Manual segmentation of the ethmoid and sphenoid sinuses, including key anatomical structures, was carried out by two independent reviewers (a radiologist and an anatomist). Discrepancies were resolved by consensus, and inter-observer agreement exceeded 0.9 (ICC).

Anatomical structures were assessed and classified as follows:

Ethmoid Sinus based on number and arrangement of air cells was classified into 3 morphotypes.

1. Simple: 1–3 large cells.
2. Intermediate: 4–6 moderate-sized cells.
3. Complex: >6 small, closely spaced cells.

Also, some structural variants were noted: concha bullosa, paradoxical middle turbinate, and ethmoid bullae.

Sphenoid Sinus was classified into 3 groups according to the pneumatization type

1. Presellar: pneumatization anterior to the sella.
2. Sellar: pneumatization extending under the sella.
3. Postsellar: pneumatization extending posterior to the sella.

And into 2 groups according to the septa location:

1. Single central, deviated, or multiple septa.
2. Septa attachment to or near the ICA or optic canal recorded.

Specific anatomical variants were y identified.

1. Onodi Cells: posterior ethmoid air cells superior/posterolateral to the sphenoid sinus, in contact with the optic canal.
2. Bony Dehiscence of optic canal and internal carotid artery canal.
3. Measurements included distance from sinus wall to optic nerve and ICA (in mm) and number and orientation of sphenoid septa.

All morphometric data were recorded in a standardized form. The following parameters were calculated:

1. Prevalence of each morphotype and variant.
2. Mean distances and standard deviations.
3. Cross-tabulation by sex and craniotype.

Descriptive statistics were calculated using SPSS (v26.0). Proportional differences were tested using chi-square analysis, with significance set at $p < 0.05$.

## Results.

Among the 400 CT scans analyzed, the ethmoid sinus architecture varied widely. Subjects were classified into three morphotypes based on the number and configuration of ethmoidal air cells:

1. **Simple morphotype (1-3 large cells):** Observed in 25% of cases (n = 100). These individuals showed broad air chambers with minimal internal septation, most commonly seen in dolichocranic skulls.
2. **Intermediate morphotype (4-6 mixed cells):** Present in 48% (n = 192). This was the most common pattern, typically associated with mesocranic skulls and moderate infundibular complexity.
3. **Complex morphotype (>6 small, crowded cells):** Found in 27% (n = 108), more frequently in brachycranic skulls. This group exhibited a dense lattice of lamellae, complicating visualization of the ethmoidal roof and posterior boundary.

The complexity of ethmoid cells was positively associated with surgical difficulty and reduced visibility of adjacent structures ($p < 0.01$).

Cross-tabulated analysis showed that complex ethmoid morphotypes were significantly more prevalent in brachycranic skulls ($\chi^2 = 16.42$, $p = 0.002$) and associated with reduced visibility of the lamina papyracea in 71% of cases. Table 3 presents cross-tabulated distributions of ethmoid morphotypes by cranial type.

Sphenoid sinus pneumatization type was categorized as:

1. Presellar: 14% (n = 56) – pneumatization remained anterior to the sella turcica.
2. Sellar: 63% (n = 252) – pneumatization extended beneath the sella, exposing the pituitary floor.
3. Postsellar: 23% (n = 92) – pneumatization extended posteriorly into the clivus, often with thinner posterior walls.

The mean sphenoid sinus volume varied significantly:

- Presellar: $2.8 \pm 0.7$ cm³
- Sellar: $4.6 \pm 1.1$ cm³
- Postsellar: $6.3 \pm 1.5$ cm³

Postsellar sinuses showed significantly reduced bone thickness overlying the internal carotid artery (mean = 1.2 mm, $p < 0.01$) (see Table 1).

Postsellar sinuses show thinner bone overlying the ICA, increasing surgical risk.

The prevalence of key anatomical variants was as follows:

1. **Onodi cells:** Identified in 13% (n = 52) of cases. In 92% of these, the Onodi cell was in direct contact with the optic canal, and in 21% the cell roof extended above it.
2. **Sphenoid sinus septations:**
   a. Single septum: 66%
   b. Multiple septa: 21%
   c. Septa deviating toward the ICA: 11%
3. **Bony dehiscence:**
   a. Optic canal dehiscence: 7% (n = 28)
   b. Carotid canal dehiscence: 6% (n = 24)

The ethmoid sinus was classified into three morphotypes based on the number and arrangement of air cells. The simple morphotype consists of 1–3 large, well-defined cells with minimal internal septation, offering relatively clear anatomical landmarks. The intermediate morphotype includes 4–6 moderately sized cells with moderate complexity and partial compartmentalization. The complex morphotype is characterized by more than six small, densely packed cells with intricate septal patterns, often obscuring key anatomical structures and increasing surgical difficulty.

In particular, patients with complex ethmoid morphotypes often demonstrated lower Keros classification types (I–II), with reduced vertical height of the olfactory fossa. This limited visualization of the fovea ethmoidalis and cribriform plate during surgery and potentially elevated the risk of iatrogenic skull base injury. Future studies should more precisely correlate ethmoid complexity with Keros class and surgical outcomes.

***Table 1.*** *Sphenoid Pneumatization Patterns.*

| Pneumatization Type | Count (n) | Prevalence (%) | Mean Volume (cm³) | Posterior Wall Thickness to ICA (mm) |
|---|---|---|---|---|
| Presellar | 56 | 14% | 2.8 | 2.4 |
| Sellar | 252 | 63% | 4.6 | 1.6 |
| Postsellar | 92 | 23% | 6.3 | 1.2 |

***Table 2.*** *Measurements and Morphometric Data.*

| Measurement | Mean (mm) ± SD | Range (mm) |
|---|---|---|
| Distance: sphenoid wall to ICA | 3.1 ± 1.2 | 0.8 – 6.5 |
| Distance: sphenoid wall to optic canal | 2.4 ± 1.1 | 0.6 – 5.9 |
| Ethmoid roof height (cribriform to lamella) | 5.6 ± 1.4 | 3.2 – 9.3 |

***Table 3.*** *Distribution of Ethmoid Morphotypes by Cranial Type.*

| Cranial Type | Simple | Intermediate | Complex |
|---|---|---|---|
| Brachycranic | 18% | 40% | 42% |
| Mesocranic | 26% | 52% | 22% |
| Dolichocranic | 31% | 51% | 18% |

## Discussion.

The last decade has witnessed widespread adoption of digital medicine, particularly driven by challenges posed by the COVID-19 pandemic and healthcare [16-18] disruptions during regional conflicts [19,20]. These factors have accelerated the need for digitally enhanced neurosurgical planning, including 3D navigation [21,22] and AI-assisted imaging, especially in the context of complex skull base anatomy [23,24]. This study presents a comprehensive analysis of the anatomical variability of the ethmoid and sphenoid sinuses using high-resolution CT imaging in a large adult cohort. Through morphometric classification, prevalence mapping of critical anatomical variants, and structural measurement, we contribute valuable insights into how these variations impact surgical planning, radiological interpretation, and risk stratification in sinonasal and skull base procedures [25,26]. That area relates to common inflammatory processes [27,28] which started in oral cavity often [29,30].

The ethmoid sinuses, located at the intersection of the nasal cavity, orbit, and anterior cranial base, are highly variable in shape and complexity. We categorized them into three morphotypes: simple, intermediate, and complex based on the number and arrangement of ethmoidal air cells [31,32]. The complex morphotype, present in approximately 27% of cases, is of particular surgical concern. It features numerous, tightly packed cells with irregular septations that can obscure anatomical landmarks and increase the risk of incomplete ethmoidectomy, orbital injury, or cerebrospinal fluid (CSF) leak, especially during dissection near the fovea ethmoidalis or lamina papyracea [33].

Our findings reinforce previous literature that highlights the surgical difficulty of densely septated ethmoids, especially when visualization is compromised by inflammation or anatomical distortion [32,34]. Surgeons should use ethmoid morphotype classification as a preoperative guide to anticipate the degree of difficulty, particularly in revision cases or procedures requiring extensive clearance of ethmoid cells [35,36].

From a radiologic perspective, structured reporting of ethmoid complexity may help flag high-risk cases before surgery [37]. This classification could be integrated into routine CT evaluation protocols to improve communication between radiologists and surgeons.

The sphenoid sinus shows not only variable volume but also critical differences in pneumatization patterns - presellar, sellar, and postsellar. Each type carries implications for surgical exposure and proximity to neurovascular structures [38]. Postsellar pneumatization, found in 23% of subjects, results in deeper sinus cavities and thinner posterior walls. Our data show that this pattern brings the internal carotid artery (ICA) and optic nerve closer to the sinus lumen, with bony thickness in some cases falling below 1.5 mm.

This has major implications for transsphenoidal surgery, where sellar and postsellar sinuses are routinely traversed to access the pituitary gland. Postsellar cases, though offering greater working space, increase the risk of injuring the ICA or optic nerve - especially if dehiscence is present. Our identification of ICA dehiscence in 6% and optic nerve dehiscence in 7% aligns with previous cadaveric and imaging studies [39-41].

These findings support the routine measurement of sphenoid wall thickness and documentation of pneumatization type during preoperative planning for endoscopic and neurosurgical approaches [42].

Onodi cells, posteriorly located ethmoid air cells that closely abut or encase the optic canal, were observed in 13% of cases. In most of these, the Onodi cell roof was directly adjacent to the optic nerve, confirming the high risk of optic nerve injury during posterior ethmoidectomy or sphenoidotomy if the variant is unrecognized [4,43] (see Figure 2).

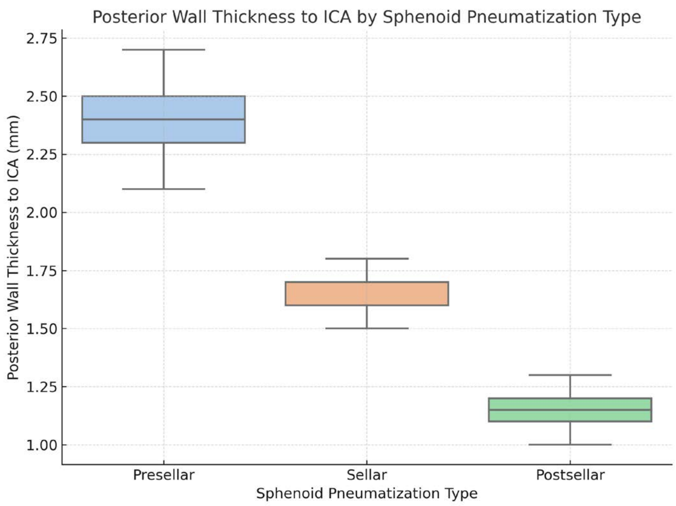


***Figure 1.*** *Boxplot showing posterior wall thickness overlying the ICA by sphenoid pneumatization type (Presellar vs. Sellar vs. Postsellar).*

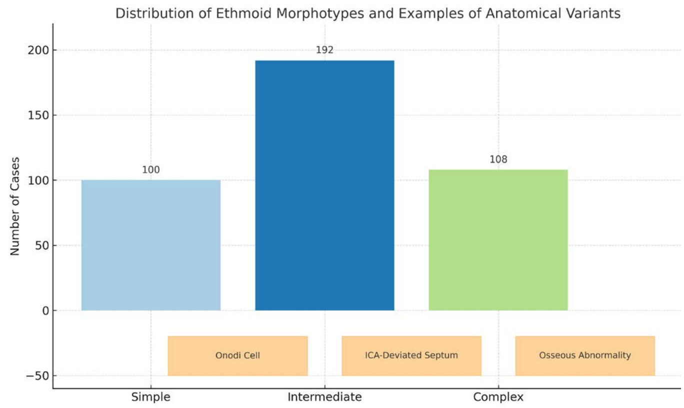


***Figure 2.*** *Visual breakdown of ethmoid morphotype distribution.*

Similarly, sphenoid septa, typically assumed to insert centrally, were found to deviate toward the ICA in 11% of cases. These septa may provide misleading visual cues during surgery and, if followed by instrumentation, could direct force into the carotid artery - a potentially fatal complication [44,45].

Both anatomical variants underline the necessity of high-resolution imaging and careful review before surgery. Image-guided navigation systems, while helpful, do not replace the need for structural awareness and individualized anatomical mapping [46].

This study's morphometric framework offers value beyond surgery. It supports:

1. Medical education by illustrating the spectrum of normal and variant anatomy.
2. Radiologic standardization through terminology and quantitative reference values.
3. Forensic anthropology via cranial-type correlation and sinus configuration.
4. Personalized medicine, where imaging guides not only diagnosis but tailored intervention strategies.

Our study has several limitations. It is retrospective and based on radiologic rather than cadaveric verification, so histological correlation (e.g., mucosal coverage of dehiscent nerves or vessels) is not available. Clinical outcomes (e.g., postoperative complications) were not assessed, and ethnic variations were not stratified, which could influence morphotype prevalence.

Additionally, the study is limited by its single-center design, which may restrict the generalizability of findings to other populations or ethnic groups. Multicentric studies are needed to validate these anatomical patterns across broader demographics and different geographic regions.

Future research should aim to correlate anatomical risk profiles with real-world surgical outcomes, expand to pediatric populations, and include multiethnic cohorts for broader generalizability.

## Conclusion.

This study highlights the significant anatomical variability of the ethmoid and sphenoid sinuses, emphasizing the importance of preoperative imaging and morphometric evaluation for safe and effective surgical planning. Our findings confirm that complex ethmoid sinus morphology increases surgical risk, particularly near the skull base and orbit. Sphenoid pneumatization patterns influence sinus volume, access to the sella, and proximity to critical neurovascular structures. Anatomical variants, including Onodi cells, deviated sphenoid septa, and bony dehiscence of the optic canal and carotid artery, are not uncommon and should be explicitly reported in imaging assessments.

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The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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