Pneumatization of Sphenoid Sinus in a South African Population: An Investigation using Computed Tomography scans

By

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A Thesis Submitted to Discipline of Clinical Anatomy, School of Laboratory Medicine and Medical Sciences, College of Health Sciences, University of KwaZulu-Natal, Durban, South Africa

In fulfilment of the requirements for the Degree of Master of Medical Science (Clinical Anatomy)

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PREFACE

This study is the author's original work, which has not been submitted to any other university. Where the work of others was used, it has been acknowledged in the text.

This research was carried out in the Discipline of Clinical Anatomy, School of Laboratory Medicine and Medical Sciences, College of Health Sciences, University of KwaZulu-Natal, Durban, South Africa, from 2022 to 2024, under the supervision of Dr C.O. Rennie, Dr E.C.S. Naidu, Prof. O.O. Azu for the award of Master of Medical Science degree (Clinical Anatomy).

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DECLARATION

I, Miss Nomthandazo Magcaba declares that:

1. The research reported in this thesis is my original work.
2. The thesis does not include other people's data, photographs, graphs, or other information unless it is clearly acknowledged as such.
3. The work described in this thesis has not been submitted to the University of KwaZulu-Natal or other tertiary institutions for purposes of obtaining an academic qualification, whether by myself or any other party.
4. My contribution to the project as primary author and principal investigator was as follows:
   - collection of data needed for literature review.
   - collection, analysis, and interpretation of data; and
   - formulation of manuscripts and compilation of the thesis
5. The contributions of others in the project were as follows:
   - Dr C.O. Rennie was the primary supervisor, helping to develop the research hypothesis and study design, assessing work before submission, and providing corrections and feedback on the submitted work.
   - Dr E.C.S. Naidu served as co-supervisor, assisting in the development of the research concept and study design, assessing all work before submission, and providing corrections and feedback on completed work.
   - Prof. O.O. Azu served as co-supervisor, assisting in the development of the research topic and study design, evaluating all work before submission, and providing corrections and feedback on finished work.

Signed: ……[redacted]…………….

ACKNOWLEDGEMENTS

The author gratefully acknowledges the following individuals and entities for their helpful assistance in preparing this master's thesis.

- I would like to express my gratitude to my siblings, Miss Sinenhlanhla Magcaba and Mr Mesuli Magcaba for their continuous support and encouragement throughout my academic journey, researching and writing.
- I would like to express my gratitude and appreciation to my supervisors, Dr C.O. Rennie, Dr E.C.S. Naidu and Prof. O.O. Azu for their guidance, expertise, support and encouragement throughout the duration of this project. I am eternally grateful,
- I would like to express my gratitude to Dr W-B.E. Mbatha for his guidance and assistance in teaching me how to analyse and read radiological images and acting as my second observer. Your assistance was very instrumental in my data collection process.
- I'd like to express my gratitude to Dr S.O. Olojede and Dr O.S. Aladeyelu for their support and mentorship through the writing of this thesis.
- Being a student at the University of KwaZulu-Natal has shaped me into an independent and goal-oriented individual. I'd like to express my gratitude to the institution and all individuals, both staff and students, who have played a role in my fantastic experience.
- I am grateful to patients whose CT scans were accessed for data gathering, as well as body donors and their families, for providing a vital resource for research.
- The National Research Foundation (NRF) provided financial support for this research. The author's opinions and findings are solely his or her own and should not be ascribed to the NRF.
- I would like to express gratitude to my friends and colleagues for their companionship and support through this journey.
- I would like to thank myself for pulling me up from my darkest thoughts and not giving up through all the personal and academic challenges faced through the course of this project.
- Lastly, I would like to thank God and my ancestors for making it all possible.

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Computed tomography	CT
Internal carotid artery	ICA
Maxillary nerve	MN
Optic nerve	ON
Sella turcica	ST
Sphenoid sinus	SS
Sphenoid sinus volume	SSV
Vidian nerve	VN

ABSTRACT

Introduction

Sphenoid air sinuses (SS) are a popular site for surgical entry when treating diseases such as intrasella and cranial base tumours. The transsphenoidal approach is more efficient and associated with lower morbidity and death compared to the standard transcranial technique. Extensive pneumatization of the SS is regarded as a prerequisite for the transsphenoidal approach. However, extensive pneumatization can endanger the optic nerve (ON) or internal carotid artery (ICA) during surgery. Understanding local anatomy is crucial for effective preoperative planning and treatment. Anatomical variations in the SS across different populations make it essential to know the anatomical details for different population groups. This study aimed to explore the pattern and extent of pneumatization, volume, and pneumatized extensions of SS in a South African population using radiological images.

Materials and Methods

This was a retrospective radiological study of an adult population (≥18 years). Computed tomography (CT) scans of 63 patients were analyzed bilaterally (n =126 SS). The sample comprised of 30 males and 33 females. The sphenoid sinus volume (SSV), pneumatization patterns, lateral extensions, posterior pneumatization and protrusion of the ON or/and ICA were assessed.

Results

The post-sella type was frequently observed (44.4%), the conchal type was the least prevalent (4%). The post-sella type was predominant in females on the left SS (58.9%). The conchal type was mainly observed in black South Africans (4.2%). The body type was frequently observed (33.3%), followed by pneumatization of greater wings of the sphenoid bone (26.7%), full lateral (23.3%) and pneumatization of pterygoid process (11.7%). Pneumatization of the lesser wing of sphenoid was least prevalent (5.0%). Statistically significant differences in different population groups were identified, with pneumatization of the greater wings of the sphenoid bone only observed in black South Africans (30.8%). The most prevalent type of posterior pneumatization was the dorsal type (60.0%). Clival type was more prevalent in Indian/White South Africans (37.5%). Subdorsal type was only observed in black South Africans.

Statistically significant differences in terms of laterality and sexual dimorphism were identified. Group 1 (no protrusion of ICA/ON) was frequently observed (54.2%), followed by group 4 (protrusion of ICA & ON) (19.2%). Group 3 was more prevalent in males (13.0%) and females accounted for only 4.5%. Females presented a higher SSV 243 (72.5-837) cm^3 and 98.5 (21.0-456) cm^3 in males ($p > 0.05$). Black South Africans presented a higher SSV compared to other South African populations.

Discussion and Conclusion

The prevalence of the different patterns of pneumatization varied within the diverse South African population, with pneumatization of the greater wings of the sphenoid bone mainly prevalent in black South Africans. Pneumatization of the clivus exhibited a higher prevalence, on the right SS, and in females as compared to other populations. Protrusion of the ON into the SS in South African patients was very low when compared to other populations. Female patients in the South African population presented with higher SSV than males, which varied from other populations. Anatomical knowledge obtained from this study can be applied in transsphenoidal surgery and in treatment of other cranial base pathologies related to SS to ensure effective preoperative evaluations and favorable postoperative outcomes.

CHAPTER 1: INTRODUCTION

1.1. Introduction

The four paired paranasal sinuses are the frontal, ethmoid, maxillary, and sphenoid sinuses, named after the bones in which they reside (Hansen, 2022). These sinuses function to relieve the weight of the facial skeleton, help to warm and humidify inspired air, contribute resonance to the voice, and drain mucus discharges into the nasal cavities (Hansen, 2022).

The sphenoid air sinuses (SS) are pneumatic cavities filled with air and lined with mucous membranes in the body of the sphenoid bone (Jaworek-Troć *et al.,* 2021). SS represents one of the most variable structures in the human body, with anatomical variations in morphology, septation, and pneumatization (Gibelli *et al*., 2020; Kang *et al*., 2022). These air sinuses are surrounded by several crucial neurovascular structures, including the internal carotid artery (ICA) and the optic nerve (ON) (Yèkpè *et al., 2018*). Emerging evidence has revealed that the greater the degree of pneumatization of the SS, the more frequently these neurovascular structures bulge into the sinus (Raseman *et al.,* 2020; Aijaz *et al.,* 2022). The pneumatization of the SS creates a dilating natural cavity that can be manipulated to access large areas of the cranial base in the treatment of cranial base pathologies (Wang *et al*., 2010b). The SS can be pneumatized to varying degrees, with its various extensions bringing it into proximity to the ON, cavernous sinus, ICA, frontal lobe, ventral surface of the brainstem, cranial nerves III to VI, and pituitary gland (Bilgir and Bayrakdar, 2021).

The pneumatization of SS varies between different population groups (Ominde *et al.,* 2021). These sinuses have significant surgical implications due to their close anatomical relation with essential neurovascular structures. In recent years, the transsphenoidal approach has been expanded for sella tumors and lesions involving other areas bordering the SS, such as the cavernous sinus, Meckel's cave, middle cranial fossa, jugum sphenoideum, suprasella region, and clivus (Lu *et al.,* 2011; Gibelli *et al.,* 2020; Fatihoglu *et al.,* 2021). The extended pneumatization of the SS (i.e. when pneumatization is beyond the body of the sphenoid bone) is a fundamental component of the extended transsphenoidal approach (Lu *et al.,* 2011).

In addition to anatomical variations of the SS, skeletal remains are some of the last features to decompose after death. Determining sex from skeletal remains has been routinely employed in biological profile reconstruction (Ramos *et al*., 2021). Studies have shown that human remains, such as fingerprints, dental morphology, cheiloscopy, and radiologic examination, play an essential role in determining sex (Ramos *et al*., 2021). Only hard tissue, such as bones, remains intact over time. The pelvis, cranium, and long bones exhibit the most apparent sexual dimorphism (Banihashem Rad *et al.,* 2023). Sex determination is accurate in cases where the skeleton is well-preserved (Uthman *et al*., 2011). However, bones, especially the pelvis and long bones, are often found in separate pieces, making sex determination difficult. Given that only the cranium is preserved in most severe events, sex determination studies based on the dimension and morphology of the cranium have increased significantly (Uthman *et al*., 2011).

Forensic studies of the morphological and dimensional characteristics of the cranium are being expanded, as only the cranium or its fragments are commonly localized in mass accidents (Ramos *et al*., 2021). This is due to its exceptional resistance to adverse environmental conditions and the passage of time. In this context, the frontal, maxillary, sphenoid, and ethmoid sinuses are structures that, in most cases, remain intact in extreme situations and can thus be used to determine sex through dimensional and volumetric characteristics (Ramos *et al*., 2021*)*. The SS is a deep cavity within the skull surrounded by various structures in the sphenoid body. As a result, it is less prone to traumas and pathological alterations (Ramos *et al.,* 2021).

Given the ample amount of variation in the anatomy of the SS, the prevalent anatomical variations in pneumatization and pneumatic extension types of the SS must be known for a specific population as they play a crucial role in the selection of surgical approach to lesions bordering the sinus. Hence, this study investigates the potential of volumetric measurements of the sphenoidal air sinuses as a tool for accurate sex determination in the study population.

1.2. Problem statement

Variations in the SS' pneumatization and dimensions can be used to determine the best surgical approach for lesions bordering the sinus, and it is for this reason that interest in the pneumatization and pneumatic extensions of the SS has grown over the years, especially with an increase in extended transsphenoidal approach and the use of endoscopy (Lu *et al*., 2011). Poor understanding of the intricate anatomy of the SS may result in complications during transsphenoidal and endoscopic surgery such as severe bleeding and blindness where the ICA and ON are involved (Anusha *et al*., 2014).

The patterns of pneumatization in the SS significantly impact safe access to the sella during surgical procedures. A highly pneumatized SS may distort the anatomic configuration (Hamid *et al.,* 2008). The degree of pneumatisation is linked with the probability of exposure of essential structures, namely the ICA, maxillary nerve, and ON into the sinuses. In addition, the pneumatisation of greater wings of the sphenoid bone increases the risk of penetration into the middle cranial fossa (Gibelli *et al.,* 2017). With the pneumatization of the SS varying between different populations, the pneumatic extensions prevalent in the South African population should be investigated, including their relationship with the protrusion of the mentioned neurovascular structures. This is essential information for pre-surgical planning.

Furthermore, the pneumatization directions act as 'windows' opening from the sinus to various areas of the cranial base. They may facilitate minimally invasive access to lesions in the corresponding areas with some anatomical basis for the extended transsphenoidal approach (Lu *et al.,* 2011). The extended transsphenoidal approach can be used in the treatment and removal of cranial base tumors such as pituitary tumors (Lu *et al*., 2011).

South Africa has a high number of unidentified bodies discovered each year. In the absence of good medical and dental records, alternative identification methods must be considered (Krüger *et al*., 2018). In South Africa, forensic anthropologists are increasingly assisting police by offering biological profiles to help determine identities. While worldwide methodologies were initially utilized, population-specificity has been demonstrated to impact the accuracy of most parameter estimations in South Africa, necessitating the re-evaluation of existing methods and the incorporation of new procedures (Krüger *et al.,* 2018). Hence, this study also investigates the use of SSV to determine sex in the South African population.

1.3. Research Questions

Does sex and population variations in the pneumatization patterns and extensions of the SS pose any challenges during endoscopic and transsphenoidal surgery? Can the volume of the SS be used for sex determination in the South African population?

1.4. Aim

This study aimed to utilize Computed Tomography (CT) images to document and measure the pneumatization, volume, and the different pneumatic extension types (lateral extensions and posterior extensions) of the SS in a South African population.

1.5. Specific objectives

The specific objectives of this study are to:

- Quantify SS pneumatization patterns and extensions (lateral and posterior extension) prevalent in adult South Africans in relation to sex and ethnicity using CT scans.
- Measure the volume of the SS for sex determination in South African individuals using CT scans.
- Quantify the prevalence of protrusion of the ON and ICA into the SS using CT scans.

1.6. Literature review

The SS vary in terms of pneumatization, protrusion of neurovascular structures and pneumatic extensions. These variations have been studied in various populations globally; however, there is still a gap in the literature focusing on the South African population.

1.6.1. Sphenoid bone anatomy

The sphenoid bone is one of the twenty-two bones that make up the skull (Drake *et al*., 2024). The name of this bone is derived from the Greek 'Sphenoeids,' which means wedge-shaped (figure 1), depicting the shape of the sphenoid bone (Jamil *et al*., 2019). The sphenoid bone lies at the centre of the skull base. Anteriorly, the sphenoid bone is anatomically related to the ethmoid and frontal bone while the occipital and temporal bones lie on it posterior aspect (Drake *et al*., 2024). The sphenoid bone lies between the ethmoid and occipital bone in the midline (Moore *et al*., 2018). The sphenoid bone connects the neurocranium and the facial skeleton (Jamil *et al.,* 2019). The body, greater and lesser wings, and the pterygoid process comprise the sphenoid bone's four main divisions. The body of the sphenoid bone lies at the midline of the bone, between two lateral greater wings of the sphenoid bone. The body has a depression called the sella turcica, in which the pituitary fossa houses the pituitary gland. The SS are also found within the body. The lesser wings arises from the anterior aspect of the body, while the pterygoid process is directed inferiorly (Jamil *et al*., 2019). When viewed anteriorly, the sphenoid's greater wings resemble bird wings, while the pterygoid projections resemble stretched limbs (Figure 1). This complex bone contains the optic canal, superior orbital fissure, foramen rotundum, foramen ovale and foramen spinosum (Chong *et al.,* 1998).

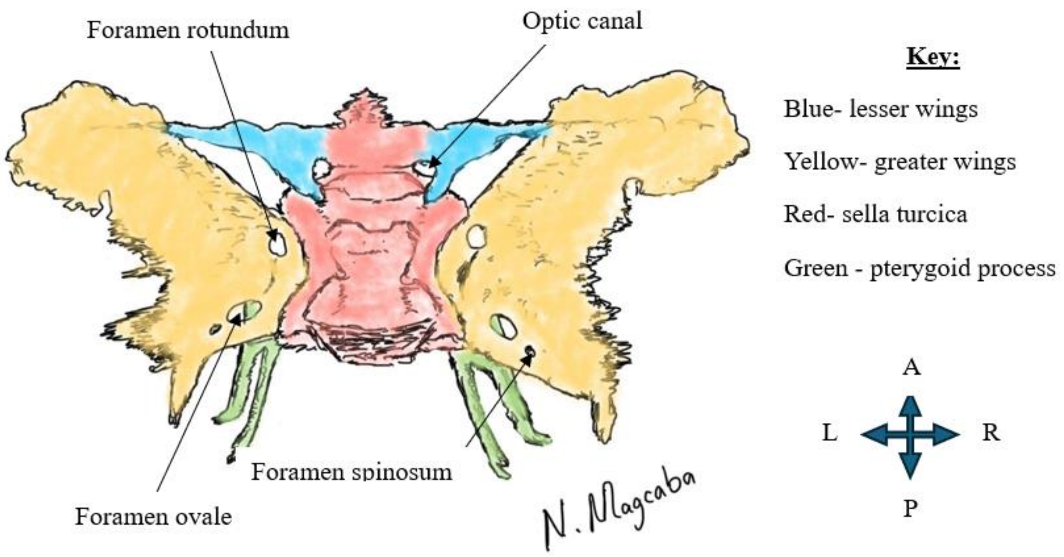

Figure 1: Diagram illustrating the sphenoid bone (adapted from Moore *et al*., 2028)

1.6.2. Development of the sphenoid sinus

Different primordia with distinct embryonic origins unite in the formation of the sphenoid bone, the basi-post-sphenoid and orbito-sphenoid from the cephalic mesoderm, and the basi-pre-sphenoid and alisphenoid of neural crest origin (Jamil and Callahan, 2019). The presphenoid and postsphenoid centers, along with the orbito-sphenoid's medial crus, form the body of the sphenoid bone. The orbito-sphenoid gives rise to the lesser wings, whereas the alisphenoid, which is more prominent, gives rise to the greater wings (Kodama, 1976). The sphenoid bone is one of the complex structures in the body. Up to fifteen different intramembranous and endochondral centers form the sphenoid bone, with a significant part of the bone derived from the endochondral bone formation (greater wings of the sphenoid bone) and lateral pterygoid plates from intramembranous ossification (Kuta and Laine, 1993). Two paired ossification centers, the sphenoidal conchae, can be seen next to the vomer. They enclose the basisphenoid's unossified rostrum. The sphenoid bone will first become pneumatized at this location (Budu *et al.,* 2013).

There are four stages in the development of the SS, which start in the third or fourth month of intrauterine life (Vidic and Stom, 1968; Özer *et al.*, 2018b). At stage 1, the SS can be identified in the cartilaginous cupola recess of the nasal cavity; in its second stage of development, it can be seen in the bony cupola recess of the nasal cavity with pneumatization of the bony cupola recess only beginning at the 3rd stage of development (Vidic and Stom, 1968). The first three stages of development are completed before the end of the fourth postnatal year (Scuderi *et al.,* 1993). Stage 4 of development is marked by the pneumatization of the body of the sphenoid bone till the sphenoid sinus reaches it full shape and size; this occurs typically occur till late adolescence or early adulthood (Wang *et al*., 2010a)

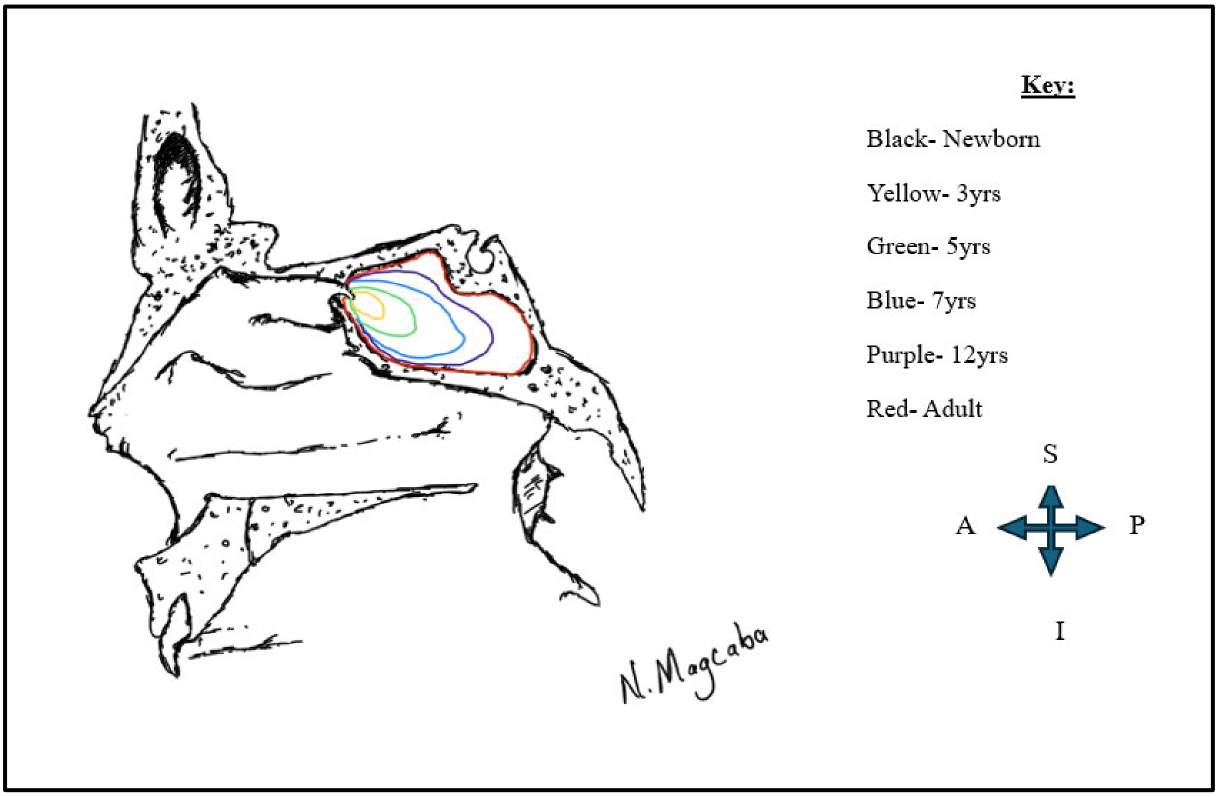

Figure 2: Sagittal diagram showing morphologic changes that occur from birth to maturity during development of the SS (adapted from Scuderi *et al*., 1993)

At birth, the sphenoid bone consists of red marrow and is not pneumatized. Between seven months and two years of age, the conversion of red marrow to yellow marrow begins at the presphenoid plates and extends posteriorly into the basisphenoid plates (Scuderi *et al.,* 1993). Pneumatization of the SS then begins in an inferior posterolateral direction, with the sinus attaining its maturity by fourteen years (Figure 2). Some authors reported that the SS achieved adult size at the age of 18/ in late adolescence (Lee *et al.*, 2012; Wang *et al.*, 2010a). The sphenoidal sinus has varying degrees of pneumatization (Scuderi *et al.,* 1993), and structural distortion could result from a severely pneumatized SS (Anusha *et al.,* 2014).

1.6.3. Anatomy of the Sphenoid Sinus

The sphenoid sinuses are located in the body of the sphenoid, right below the sella turcica. They open into the sphenoethmoidal recess via the anterior wall (Gosling *et al.*, 2017). The superior wall of the sinus connects to the roof of the ethmoid sinus and is located on the anterior and middle floors of the skull base. It has direct contact with the olfactory nerves, optic chiasm, and hypophysis (Budu *et al.,* 2013; Moore *et al.*, 2018). The anterior wall attaches to the perpendicular plate of ethmoid bone and vomer at the midline. Highly developed Onodi or ethmoidosphenoidal cells can break down this wall (Onodi, 1910). Onodi cells, according to Onodi (1910) are the most posterior ethmoid air cells that extend superolateral to the SS and are near the ON (Onodi, 1910; Ali *et al.*, 2020). Unrecognized Onodi cells can cause severe optic nerve injury when present during sinus surgery (Ali *et al.,* 2020). The SS is related to the choana inferiorly, the pituitary fossa and planum sphenoidale superiorly, and the cavernous sinus laterally (Famurewa *et al.,* 2018; Moore *et al.*, 2018). The sphenoid sinus vary significantly in size, shape, and relationship to the sella turcica. The structure is typically divided by asymmetrical vertical septa (Sareen *et al.*, 2005; Lazaridis *et al.,* 2010; Moore *et al.*, 2018). The septa are typically long, thin, flat bone layers that partition the SS into compartments (Fernandez-Miranda *et al.*, 2009) (Figure 3). There are two types of septa: intersinus septa, which separate two or more sinuses, and intrasinus septa, which are found within a single sinus (Drake *et al.,* 2024). The sinus septum may be missing, numerous, or partially present (Famurewa *et al.,* 2018).

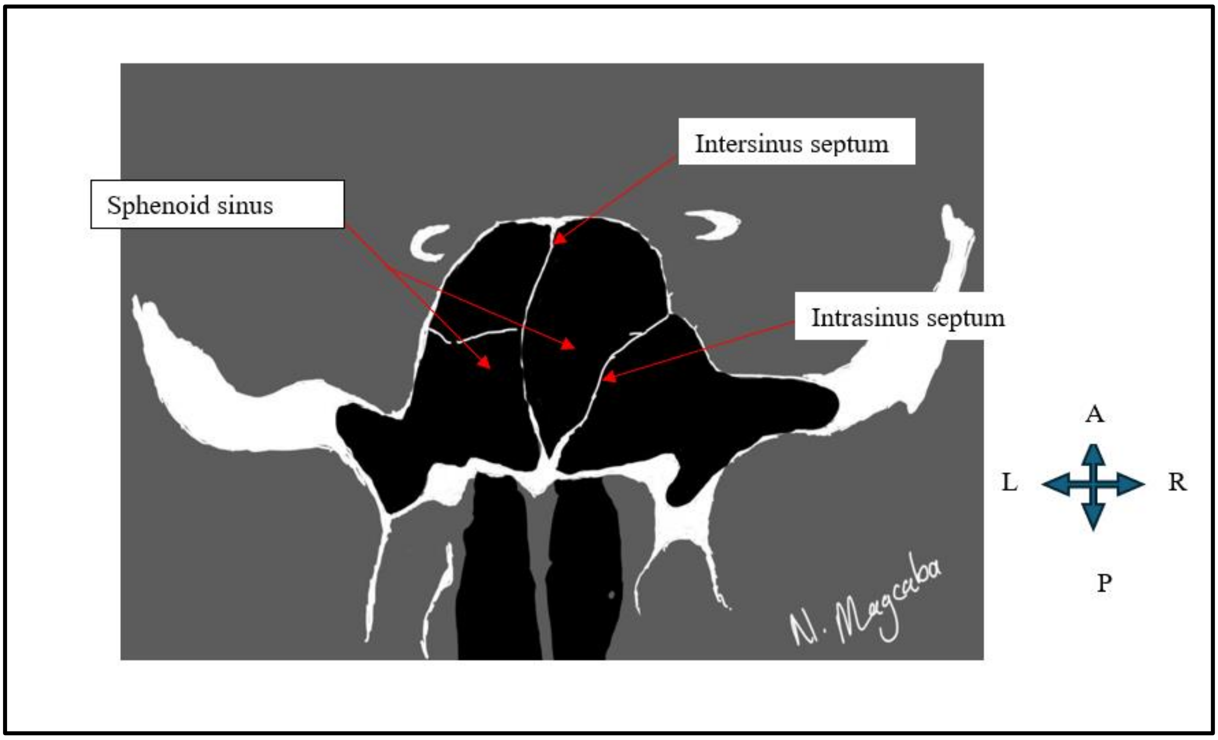

Figure 3: Axial diagram illustrating the SS septum (adapted from Lalchan *et al*., 2021)

The right and left SS (Figure 3) are often asymmetrical and located in the sphenoid bone above the nasal cavity, with each sinus draining anteriorly into the sphenoethmoidal recess (Kumar *et al*., 2019).

1.6.4. Sphenoid Sinus pneumatization

"Pneumatization" describes the development or existence of air-filled spaces in a bone (Moore *et al.,* 2018). The SS are pneumatized in varying degrees. The walls of the SS reflect its anatomical relationships (Figure 4). Adjacent structures, which existed before the sinus developed, cause abnormalities in the sinus walls when the cavity expands to meet and pass beyond them (Van Alyea, 1941).

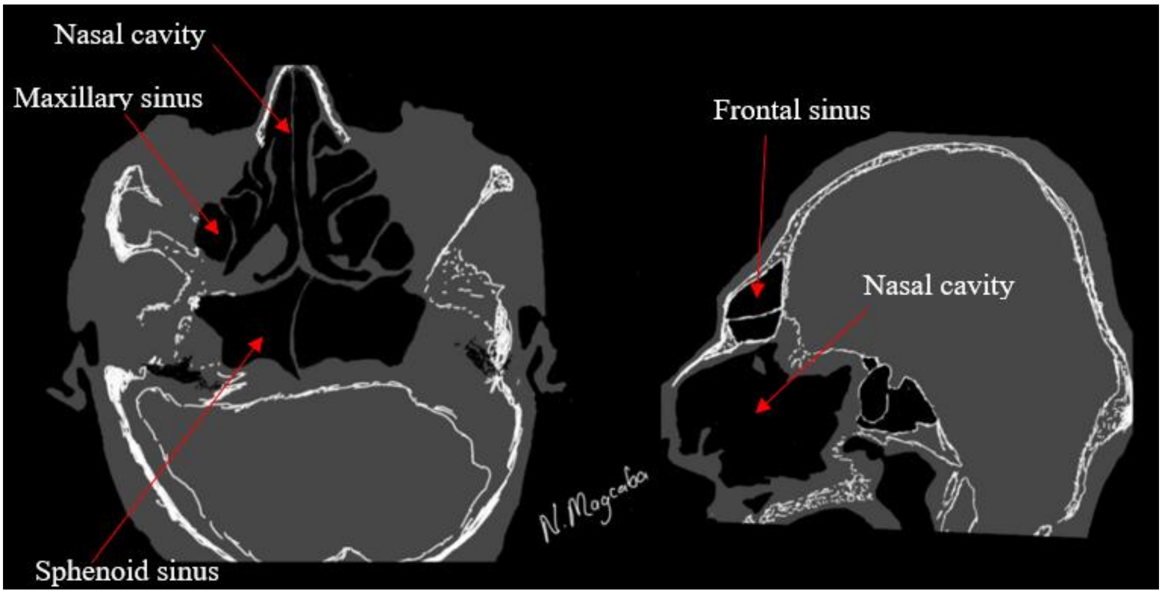

Figure 4: Axial and sagittal scan diagram illustrating the paranasal air sinuses adapted from (Souadih *et al*., 2020)

The SS has been categorized into distinct main types based on its posterior limits and relation to the sella turcica (Cope, 1917; Hammer and Radberg, 1961). However, the most popular form of classification is the Hammer and Radberg method. Hammer and Radberg classified the SS into three types: conchal, pre-sella, and sella. The terms 'pre-sella' and 'sella' refer to presphenoid and postsphenoid types (Cope, 1917), respectively, to clarify the relationship between the sinus and the sella turcica (Cope, 1917; Hammer and Radberg, 1961) (Figure 5).

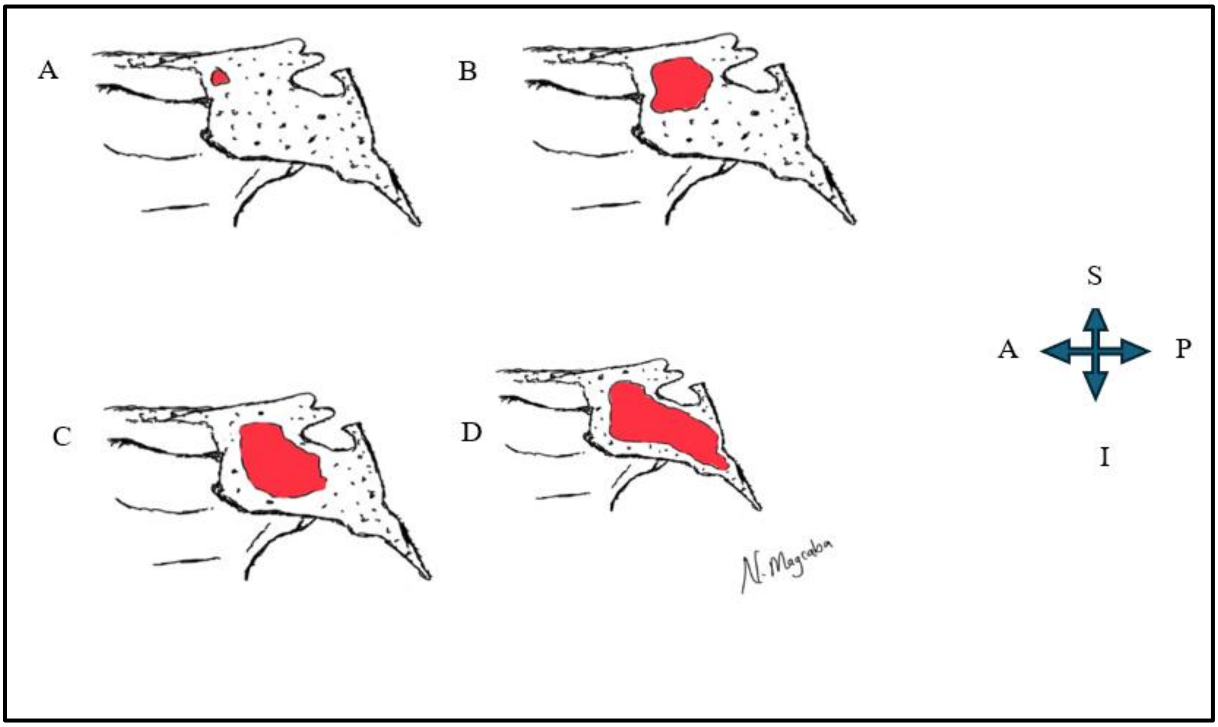

Figure 5: Illustration of different types of SS (adapted from Kayalioglu *et al*., 2005)

Key: A = conchal type, B = pre-sella type, C = sella type, D = post-sella type

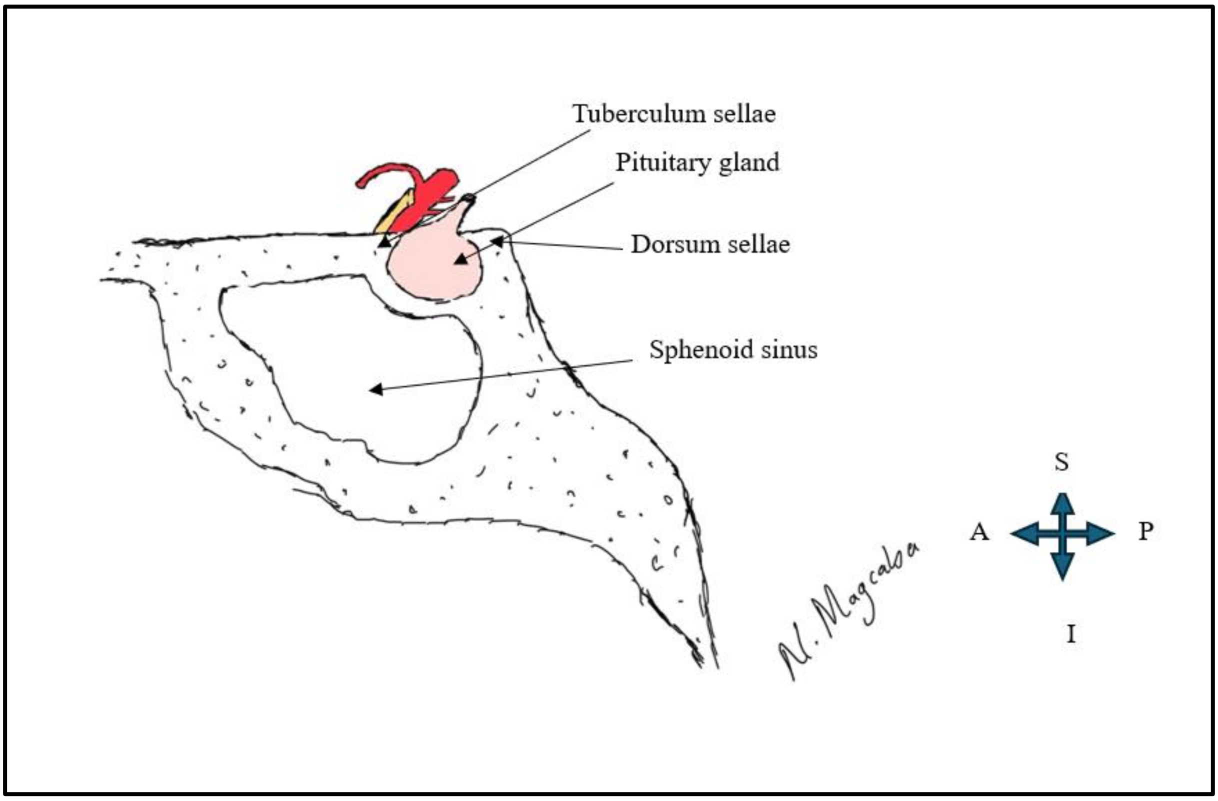

Figure 6: Sagittal diagram illustrating the tuberculum sellae and dorsum sellae of the sella turcica (adapted from Wang *et al*., 2010a)

The conchal type, also known as the fetal type, is a tiny sinus separated from the sella turcica by around 10 millimeters of trabecular bone (Hammer and Radberg, 1961). In the pre-sella type, pneumatization of the SS does not extend posteriorly to the anterior limit of the sella turcica (Figure 6). In this form, the intersinusal septum runs in the sagittal plane with no significant deviations to either side. The pneumatization is not symmetrical, with one sphenoidal sinus slightly larger than the other, even if both are pre-sella (Hammer and Radberg, 1961). In the sella type, the SS is pneumatized to the level of the sella turcica (Lalchan *et al.,* 2021). In this form, the anterior wall and floor of the sella turcica protrude into the sphenoidal cells. Typically, the front wall of the sella turcica is fragile and lacks spongy bone (Hammer and Radberg, 1961).

In some cases, both a pre-sella and a sella type may be present, with pneumatization progressing on one side and negatively impacting the contralateral sinus. The sella type is the most common type of SS (Hammer and Radberg, 1961). Banna and Olutola (1983) described a SS that is over-pneumatized as post-sella (occipito-sphenoid). Post-sella pneumatization occurs when the posterior boundary of SS extends beyond the dorsum sellae and even across the occipital synchondrosis (Banna and Olutola, 1983; Kayalioglu *et al*., 2005).

However, the pneumatization of the SS is not limited to these three classifications, it can range from non-existent to extensive, occasionally extending into the clivus, vomer, palatine, and occipital bones as well as the anterior clinoid process, pterygoid process, sphenoid greater wings, and clivus. It can also extend laterally between the maxillary nerve and the nerve of the pterygoid canal (Cellina *et al.,* 2020) (Figure 7). Wang *et al.* (2010) further introduced a new classification method focusing on the sella/post-sella type as a guide to surgical approaches extending beyond the sinus (Wang *et al*., 2010). Wang *et al*. (2010) studied the relationship of the SS to the lateral walls and recess and formulated classifications in relation to the VR line (Lalchan *et al.,* 2021). The VR line was defined as a line connecting the medial borders of the anterior aperture of the vidian canal to the extracranial end of the foramen rotundum (Figure 7). The VR line separates the sphenoid body from the lateral sections of the bone, which include the greater wings of the sphenoid bone and pterygoid process (Wang *et al.,* 2010).

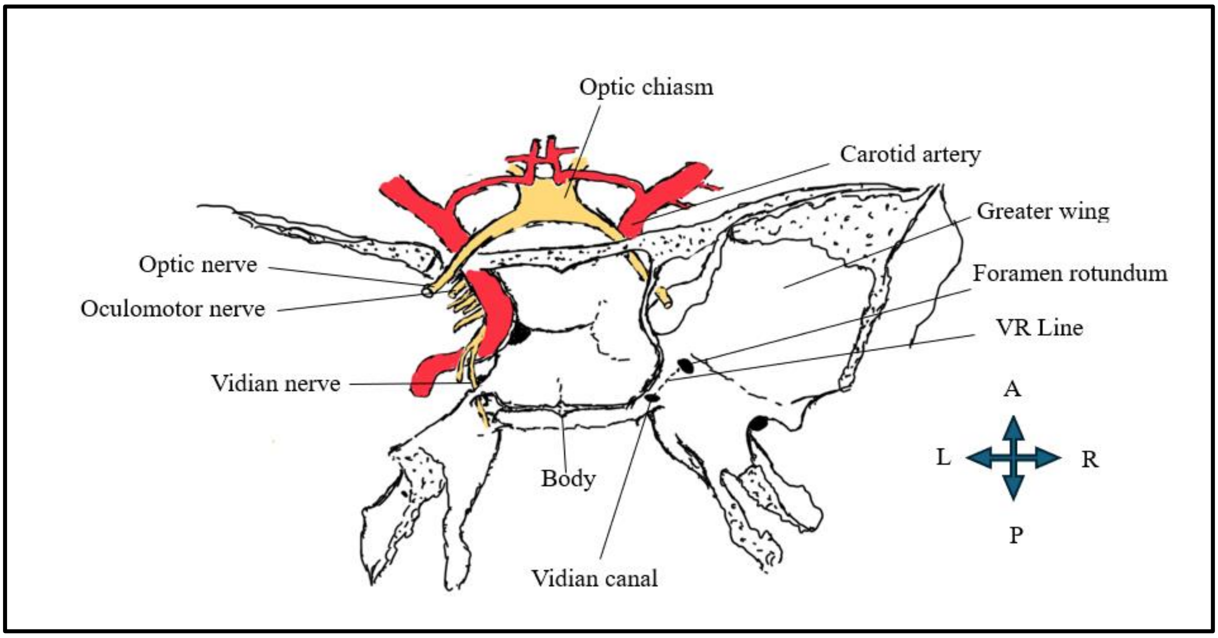

Figure 7: Diagram illustrating body type of SS and surrounding neurovascular structures forming prominences and recess inside the sinus due to extensive pneumatization (adapted from Wang *et al*., 2010a)

In the sphenoid body type of sinus, the lateral wall overlaps with the medial wall of the cavernous sinus but does not extend beyond the VR line (Wang *et al*., 2010). When pneumatization extended beyond the VR line and beyond the sphenoid body into the greater wings of the sphenoid bone and/ pterygoid process it was classified as a lateral type of sinus. The lateral recess can extend into the greater wings of the sphenoid bone, pterygoid process, or both. It is classified as a greater wing type if it just extends into the greater wings of the sphenoid bone, a pterygoid type if it only extends into the pterygoid process, or a full lateral type if it extends into both the greater wings of the sphenoid bone and the pterygoid (Wang *et al.*, 2010; Lalchan *et al.,* 2021) (Figure 8).

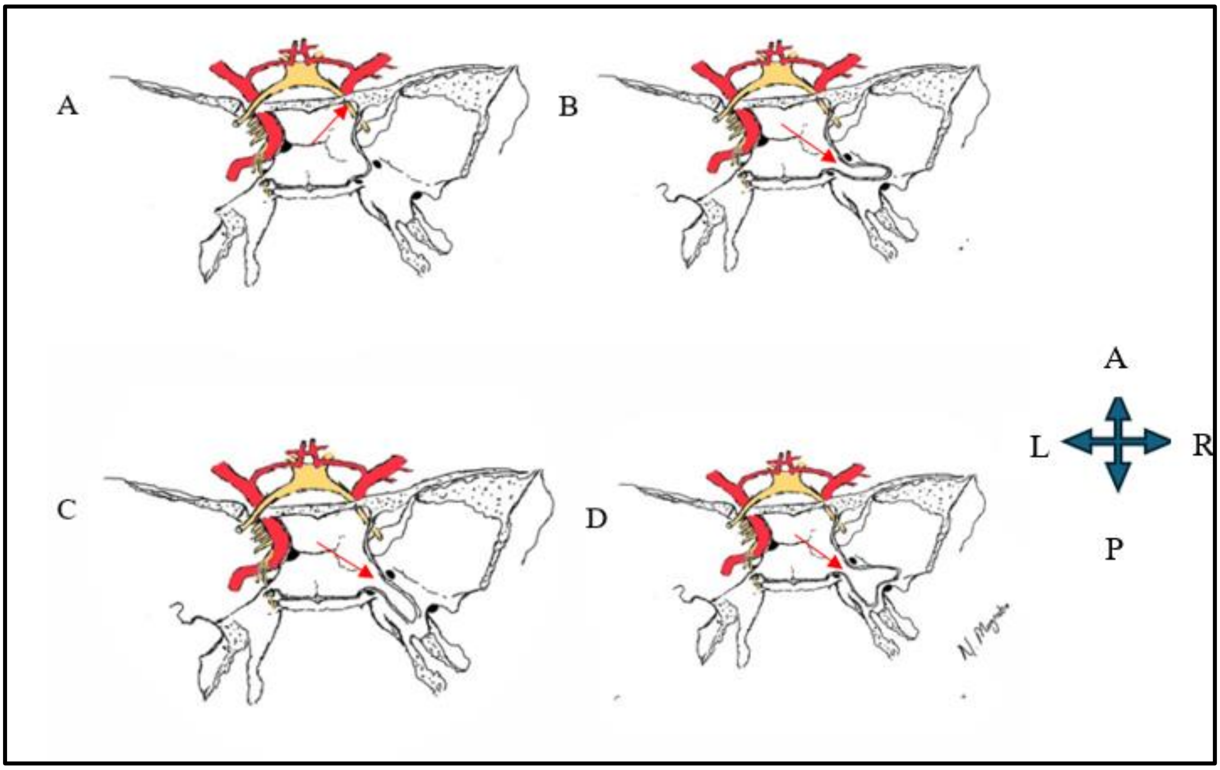

Figure 8: Diagram showing the lateral extensions / lateral recess (adapted from Wang *et al*., 2010a)

Key: A = lesser wing type, B = greater wing type, C = pterygoid type, D = full lateral type

Wang *et al.* (2010) also examined the pneumatization of the SS in relation to the posterior wall of the sinus (posterior extensions), which connects the dorsum sellae and basilar section of the occipital bone with the pituitary fossa. Pneumatization extending beyond the posterior wall of the sinus or beyond the vertical coronal plane of the pituitary fossa was classified as clival type of SS. Even if only half of a sinus was clival, it may still be categorized as such (Wang *et al.,* 2010). There are three types of clival recess introduced by Wang *et al.* (2010) (Figure 9): the dorsum type of SS, which extends above the pituitary floor and into the dorsum sellae; subdorsum type of SS, which lies between the pituitary floor and the horizontal plane passing through the anterior opening of vidian canals; and occipital type of SS, which extends inferiorly below the horizontal plane crossing the anterior opening of the paired vidian canal (Wang *et al.,* 2010).

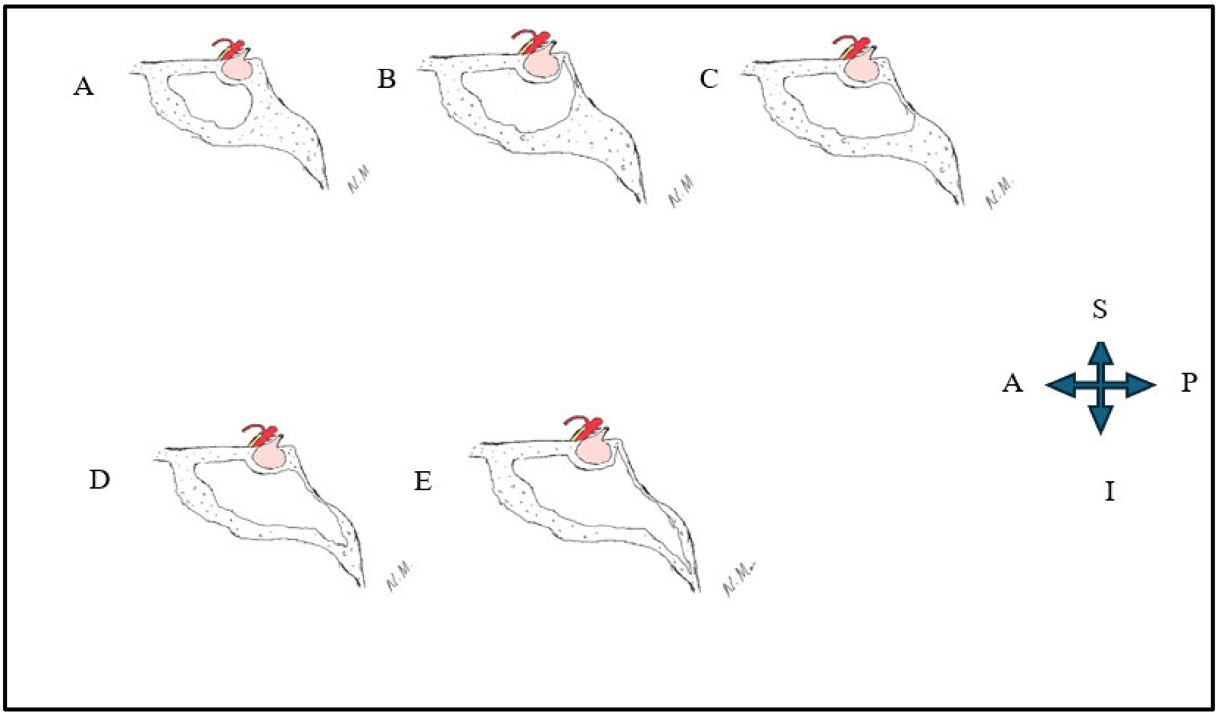

Figure 9: Diagram showing posterior pneumatization / clival recess (adapted from Wang *et al*., 2010a)

Key: A = body type with no posterior pneumatization, B = subdorsum type, C = occipital type, D = clival type, E = dorsum type

The pneumatization patterns of the SS have proven to vary between different population groups (Table 1, 2 and 3). Authors have documented patterns observed in different population groups globally, and sella and post-sella type of SS are observed to be the most common type of SS. Prevalence of the pre-sella and conchal type is however significantly variable across different populations globally (Table 1). Extensions of the SS, both laterally and posteriorly have been explored in literature (Table 2 and Table 3) and there is a great deal of variability between different population groups.

Table 1: Incidence (%) of the types of SS in different populations

Study	Population	Sample size	Conchal type	Pre-sella type	Sella type	Methodology
Lu *et al.* (2011)	Chinese	200	6	28.5	65.5	CT
Özer *et al.* (2018a)	Turkish	144	1.4	8.3	23.6	CT
Degaga *et al*. (2020)	Ethiopian	200	2	25.5	50	CT
Andrianakis *et al.* (2020)	Australian	50	1	22	77	Cadaveric study
Ominde *et al*. (2021)	Nigerian	336	8.3	19.3	53.9	CT
Treviño-Gonzalez *et al*. (2021)	Hispanic	160	0	27.3	45.3	CT
Sagar *et al*. (2023)	Indian	114	5.2	26.3	68.4	CT

Table 2: Incidence of the SS lateral extensions in different populations (%)

Study	Population	Sphenoid body	Lesser wing	Greater wing	Pterygoid process	Full lateral	Methodology
Lu *et al.* (2011)	Chinese	–	0.8	_	22.3	11.4	CT
Özer *et al.* (2018a)	Turkish	32.6	16.66	6.94	9.02	34.72	CT
Degaga *et al.* (2020)	Ethiopian	_	_	16.5	15	_	CT
Andrianakis *et al.* (2020)	Australian	24	0	_	_	11	Cadaveric
Ominde *et al.* (2021)	Nigerian	_	_	17.9	42	_	CT
Treviño-Gonzalez *et al.* (2021)	Hispanic	_	_	57.5	26.7	_	CT
Sagar *et al.* (2023)	Indian	_	_	12.3	23.6	_	CT

Table 3: Incidence of posterior extensions of the SS in different populations (%)

Study	Population	Subdorsal	Dorsal	Occipital	Clival	Methodology
Lu *et al.* (2011)	Chinese	_	_	_	_	CT
Özer *et al.* (2018a)	Turkish	_	_	_	_	CT
Degaga *et al.*(2020)	Ethopian	_	_	_	_	CT
Andrianakis *et al.*(2020)	Australian	_	_	_	19	Cadaveric
Ominde *et al.* (2021)	Nigerian	7.4	5.4	1.0	_	CT
Treviño-Gonzalez *et al.* (2021)	Hispanic	_	_	_	_	CT
Sagar *et al.* (2023)	Indian	_	_	_	_	CT

Lu *et al.* (2011) investigated the extended pneumatization of the SS, both lateral and posterior pneumatization types in Chinese individuals, and differences from those in Caucasians. They analyzed these differences with respect to the application of the extended transsphenoidal approach. In their population, the conchal, pre-sella, and sella types comprised 6%, 28.5%, and 65.5% of subjects, respectively. According to the extra extension, the prevalence of the lateral, clival, lesser wing, and combined extension sinus types was 11.4%, 21.4%, 0.8% and 48.1% of subjects, respectively. The percentages of pneumatization of the anterior and posterior clinoid process, pterygoid process, and optic strut were 5.0%, 1.0%, 22.3%, and 7.0%, respectively. Onodi cells, posterior ethmoidal cells that lie superior to the SS, were observed in 61.1% of the sides of the cadaveric heads, including 30.6% with good pneumatization with identifiable optical or ICA bulges. These variations were related to poor lateral and clival pneumatization in Chinese compared with Caucasians, which might make extended surgery more dangerous. However, the anterior pneumatization, especially the higher presentation of

Onodi cells, ensures that the anterior extended transsphenoidal approach can be performed safely in Chinese patients. In general, measurements showing smaller sinus volumes and thicker bones in Chinese compared with those in Caucasians suggest increased surgical risks in the Chinese population (Lu *et al.,* 2011).

Pneumatization of the SS in Turkish individuals has been reported (Özer *et al.*, 2018a), in which the majority of the population was reported to have the post-sella type of pneumatization (66%). The majority of sella-type sinuses were identified as body type (38.2%), and no greater wing type was encountered in the sella type of SS. The full lateral type of sinus was found to be the most prevalent subtype of pneumatic extension, and the greater wing type was reported to be the least common subtype (6.9%) (Özer *et al*., 2018a). They further concluded that the SS is highly variable, making a thorough preoperative evaluation for surgery in this area necessary to enable secure access via the sinus to various target locations.

Ominde *et al.* (2021) also conducted a retrospective study in Nigeria; brain CT images of 336 patients (137 females,199 males) aged ≥20 years were studied for the variant pneumatization patterns of the SS. A Chi-square test was used to assess the association of the variants with sex and laterality. The findings were as follows: the predominant pneumatization pattern in relation to the sella turcica was the sella type 181 (53.9%), followed by the pre-sella type 65 (19.3%), post-sella 62 (18.5%), and lastly the conchal type 28 (8.3%). The most prevalent clival recess was the subdorsal type 25 (7.4%), followed by the dorsal 18 (5.4%), combined 7(2.1%), and lastly, occipital 3 (0.9%). The frequency of the pneumatized anterior clinoid process, greater wing of the sphenoid, and the pterygoid process were 76 (22.6%), 60 (17.9%), and 141 (42%), respectively, and these showed significant side differences (p=0.001). The pneumatization patterns in their study varied from the findings in previous Nigerian studies and other populations. There is, therefore, the need for preoperative evaluation before endoscopic transsphenoidal surgical procedures (Ominde *et al*., 2021).

Sagar *et al. (*2023) investigated the variations of the SS and pneumatization of adjacent structures in the Indian population. In 71 (62.2%) cases, one or more nearby structures were pneumatized. The surrounding structures that were found to be pneumatized were the greater wings of the sphenoid in 12.3% of cases, the pterygoid process in 23.6%, and the anterior clinoid process in 26.3% of cases (Sagar *et al.,* 2023). They concluded that in their study population, in terms of the pneumatization of the SS' right and left sides, there was no statistically significant difference. Regarding sinus conditions, sella and central skull base lesions, the degree of pneumatization of the SS has clinical and surgical ramifications (Sagar *et al.,* 2023). The variability in SS pneumatization is evident in the literature (Lu *et al*., 2011; Özer et al., 2018; Degaga *et al*., 2020; Ominde *et al*., 2021; Treviño-Gonzalez *et al.,* 2021; Sagar *et al.,* 2023).

Although some authors (Rennie *et al.,* 2017*;* Ngubane *et al.,* 2018) have studied the morphology of the SS in the South African population, none have gone so far as to study the incidence of the SS subtypes, common pneumatized extensions, and volume of the SS with a focus on adult South Africans. This study aims to close that gap in the body of knowledge. Rennie *et al*. (2017) used 480 patient CTs to show the three-dimensional (3D) morphology of the sphenoid air sinus from ages one to 25 years in a South African population, observing the frequency of SS characteristics such as presence, shape, and septa. The sphenoid air sinus was present in (442/480) 92.1% on the right and (441/480) 91.9% on the left side. The sphenoid air sinus was absent in 7.9% and 8.1% of cases on the right and left sides, respectively. The anterior/coronal view revealed six distinct forms. Overall, the most common shape observed in the anterior view was quadrilateral on the right (n=243; 50.6%) and left (n=238; 49.6%). There was no correlation between the anterior form and sex or population group. Furthermore, three lateral variants were documented, namely, sella, pre-sella, and conchal types. The predominant form was sella type on both sides (45.2% R; 49% L). Laterally, there was a connection between form and sex on the left side exclusively, as well as between population groups ($p<0.05$). Intersinus septa were seen in 90.2% of cases and were primarily concentrated in the center in 55.4%. A maximum of seven partial intrasinus septa were found. A detailed investigation and classification of the three-dimensional morphology of the sphenoid air sinus based on age 1-25 years was described.

Ngubane *et al*. (2018) also investigated the SS in the South African population, mainly focusing on the septation of the sinuses. Forty-five adult cadaveric material were utilized, consisting of 39 South African white and 6 Black population groups. The sphenoidal sinus intersinus septa were recorded as follows: Type 0 (absent septum) in 7.5%, Type 1 (single septum) in 65% and Type two (double septa) in 22.5% of cases. Intersinus septa deviating to the left was prevalent; hence, the right sphenoidal sinus was dominant. The occurrence of intrasinus septa was observed in 93.3 % of cases, with a higher prevalence in males. The intrasinus septa formed cave-like chambers on the sinus walls in 65.6% of cases. Incidences of the intersinus septa attaching to sella turcica (ST) (46.25%) were prevalent compared to cases where they attached to the internal carotid artery (ICA) (6.25%), maxillary (MN) (1.25%) and vidian (VN) (1.25%) nerves. However, the intrasinus septa attached more to the ICA (52.63%) compared to their attachment to the other neurovascular structures (ST – 26.32%; MN – 5.36% and VN – 2.63%).

1.6.5. Protrusion of the Optic Nerve and Internal Carotid Artery

The SS is closely related to nearby structures, such as the optic nerve (ON) and internal carotid artery (ICA), the maxillary nerve with the greater wings of the sphenoid bone, and the vidian nerve and artery with the pterygoid process (Sagar *et al.,* 2023*)*. SS pneumatization varies widely, ranging from minimal pneumatization to pneumatization up to clivus *(*Treviño-Gonzalez *et al.,* 2021). With extensive pneumatization, the adjacent anatomical structures, such as the anterior clinoid process and the greater wings of the sphenoid bone and pterygoid process, can be pneumatized (Gibelli *et al*., 2019). The SS can cause pneumatization in the anterior clinoid process. When present, this pneumatization might intrude on the ON (Budu *et al.,* 2013) (Figure 10).

Figure 10: Coronal CT scan diagram illustrating pneumatization of anterior clinoid process and protrusion of the ON (indicated by the red arrow) (adapted from Budu *et al*., 2013)

The ICA is the most medial structure in the cavernous sinus and is directly connected to the lateral wall of the SS. Depending on the sphenoid's pneumatization, the ICA impression can be minimal or prominent. The ICA bulges into the SS in 34-93% of instances, with noticeable differences between different population groups (Budu *et al*., 2013). In some situations, the thin bone covering the ICA dehisces, exposing it to the sinus cavity.

The increase in transsphenoidal procedures over the years has brought attention to the anatomy of SS (Wang *et al.,* 2010*;* Gibelli *et al.,* 2019). The SS becomes the best surgical entry for treating various diseases, including intrasella and cranial base tumors. A common risk in these procedures is damage to the ON or ICA, which may protrude into the sinus (Gibelli *et al.,* 2019). Endoscopic sinus surgery may result in an unfavorable consequence that could cause blindness, particularly when the SS is involved (Anusha *et al.,* 2014). In the majority of investigations, protrusion of the ON was defined as an expansion of the optic canal into the SS cavity that exposed more than half of the nerve's circumference, with or without bony boundary abnormalities (Dessi *et al.,* 1994 ; Unal *et al.,* 2006). Unal *et al.* (2006) reported a rate of 31% for ON protrusion into the SS in Turkish patients, which is the same as one in three cases; however, Tan *et al*. (2007) found that the Asian equivalents had an incredibly high proportion of 69% ON protrusion. The prevalence of ICA and ON protrusion varies significantly between different populations globally (Table 4).

Table 4: Protrusion of the ON and ICA

Study	Population	ON (%)	ICA (%)	Methodology	Sample size
Unal *et al.* (2006)	Turkish	31	30.3	CT	66
Tan *et al.* (2007)	Asian	69	67	Cadaveric material	48
Araujo *et al.* (2008)	Brazilian	36,9	48.8	Cadaveric material	45
Tomovic *et al.* (2013)	African American	24.6	24.6	CT	170
Lupascu *et al.* (2014)	Romanian	65	57	CT	200

The risk of damage during surgery is higher for an ICA that is protruding protruding into the SS with possibility of dehiscence should it be bumped; a damaged artery would cause significant bleeding, making it difficult to do surgery *(*Anusha *et al.,* 2014*)*. Operating in such a scenario would be challenging, and finding and securing the bleeder would be strenuous. Protrusion of the ICA has been defined as the presence of more than half of the vessel's diameter within the SS (Unal *et al.,* 2006*)*. Tan *et al.* (2007) reported that the protrusion of ICA in Asian patients was at 67%, which was high compared to Unal's 30.3% in Turkish patients (Unal *et al.,* 2006). Studies conducted on Asian patients generally report a higher rate of ICA protrusion than those conducted on Turkish individuals. This highlights the variation that exists between different and local populations.

Gibelli *et al.* (2017) studied the SSV in relation to the protrusion of the ICA and classified the subjects into four groups: no protrusion of any structure (group 1), protrusion of ICA (group 2), protrusion of ON (group 3), protrusion of both ICA and ON (group 4). In their population sample, group 1 was the most frequent (40.0%), followed by group 4 (27.7%) and group 2 (18.5%), without any difference according to sex. Cases of ICA and concomitant ICA + ON protrusion had significantly larger sinuses, whereas isolated ON protrusion did not modify sinus volume. Variations in SS pneumatization and protrusion of ICA and ON have been reported in the literature. The fact that these anatomical variations differ depending on the patients' population group is one similarity between these investigations (Anusha *et al.,* 2014).

1.6.6. Sphenoid Sinus volume

Despite significant advances in numerous diagnostic tools, identifying human skeletal and decaying components remains one of the most challenging tasks in forensic medicine. Because human bones are the last to degrade in the postmortem era (followed by tooth enamel), skeletal remains have long been used to estimate sex (Sherif *et al*., 2017). Sex estimate is a critical component in developing a biological profile (Sherif *et al*., 2017). Precise sex assessment of the human remains quickly excludes half of the population during identification (Simpson and Byard, 2008; Jasim and Al-Taei, 2013). Bone sex determination is based on morphological and morphometric factors (Sherif *et al*., 2017). The combination of both elements typically produces the most accurate results (Sherif *et al*., 2017). The skull, along with the pelvis, is the most easily sexed part of the human skeleton. In a colossal disaster, the skull and other bones are found to be extensively broken or incomplete. As a result, multiple parameters must be gathered from a single bone (Kanchan and Krishan, 2011). In this regard, the frontal, maxillary, sphenoid, and ethmoid sinuses are structures that, in most cases, survive harsh conditions and can thus be used as alternative method in the determination of sex (Wanzeler *et al.,* 2019; Ramos *et al.,* 2021; Rad *et al.,* 2023).

Radiological sex determination plays a vital role in forensic medicine. Computerized Tomography (CT) is regarded as an outstanding imaging technology and is the modality of choice for the examination of paranasal sinuses and craniofacial bones, where exact measurement of paranasal sinuses dimensions can be obtained (Carvalho *et al.,* 2009; Sahlstrand-Johnson *et al*., 2011). Various authors have investigated the dimensions of the paranasal air sinuses with regards to sex determination, in which males commonly demonstrated greater length and volume for all paranasal air sinuses compared to females (Sahlstrand-Johnson *et al.,* 2011; Jasim and Al-Taei, 2013; Sherif *et al.,* 2017). Table 5 compares the various studies that have utilised SSV to determine sex. However, there is limited data on the SS related to sex determination, with no documentation on the South African adult population.

Table 5: Sphenoid sinus volume in adults

Authors	Population	Volume in males	Volume in females	Methodology
Karakas and Kavakli (2005)	Turkish	$8.53 \pm 4.19cm^3$	$7.88 \pm 2.99cm^3$	CT
Emirzeoglu *et al.* (2007)	Turkish	$1.50\text{-}18.60cm^3$	$0.30\text{-}20.30cm^3$	CT
Gibelli *et al.* (2018)	Italian	$10.01 \pm 5.10cm^3$	$7.92 \pm 3.18cm^3$	CT
Andrianakis *et al.* (2020)	Australian	$5.27 \pm 2.49cm^3$	$4.32 \pm 2.22cm^3$	Cadaveric
Ramos *et al.* (2021)	Brazilian	$11.36 \pm 4.29mm^3$	$7.48 \pm 2.33mm^3$	CT
Banihashem Rad *et al.* (2023)	Iranian	$14.12 \pm 4.11cm^3$	$7.48 \pm 2.33cm^3$	CBCT
Tuang *et al.* (2023)	South Asian	10.19 (3.75-18.72) cm^3	12.22 (4.93-21.09) cm^3	CT

Banihashem Rad *et al.* (2023) evaluated the validity of the SS in sex determination in the Iranian population; the most common morphology of the SS in both sexes was the sella type (50.5%). SSV was significantly larger in males than in females ($p< 0.001$). Discriminant function analysis showed that the capability of SSV in sex identification was 86.0% and 92.9% in males and females, respectively. Ramos *et al.* (2021) also reported that the SSV was significantly larger in males compared to females in the Brazilian population; they concluded that the SSV could be used for sex determination in his study population. However, Oliveira *et al.* (2017) found no statistically significant sex-related variations in the volume of SS in their study population ($p>0.05$), similar to Nejaim *et al.* (2019) ($p = 0.0923$).

Tuang *et al.* (2023) investigated the volume of the SS among different populations in the South Asian population; they reported that the males' total SSV was found to be larger than the females', measuring 12.22 (4.93 - 21.09) cm^3 as opposed to 10.19 (3.75 - 18.72) cm^3 ($p =0.0090$). In comparison to the Malays population, who had a larger overall SSV of 10.68 (4.13 - 19.25) cm^3, the Chinese population had a volume of 12.96 (4.62 - 22.21) cm^3 ($p =0.0057$). They further concluded that the SS volumetric analysis may be used to determine a person's sex and ethnicity.

1.7. Justification

1.7.1. Clinical significance

The SS is thought to be the most variable cavity in the human body, and it is crucial for achieving the best possible surgical access to the pituitary gland (Štoković *et al.,* 2016*)*. First used in 1907, transsphenoidal surgery is now a widely used method for treating intrasella lesions *(*Perondi *et al.,* 2013*)*. Transsphenoidal means "through the sphenoid." It refers to a surgical procedure or approach that allows surgeons to access the pituitary gland or other structures at the base of the skull by going through the SS (Wang *et al*., 2010a). The transsphenoidal technique is more effective and linked to lower morbidity and mortality than the alternate transcranial (through the cranium) approach (Aydin *et al.,* 2007*;* Štoković *et al.,* 2016*)*. The degree and pattern of SS pneumatization are critical factors when planning transsphenoidal and endoscopic surgery. Understanding the pathophysiology of the process that can develop in the sinus cavity and preventing iatrogenic injuries depend on being aware of the anatomical variations of the SS (Štoković *et al.,* 2016*).* Additionally, pneumatization of the SS may open up access to additional areas of the skull base (Wang *et al.,* 2010a*)*. Various authors have evaluated the pneumatization and pneumatic extensions of the SS in different populations. These variations are population-specific, sex-related, and vary in ethnic groups (Ominde *et al*., 2021).

1.7.2. ***Forensic Significance***

A forensic anthropologist must conduct the biological profile on highly degraded or skeletonized remains. The biological profile includes determination of sex, age, ancestry, and height. It is critical to get a reliable sex determination, as this identification will reduce the search through missing person reports by half (Spradley, 2016). However, sex determination can be population-specific, requiring precise ancestry assessment. Metric and morphological (non-metric) analyses are commonly employed to determine the sex of human bones (Steyn and İşcan, 2008*)*. The pelvis, cranium, long bones, and femur exhibit the most apparent sexual dimorphism. However, these bones are not always well-preserved (Uthman *et al.,* 2011). Given that only the skull or its parts are often isolated in mass accidents, forensic evaluations of the morphological and dimensional features of the cranium are increasing (Ramos *et al*., 2021). In this regard, the frontal, maxillary, sphenoid, and ethmoid sinuses are structures that, in most cases, survive harsh conditions and can thus be used to establish sex based on their dimensional properties (Wanzeler *et al.,* 2019; Ramos *et al.,* 2021; Rad *et al.,* 2023).

Although some authors have investigated the SS morphology in the South African population (Rennie *et al.,* 2017*;* Ngubane *et al.,* 2018), none have gone as far as investigating the incidence of the SS lateral extensions, posterior pneumatization/extensions, protrusion of neurovascular structures, and volume of the SS for sex determination on adult South Africans. This, therefore, justifies the need for this study.

1.8. Methodology

1.8.1. Study population

This study was a retrospective review of CT scans of patients aged 18 years and above. According to Wang *et al*., (2010), SS are present at birth, but they do not get pneumatized until adolescence when they reach their maximum size. The CT scans were from previously approved UKZN Department of Clinical Anatomy studies with BREC reference (BE247/11) and one with protocol reference (BREC/00002263/2020). A total of 385 head and neck CT scans of the last ten years were retrieved and reviewed, from which only 63 scans (126 sides: right and left SS) were suitable and selected for this study. The CT scans/images were obtained from the Picture Archiving and Communication Systems (PACS) at Greys Hospital KwaZulu-Natal Province, South Africa.

The sample was divided into three population groups: Black South Africans, White South Africans, and Indian South Africans. In South Africa, Black South Africans account for approximately 79.8% of the population, White South Africans for about 8.7%, and Indian South Africans for about 2.5% (Khalfani and Zuberi, 2001; L' Abbé *et al.,* 2011; Aladeyelu *et al*., 2024).

1.8.2. Ethical clearance

Ethical approval for this study was obtained from the UKZN Biomedical Research Ethics Committee (BREC/00004712/2022). All the data was collected post-ethical approval [Appendix B and Appendix C]. In addition, permission to conduct this study was obtained from the School of Laboratory Medicine and Medical Science (SLMMS) at the University of KwaZulu-Natal [Appendix A]. This study maintained confidentiality and anonymity by recording patients' ages, genders, and population groups. Other health information gathered was purely for this study.

1.8.3. Inclusion criteria

Male and female patients of at least 18 years of age and above were included in this study. Only CT scans that visibly showed the SS without any sign of pathology in the sinus cavity was utilized; these included high-resolution multi-detector CT images obtained with a 0.6 mm collimation.

1.8.4. Exclusion criteria

Computed tomography scans that were performed for head trauma, sinus tumor, or nasosinusal polyposis, as well as those with a sinus surgical history, were excluded from this study as these pathologies are likely to cause changes in the SS (Yèkpè *et al*., 2018). Computed tomography scans with any sign of pathology in the SS were also excluded as that may affect the volume of the SS. Patients under the age of 18 were excluded from this study. Distorted CT scans were not utilized.

1.8.5. Scanning protocol

The CT images of the sphenoid bones were taken using a multi-detector row Computed Tomography (MDCT) Scanners (SOMATOM Definition Flash CT Scanner, Siemens Healthineers, Forchheim, Germany, 128 slice configuration). The scans were performed in a craniocaudal topographical direction using 140 kV, modulated mAs ranging between 280 – 400 mA (beam collimation 64 × 0.625; rotation 0.5 sec) with 30% dose reduction and ASIR-V application in a bony algorithm with a window width of >3000 HU and a window level of 500 HU. The slice thickness was 0.625 mm with a detector coverage of 20mm and a PITCH of 0.5. The voxel size of images is isotropic.

1.8.6. Methods of data collection

Approximately 385 CT scans of the head were transferred to a Miele-lxiv workstation and viewer [Version 9.31] (Figure 11). Further screening was done on each scan to select scans that met the inclusion criteria. Post-exclusion, 63 patients (n=126 SS) remained. Data was collected from the 63 patients (30 Males, 33 Females). The Miele-lxiv viewer was used to analyze and collect all necessary data for this study. A data collection sheet was prepared to record all necessary observations and measurements taken from each scan that met the inclusion criteria.

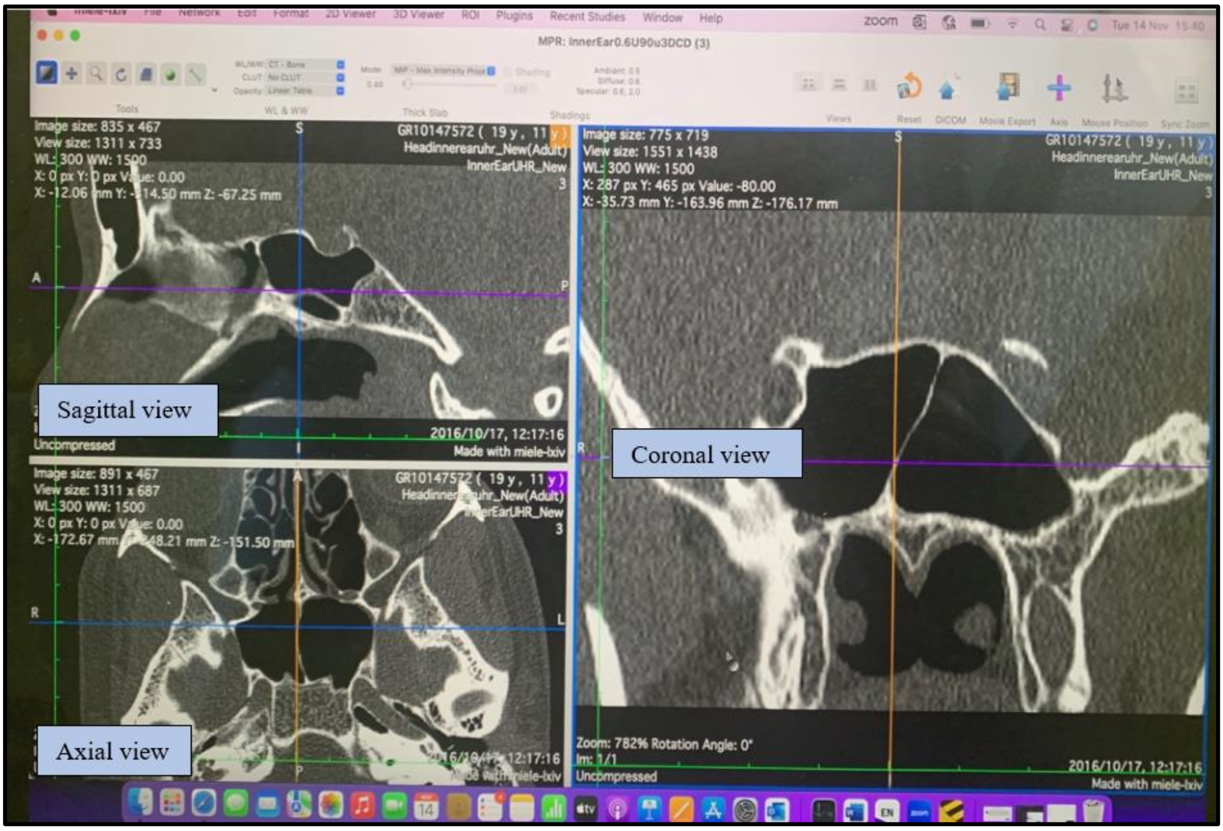

Figure 11: Mielie viewer software used to analyse CT scans**.**

1.7.4. ***Morphological parameters***

a. Type of Sphenoid Sinus

The SS were classified into conchal, pre-sella, sella, and post-sella types based on pneumatization around the sella turcica (Hammer and Radberg, 1961; Lalchan *et al.,* 2021). A vertical line was drawn along the anterior and posterior walls of the sella turcica and used as a reference point for this classification (Figure 12).

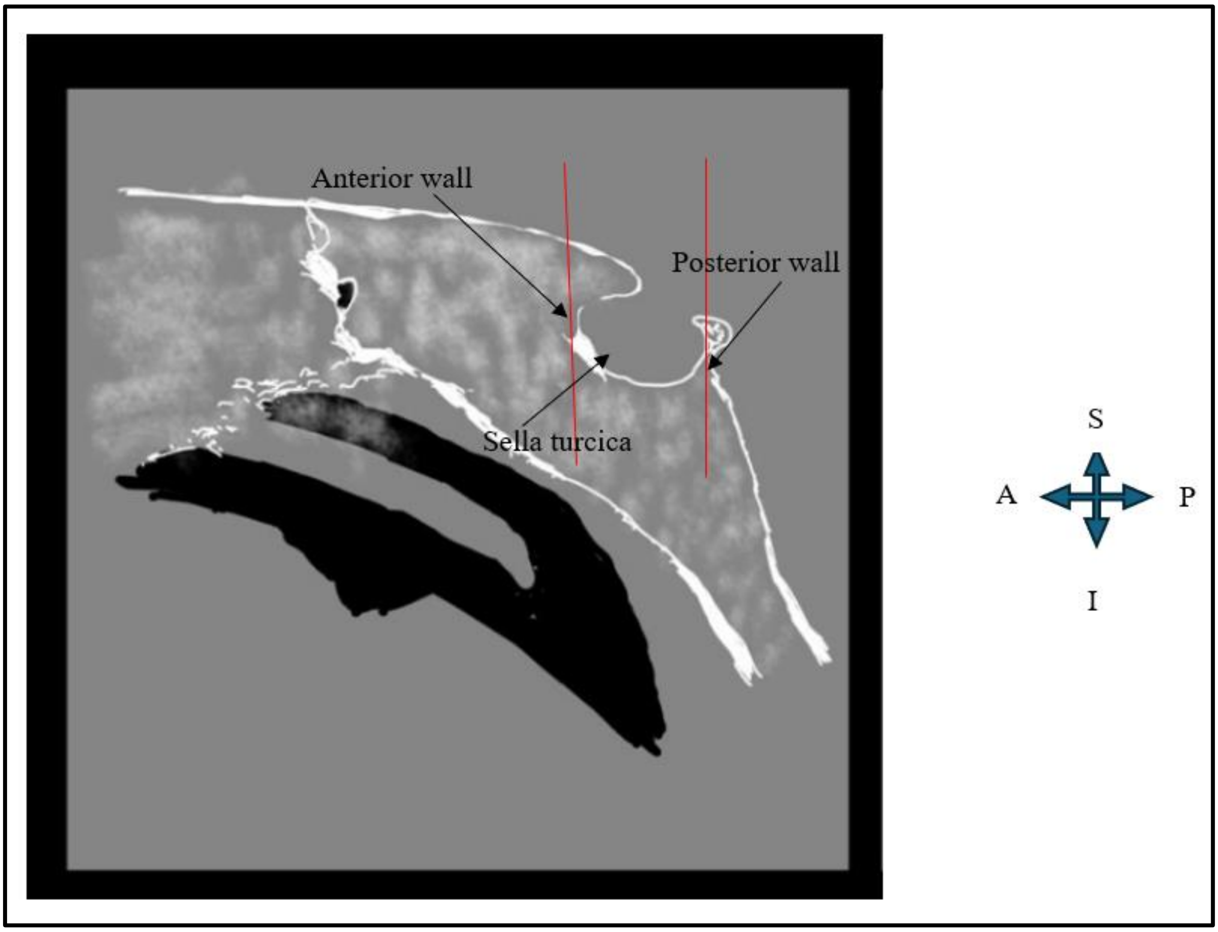

Figure 12: Sagittal CT scan diagram of sphenoid bone and SS illustrating reference lines (red lines) used for classification of SS (adapted from Lalchan *et al*., 2021)

- Conchal type - Pneumatization extending >10mm anterior to the anterior wall of the sella
- Pre-sella type – Pneumatization not extending beyond the anterior wall of the sella
- Sella type - Posterior margin of pneumatization beneath the sella but anterior to the posterior wall of the sella
- Post-sella type - posterior margin of pneumatization posterior to the posterior wall of the sella

b. Posterior extensions

For the classification of posterior extensions or clival recess of SS, on each SS horizontal lines were drawn at the inferior margin of the sella turcica and along the vidian canal. A vertical line was drawn along the posterior wall of the sella turcica. This classification method is adopted from Wang *et al*., 2010 (Figure 13).

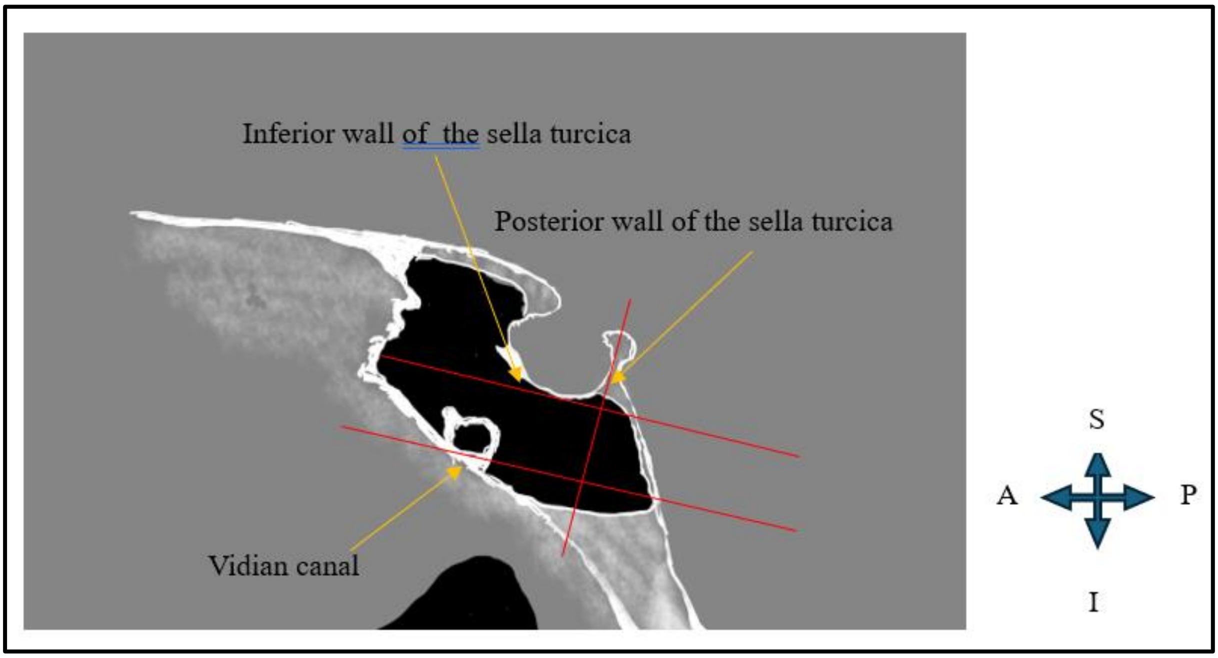

Figure 13: Sagittal CT scan diagram showing reference lines (red lines) for classification of posterior extensions of SS (adapted from Lalchan *et al*., 2021)

The posterior extensions were classified into subdorsal type, dorsal type, occipital type, and clival/combined type (Wang *et al*., 2010).

- Subdorsal- Pneumatization is not extending above the line drawn at the inferior margin of sella turcica, and below the line is drawn along the vidian canal
- Dorsal- Pneumatization extending superiorly into the dorsum sellae or above the line drawn along the inferior margin of the sella turcica
- Occipital- pneumatization extends below the level of the vidian canal
- Combined- Pneumatization exhibiting both dorsal and occipital types

c. Lateral extensions

The lateral extensions of the SS extend beyond the straight line crossing the medial edges of the foramen rotundum and the vidian canal (VR line)(Wang *et al.,* 2010a).

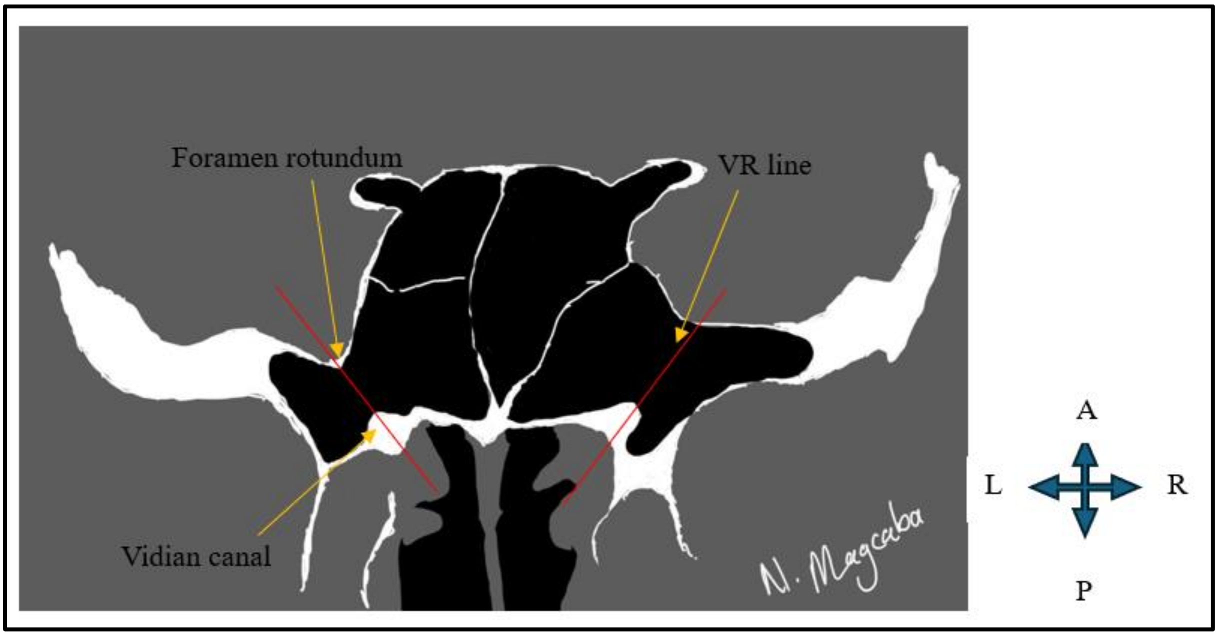

Figure 14: Coronal CT scan diagram illustrating the VR line, a reference plane for classification of lateral extensions of SS (adapted from Lalchan *et al*., 2021)

The VR line, which extends from the medial edge of the anterior end of the vidian canal and the extracranial end of the foramen rotundum, was drawn on the CT scans (Figure 14). The lateral extensions were classified as follows using Wang's classification method for lateral extensions of the sphenoid sinus (Wang *et al*., 2010):

- Body type - Pneumatization which is confined to the sphenoid body and does not extend beyond the VR line.
- Lesser wing type - Pneumatization through the optic strut and anterior clinoid process.
- Greater wing type - Pneumatization, in which the lateral wall of the sinus extends laterally beyond the VR line between the foramen rotundum and vidian canal into the greater wings of the sphenoid bone.
- Pterygoid type - Pneumatization extending laterally beyond the VR line between the foramen rotundum and the vidian canal and inferiorly into the pterygoid process.
- Full lateral type - Pneumatization extending laterally into both the greater wings of the sphenoid bone and pterygoid process.

These extensions were evaluated in both the right and left SS. Both sagittal and coronal CT scans were used for classification.

d. Protrusion of neurovascular structures

Morphology of the SS was assessed on each CT scan, with particular attention to the possible protrusion of ICA and ON. Protrusion into the air space was defined whenever a part of the ICA or ON section produced an indentation of the SS in the transverse and coronal views, respectively (Gibelli *et al.,* 2019).

The entire sample was classified into four groups (Figure 15) according to the protrusion of ON and ICA into the SS adopting the method described by Gibelli *et al*. (2019):

- Group 1: No protrusion of any structures
- Group 2: protrusion of the ICA
- Group 3: protrusion of the ON
- Group 4: protrusion of ICA & ON

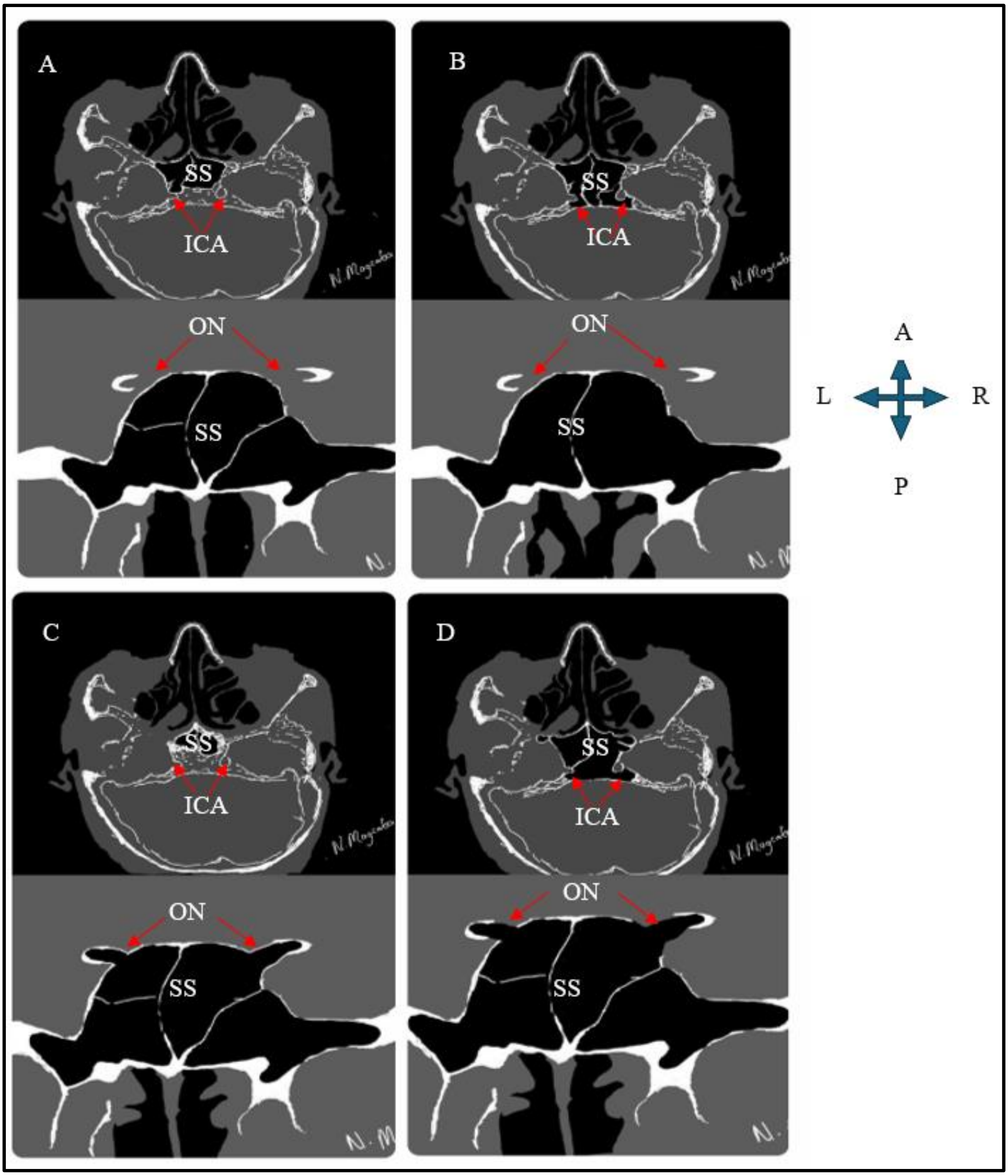

Figure 15: Axial and coronal CT scan diagrams illustrating the classification of protrusion of ICA and ON through four groups (adapted from Gibelli *et al*.,2018)

Key: A = group 1, B = group 2, C = group 3, D = group 4, ICA- internal carotid artery, SS-sphenoid sinus, ON-optic nerve

1.7.5. *Morphometric parameters - Volume of the sphenoid sinus*

The clip and segmentation process ISP viewer software (version 11.1) on the workstation was used to achieve the volumetric measurements of the SS. With the surface rendering algorithm of the lowest limit window level -1,024 hU and the uppermost limit window -318hU, the axial image was double-clicked to be enlarged. Next, the smart segmentation option on ISP viewer software was used to highlight and select air cells in the sphenoid (figure 16). The ISP then provided a calculator that automatically calculates the volume of each SS selected for this study.

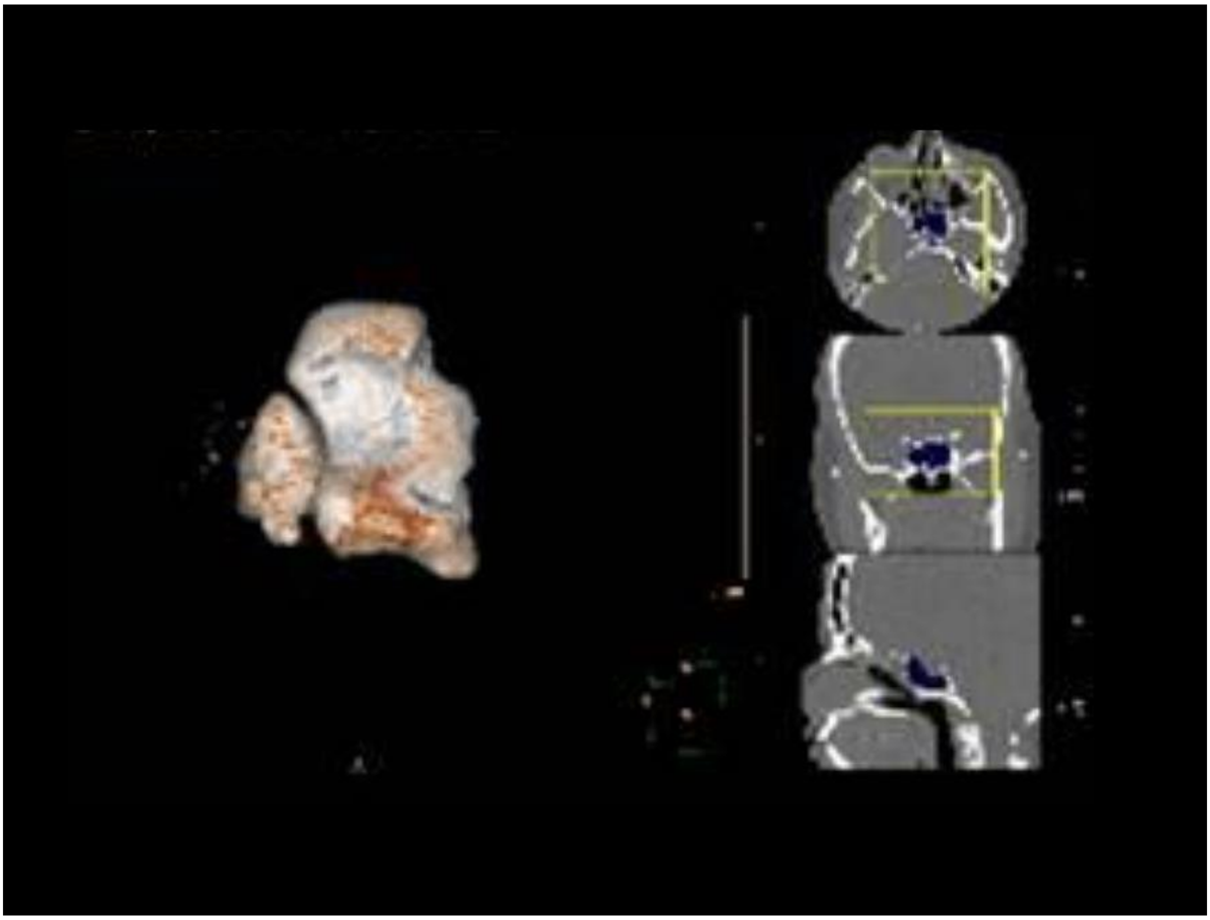

Figure 16: Showing SS segmentation on ISP viewer software

1.8. Scientific Validity

Computed tomography scans of the SS diagnostic imaging offer detailed visualization of its bony components, organs/tissues, and related vessels and nerves. Raw data of SS from multiplanar CT acquisitions were loaded on Miele-lxiv viewer software [Version 9.31]. The data were reconstructed into 0.6 mm axial images using the bone algorithm, and data were displayed in the three orthogonal planes (axial, sagittal, and coronal) for each sphenoid bone. Specific landmarks based on clinal relevance were adopted for specific morphological observations defining each classification type of sphenoid pneumatization, neurovascular protrusion, and morphometric analysis.

A pilot study was conducted on 10% of the sample size (SS CT images) that are not included in the study to ascertain these specific landmarks. Intra-observer error was calculated utilizing the three measurements taken by the principal investigator. If a significant difference was observed in the three repeated measurements, the process was restarted, with the radiological landmarks located again. Final findings were derived from the second attempt; however, this was rarely the case. For inter-observer reliability testing, 20 randomly selected sphenoid CT images (both left and right) were reviewed by a secondary observer (clinical anatomist with experience in radiological analysis). Each measurement was repeated three times to ensure accuracy. If there was a significant difference between the measurements taken by the principal investigator and the second observer, the measuring process was restarted with the radiological landmarks being identified and documented. The second attempt was rarely used to obtain final results. All three measurements (raw data) were used to conduct statistical analysis. All statistical approaches and analyses were carried out with the help of a university statistician.

1.9. Statistical Analysis

The study sample consisted of sixty-three CT images (analyzed bilaterally n = 126 sides). The statistical computing software developed by the R Core Team, version 3.6.3, was utilized to analyze all data. Reliability analysis and intraclass correlations (ICC) were employed to determine intra-observer and inter-observer correlations. Each inferential statistical analysis test was run at five percent significance levels. The t-test, or the Wilcoxon rank-sum, was used to examine the mean or median differences depending on how the numerical variables were distributed between the two independent groups. When the cross-tabulation distribution's anticipated value was less than five, a Fisher's exact test was run. The Chi-Square test was utilized to determine the association between categorical variables. The results were presented using both descriptive and inferential statistics. When applicable, the descriptive statistics of numerical measurements were summarized using the lowest, maximum, quartile, and interquartile ranges. The categorical variables were visually represented using simple and multiple bar charts. The statistical methodology and analysis for this investigation were carried out with the help of the university statistician.

1.10. Layout of thesis

This master's thesis was written in manuscript format, following the College of Health Sciences, UKZN guidelines. As a result of using the same sample of 63 scans in all investigations, sections of the sample demographics and technique had to be replicated in each chapter. The thesis provides thorough methodologies for each study component to achieve its objectives. The structural outline is as follows:

1.10.1. Chapter 1: Introduction

This chapter included background information and a detailed literature review on the anatomy of the SS, pneumatization, protrusion of neurovascular structures, and volume. This chapter also outlines the study's objectives, problem statement, research question, and methodology.

1.10.2. Chapter 2: Manuscript

This chapter consists of the original research manuscript titled "Pneumatization of SS in a South African population: a radiological study," which address the research aims and objectives in relation to the pneumatization of the SS, lateral and posterior extensions of pneumatization, protrusion of ICA and ON into the sinus cavity as well as the volume of the SS. The study sample size was sixty-three CT scans, analyzed bilaterally.

1.10.3. Chapter 3: Synthesis

This chapter summarizes the main findings from Chapters two and three and concludes the thesis. Normative data on the SS and related investigated parameters for the South African population were provided. The study also examined correlations based on sex, laterality, and modalities, compared them to existing work, and made recommendations for future research.

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CHAPTER 2: MANUSCRIPT

The first chapter included a review of published literature highlighting the anatomical variations that exist in the pneumatization of the SS in different populations and their clinical significance, with particular focus on the lateral and posterior extensions of the SS in cases of extensive pneumatization, volume, and anatomical structures that may be at risk during transsphenoidal procedures and endoscopic surgery (ICA and ON). Chapter One demonstrated that variations in SS pneumatization patterns, extensions, and volume are evident across different population groups globally. Knowledge of these anatomical variations is essential in pre-surgical planning for transsphenoidal surgery and other cranial base pathologies (Wang *et al.,* 2010). However, there is a gap in the literature on South African-specific data on these variations.

The manuscript in chapter two sought to develop normative data on the pneumatization patterns, lateral and posterior extensions of the SS, volume, and protrusion of neurovascular structures (ICA and ON) in the diverse South African adult population using radiological imaging.

The manuscript has been written and presented according to the author guidelines outlined by *European Journal of Anatomyl* and submitted for publication in this journal with manuscript number: 240541nm (still under review). The referencing style of the manuscript is Harvard referencing, as required by the journal.

Reference

Wang, J., Bidari, S., Inoue, K., Yang, H. & Rhoton jr, A. 2010a. Extensions of the SS: a new classification. *Neurosurgery,* 66, 797-816.

Title : Pneumatization of Sphenoid Sinus in a South African population: a radiological study.

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2.1. Abstract

***Introduction*:** For the safe execution of transsphenoidal surgery, detailed anatomical knowledge of the sphenoid sinus (SS) is necessary. SS displays significant population-specific anatomical variations in pneumatization, volume, and protrusion of important neurovascular structures. ***Purpose*:** This study intended to investigate the pneumatization, volume, and pneumatized extensions of the SS within a South African population. ***Methodology*:** Computed tomography images of 63 patients were analyzed bilaterally using Miele-lxiv workstation and viewer for macOS, Version 9.31. The scans were assessed for pneumatization patterns, lateral extensions, posterior pneumatization and protrusion of the optic nerve (ON) or internal carotid artery (ICA), and volume. ***Results*:** Post-sella pneumatization was frequently observed (44.4%), predominant in females, on the left SS (58.9%). Body type was observed (33.3%), greater wing pneumatization (26.7%), full lateral extension (23.3%), and pneumatization of the pterygoid process (11.7%). Pneumatization of lesser wings was the least prevalent (5.0%). Statistically significant differences in ethnicity were identified, with pneumatization of the greater wings of the sphenoid bone only observed in black South Africans (30.8%). The dorsal type was the most prevalent type of posterior pneumatization (60.0%). Clival type was prevalent in Indian/White South Africans (37.5%). The subdorsal type was only observed in black South Africans. The clival type was prevalent in females on the right SS (39.4%). Group 1 (no protrusion of ICA/ON) was frequently observed (54.2%), followed by group 4 (protrusion of ICA & ON) (19.2%) and group 2 (protrusion of ICA) (18.3%). The ON (group 3) was the least prevalent protruding into the sinus (8.3%). Group 3 was prevalent in males (13.0%). Females presented a higher sphenoid sinus volume (SSV) 243(72.5-837) cm^3 and 98.5(21.0-456) cm^3 in males ($p < 0.05$). ***Conclusion*:** Females displayed a higher SSV, which varied from other populations. Knowledge gained from this study can be applied in pre-surgical planning for transsphenoidal surgery to minimize complications during surgery and ensure good postoperative results.

Keywords: pneumatized extensions, protrusion of internal carotid artery and optic nerve, sphenoid sinus volume

2.2. Introduction

The morphology of the sphenoid sinus (SS) has been a subject of interest due to the rise of transsphenoidal surgeries over the years (Gibelli *et al.,* 2019). In these procedures, the SS is the ideal surgical entry for treating various illness, including intrasella and cranial base tumors. The transsphenoidal approach is associated with reduced morbidity and death rates and is more efficient than the traditional transcranial technique (Perondi *et al.*, 2013). Without detailed anatomical knowledge of SS pneumatization, a transsphenoidal approach may cause substantial complications, including damage to the middle meningeal and vidian arteries, major cranial nerves, and cavernous sinus thrombosis (Keerthi *et al.*, 2022). Though extensive pneumatization of the SS is a necessary component for the transsphenoidal approach, damage to the optic nerve (ON) or internal carotid artery (ICA), which may protrude into the sinus, is a common danger associated with these procedures (Lu *et al.,* 2011; Gibelli *et al.,* 2019). When the SS are extensively pneumatized, the ICA and ON may emerge into the sinus (Sagar *et al.,* 2023). This can cause bleeding during surgery or result in blindness.

The most difficult-to-reach paranasal sinuses are the SS, which are encircled by important anatomical features such as the orbit and its contents, the cavernous sinus and ICA, and the anterior cranial fossa (Unal *et al.,* 2006). These sinuses are located within the body of the sphenoid bone. The SS is considered highly variable when compared to other paranasal air sinuses, with anatomical variations ranging from degree of pneumatization, size, shape, septation, and protrusion of neurovascular structures (Cellina *et al.,* 2020; Tesfaye *et al.,* 2021). The embryological development of the SS begins with bilateral posterior invaginations of nasal mucosa into the sphenoid bone region of the base of the skull (Harnsberger, 1995; Degirmenci *et al.,* 2005). These sphenopalatine invaginations of the mucosa are located close to the future sphenoidal apertures of the fully developed SS. A newborn has SS, although they are not yet aerated (Jaworek-Troć *et al.,* 2019b). Aeration of the SS achieves its climax during puberty; they take on their final form and shape and continue to expand in the space beyond the sphenoid body, which indicates the beginning of the sphenoid recess that occur after the maturation period (Antoniades *et al.,* 1996; Jaworek-Troć *et al.,* 2019a)

According to Hammer and Radberg, depending on the degree of pneumatization, the aeration process' morphological differences allow for the differentiation of three primary categories: conchal, pre-sella, and sella (Hammer and Rådberg, 1961). The sella type was further divided into two, resulting in the post-sella type (Güldner *et al.,* 2012). Conchal (fetal) pneumatization is similar to SS aplasia or hypoplasia (underdevelopment) and involves only the area of the sphenoid rostrum and does not extend to the sphenoid body. Pneumatization of the sella tubercle and the front wall of the hypophysial fossa are both examples of pre-sella pneumatization. Sella pneumatization of the SS involves the anterior wall and floor of the sella turcica and extends to the vertical plane of the posterior clinoid process. Post-sella pneumatization of the SS continues to the basilar portion of the occipital process, past the sella turcica (Jaworek-Troć *et al.,* 2021). Wang *et al.* (2010) further investigated and classified the pneumatized extensions of the SS.

The pneumatization of the SS ranges from absent to extensive (Wang *et al.,* 2010). Transsphenoidal surgery for a sella lesion is deemed unfavorable for the conchal type of SS, and an extended transsphenoidal approach is contraindicated (Lalchan *et al.,* 2021).

In extra pneumatized sinuses, the pneumatization directions provide access to multiple areas of the cranial base, facilitating minimally invasive access to lesions (Lu *et al.,* 2011). However, variations in the prevalence of these pneumatized extensions are population-specific (Ominde *et al*., 2021). Failure to recognize the ethnic variations in the SS' pneumatization is frequently cited as a potential risk factor in clinical procedures (Hewaidi and Omami, 2008a*;* Tesfaye *et al.,* 2021). Knowledge of the detailed anatomy of the SS per specific population has grown more crucial as the usage of transsphenoidal surgery, either microscopic or endoscopic, has increased (Kainz *et al.,* 1993*;* Unal *et al.,* 2006). Moreover, the transnasal approach is more suitable for biopsies and resections of clival chordoma and other lesions of the craniovertebral junction. Suppose pneumatization of the SS is extensive. In that case, there is an increased risk of post-procedure cerebrospinal fluid rhinorrhea due to potential bone dehiscence and neurovascular structures extending into the sinus (Hiremath *et al.,* 2018).

Studies have reported on the pneumatization and pneumatic extensions of the SS in different populations globally (Lu *et al.,* 2011; Özer *et al.,* 2018a; Degaga *et al.,* 2020; Ominde *et al.,* 2021)*;* none have focused on the South African population. This study intends to fill that gap in the literature. The current study provides detailed anatomical knowledge on the pneumatization of the SS, including SSV and protrusion of neurovascular structures into the sinus cavity within the diverse South African population.

2.3. Materials and methods

This retrospective study retrieved and reviewed approximately 385 head and neck CT scans, from which only 63 ($n =$ 126 SS) were suitable and selected for this study. The CT scans/images were obtained from the Picture Archiving and Communication Systems (PACS) at Greys Hospital KwaZulu-Natal Province, South Africa. The sample consisted of adult patients (33 females and 30 males) ranging between 18 and 38 years. Eighty-seven and three tenths' percent of the sample were Black South Africans, 7.94% were Indian, and 4.76% were White South Africans. The CT scans were from previously approved UKZN Department of Clinical Anatomy studies with BREC reference (BE247/11) and one with protocol reference (BREC/00002263/2020). Permission to access the scans was obtained from the UKZN School of Laboratory Medicine and Medical Sciences. Ethical clearance for this study was obtained from the UKZN Biomedical Research Ethics Committee (BREC/00004712/2022). All the data was collected post-ethical approval. Selection criteria were as follows: ≥ 18 years; no visible signs of pathology; scans without distortion.

The digital imaging and communication in medicine (DICOM) images were viewed and analyzed using Miele-lxiv workstation Version 9.31 (Freelance Software, GBL 3.0 License) and Intellispace Portal (ISP) viewer Version 11.1 (Philips Image and Information Management Software, Nederland). The Miele-lxiv viewer program (Version 9.31) was used to load raw data from multiplanar CT acquisitions. The bone algorithm reconstructed the data into 0.6 mm axial images, which were then shown for each sphenoid bone in the three orthogonal planes (axial, sagittal, and coronal). For distinct morphological observations defining each categorization type of sphenoid pneumatization, neurovascular protrusion, and morphometric analysis, specific landmarks were adopted based on clinal relevance. In order to assess these precise landmarks, a pilot study was carried out on 10% of the sample size.

The volumetric measurements of the SS were obtained using the clip and segmentation method and ISP viewer software (version 11.1) on the workstation. The axial image was double-clicked to enlarge using the surface rendering algorithm with the lowest limit window level of -1,024 HU and the highest limit window of -318 HU. Next, ISP viewer software's smart segmentation capability was used to highlight and select air cells in the sphenoid. The ISP then offered a calculator that automatically determines the volume of each SS used in this investigation. Each measurement was repeated three times, and the intra-observer error was determined. To ensure the accuracy and repeatability of the technique utilized in this investigation, eight sphenoid CT images (both right and left) were randomly selected, and a first, second, and third observer performed morphological observations and morphometric analysis.

The SS was classified into four types based on pneumatization around the sella turcica in reference to Lalchan *et al.* (2021) (a vertical line was drawn along the anterior and posterior walls of the sella turcica) (Figure 1)

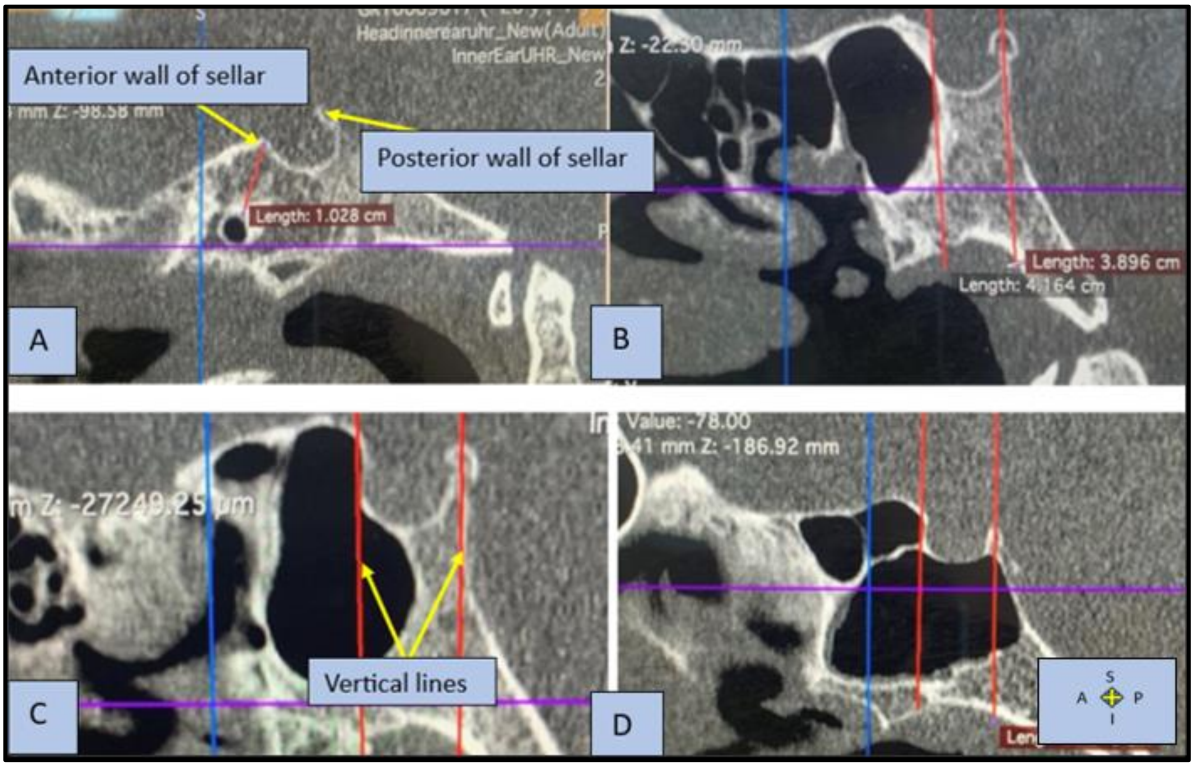

Figure 1: Sagittal CT scans illustrating classification of different types of SS

Key: A = conchal type, B = pre-sella type, C = sella type, D = post-sella type

- Conchal type - Pneumatization extending >10mm anterior to the anterior wall of sella turcica.
- Pre-sella type - The posterior margin of pneumatization located anterior to the anterior wall
- Sella type - Posterior margin of pneumatization beneath the sella turcica but anterior to the posterior wall of the sella turcica.
- Post-sella type - Posterior margin of pneumatization posterior to the posterior wall of the sella turcica.

Pneumatization of the lateral walls and structures (prevalence of lateral extensions) was identified according to Wang's method (Wang *et al.,* 2010). On a CT scan, the extracranial end of the foramen rotundum and the medial border of the anterior end of the vidian canal were used to draw the VR line (Figure 2).

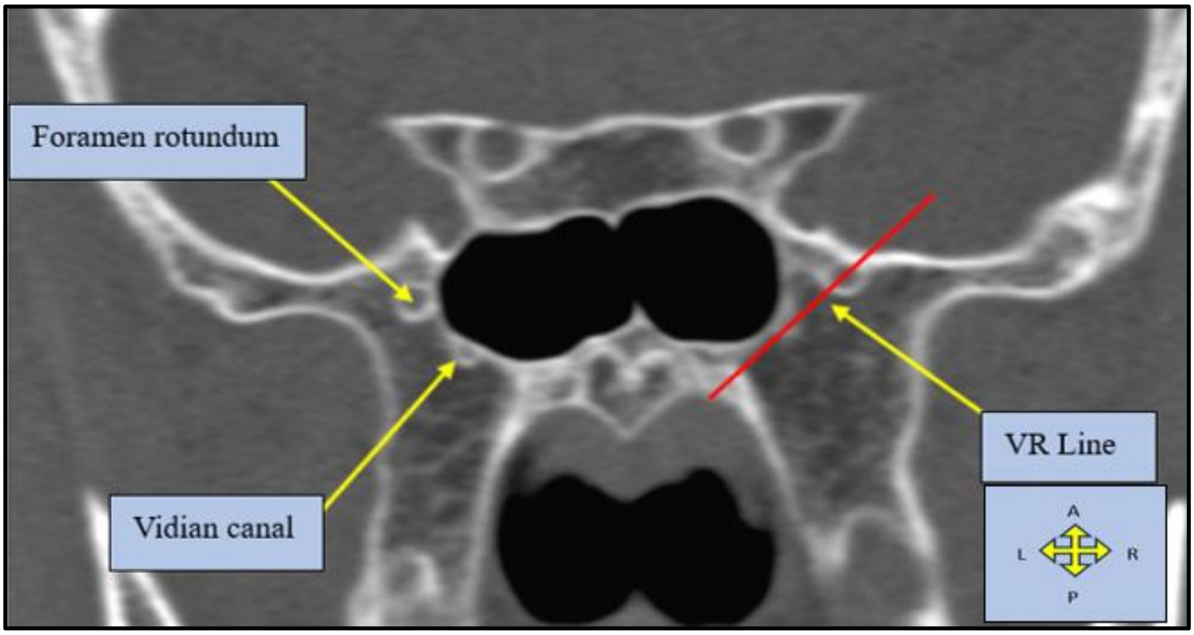

Figure 2: Coronal CT scan showing anatomical landmarks for the VR line (red line), used for classification of lateral extensions of the SS.

- Body type - Pneumatization is confined in the sphenoid body and does not extend beyond the VR line.
- Lesser wing type - Pneumatization through the optic strut and anterior clinoid process.
- Greater wing type - Pneumatization, in which the lateral wall of the sinus extends laterally beyond the VR line between the foramen rotundum and vidian canal into the greater wings of the sphenoid bone.
- Pterygoid type - Pneumatization extending laterally beyond the VR line between the foramen rotundum and the vidian canal and inferiorly into the pterygoid process.
- Full lateral type - Pneumatization extends laterally into the greater wings of the sphenoid bone and pterygoid process.

Posterior pneumatization of the SS (clival recess) was classified in reference to Lalchan *et al.* (2021). Along the vidian canal and at the inferior margin of the sella turcica, horizontal lines were drawn (red horizontal lines in Figure 3). A line was also drawn vertically along the posterior wall of the sella turcica. (Lalchan *et al.,* 2021)

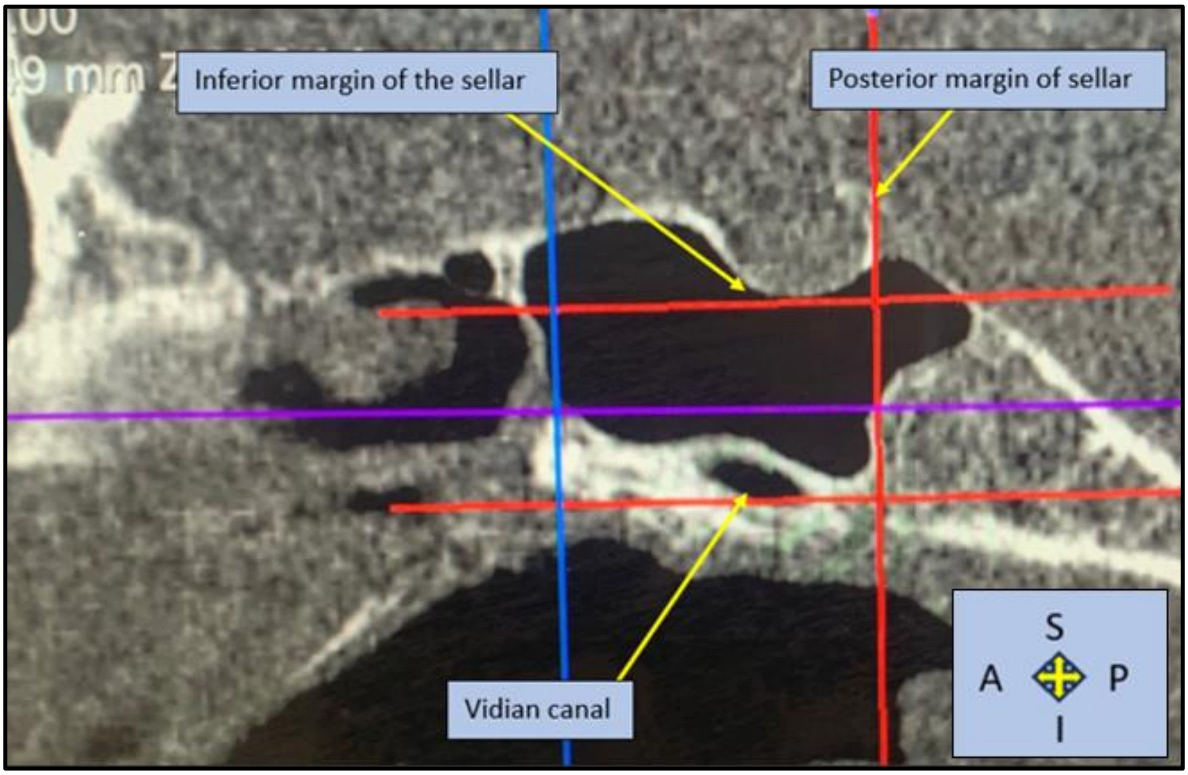

Figure 3: Sagittal CT scan illustrating reference lines and anatomical landmarks for classification of posterior pneumatization of the SS.

- Subdorsal type - Pneumatization not extending above the line drawn at the inferior margin of sella turcica and below the line drawn along the vidian canal.
- Dorsal type - Pneumatization extending superiorly into the dorsum sellae or above the line drawn along the inferior margin of the sella turcica.
- Occipital type - Pneumatization extending below the level of the vidian canal.
- Clival type - Pneumatization exhibiting both dorsal and occipital types.

Protrusion of the ON and ICA into the SS cavity was also identified. This was classified into four groups (Gibelli *et al.,* 2019*)* (Figure 4).

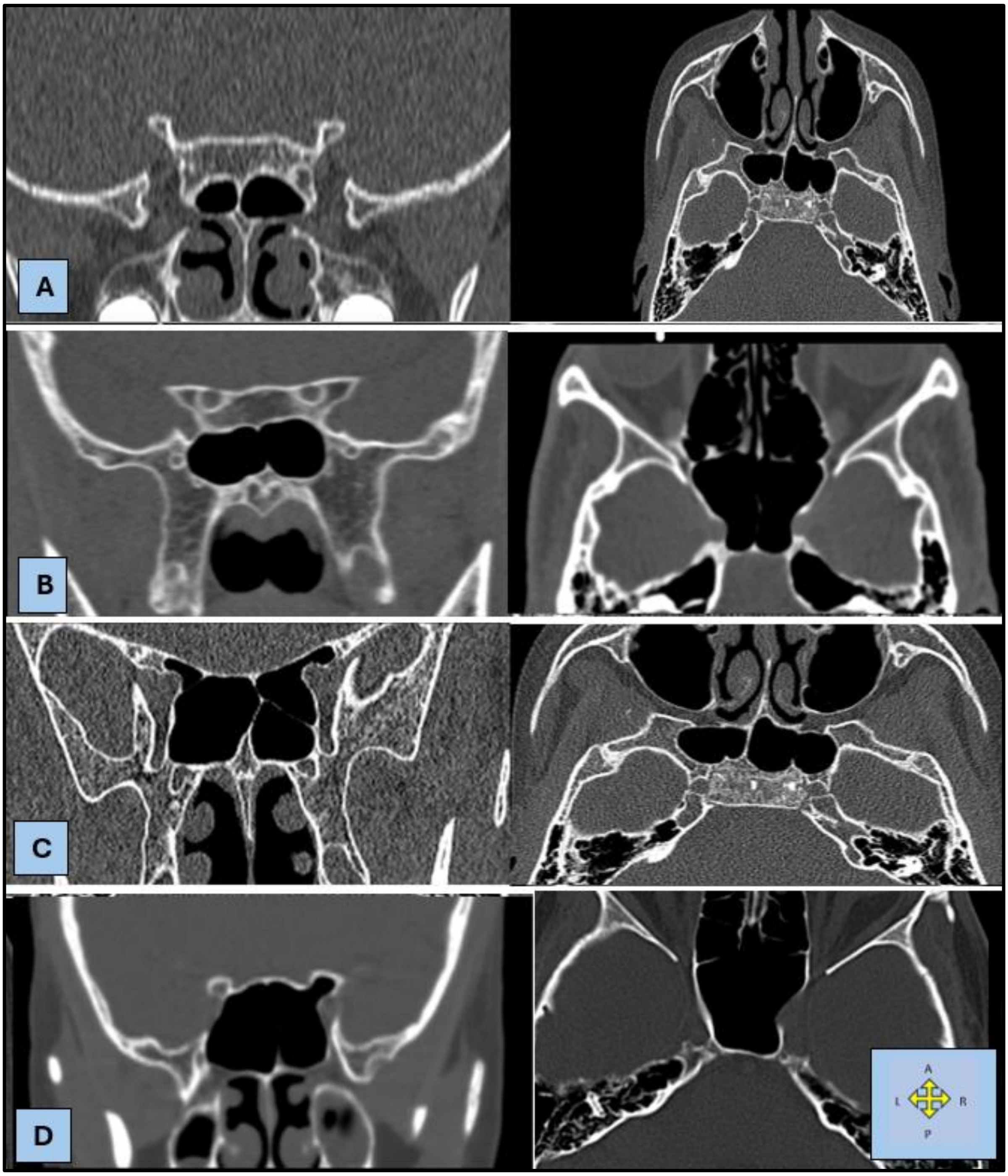

Figure 4: Coronal and axial CT scans illustrating classification landmarks for protrusion of ICA and ON into the SS.

Key: A = group 1, B = group 2, C = group 3, D = group 4

- Group 1: no protrusion of any structures
- Group 2: protrusion of the ICA
- Group 3: protrusion of the ON
- Group 4: protrusion of ICA & ON

2.4. Statistical analysis

Sixty-three CT scans that satisfied the inclusion requirements were included in this investigation. Statistics, both descriptive and inferential, were used to present the findings. Where applicable, the lowest, maximum, quartiles, and interquartile ranges were used to summarize the descriptive statistics of numerical measurements. On the other hand, pie, simple, and multiple bar charts were also utilized to visually represent the categorical variables, which were described as counts and percentage frequencies. Mean or median differences were evaluated using the t-test or the Wilcoxon rank-sum test, depending on how the numerical variables were distributed between the two independent groups. A Fisher's exact test was performed when the distribution of the cross-tabulations had an expected value of less than five. The chi-square test was utilized to ascertain the relationship between categorical variables. Intra-class correlations (ICC) and reliability analysis were used to evaluate intra- and inter-rater correlations. Every inferential statistical analysis test was carried out at significance levels of 5%. Version 3.6.3 of the R Core Team's statistical computing software was used to analyze the data statistically.

2.5. Results

Sixty- three computed tomography (CT) scans were examined bilaterally (n=126 SS). The CT scans belonged to patients with a median age of 24 years. The sample comprised of 33 females and 30 males.

2.5.1. Sphenoid sinus classification

The SS was classified into different types by the Hammer and Radberg classification method. The predominant type of SS pneumatization in relation to the sella turcica was the post-sella type observed in 44.4% of the 126 SS, followed by the sella type (31.7%), and pre-sella type (20%). Post-sella pneumatization was more prevalent in females, predominantly on the left SS at 58.9% (Table 1). The conchal type was mainly observed in Black South Africans at 3.9%, predominant on the right SS at 5.5%. The pneumatization of the SS did not significantly correlate with sex or laterality.

Table 1: Classification of SS n (%)

	Right		Left		Right		Left		Total
	M	F	M	F	B	W/I	B	W/I	
Pre-sella	5(18.6)	7(20.6)	7(25.9)	5(14.7)	13(23.6)	0(0.0)	11(20.7)	0(0.0)	25(20.0)
Sella	10(37.0)	10(29.4)	10(37.0)	8(23.5)	17(30.9)	3(42.9)	17(32.1)	2(28.6)	40(31.7)
Post-sella	11(40.7)	15(44.1)	9(33.3)	20(58.9)	22(40)	4(57.1)	23(43.4)	5(71.4)	56(44.4)
Conchal	1(3.7)	2(5.9)	1(3.8)	1(2.9)	3(5.5)	0(0.0)	2(3.8)	0(0.0)	5(3.9)
p-value	0.953		0.268		0.584		0.517		0.945

2.5.2. Lateral extensions

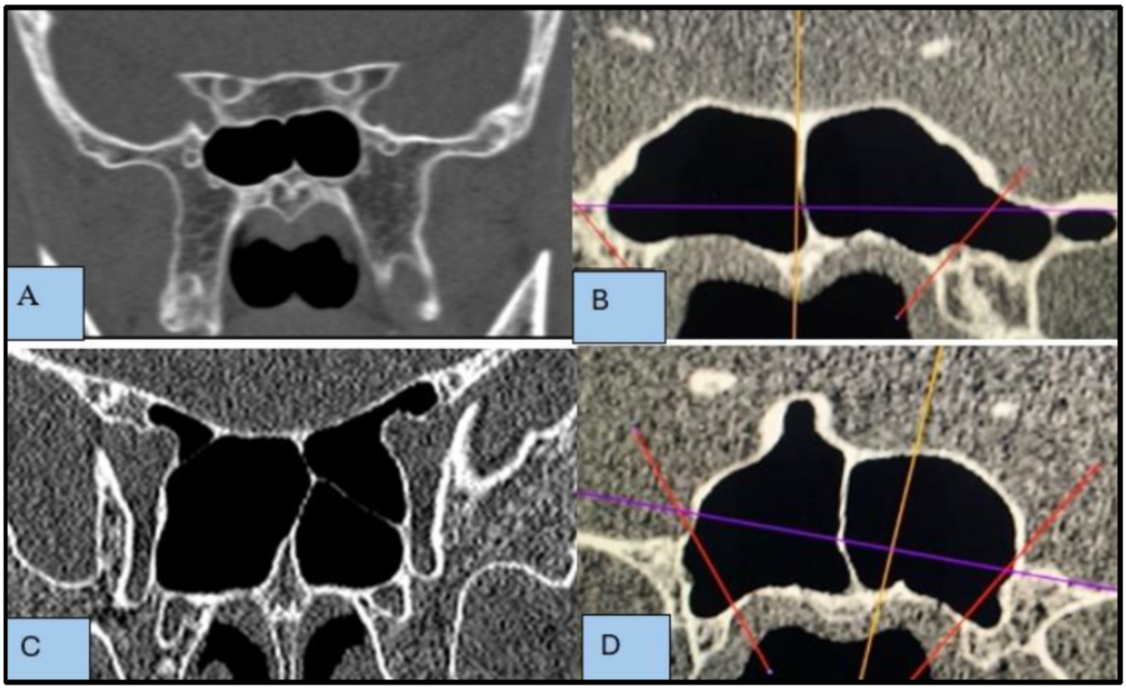

Fig. 5 Coronal CT scans showing different types of lateral extensions of SS.

Key: A = body type, B = Greater wing type, C = lesser wing type, D = pterygoid type, red line = VR line

The pneumatization of the SS can proceed beyond the sella turcica and sphenoid body laterally to the nearest structures (Fig. 5). These lateral extensions are usually in relation to the sella and post-sella type of sphenoid pneumatization. The most prevalent lateral extension was the body type observed in 33.3% of the 126 sinuses, followed by the greater wing type (26.7%), full lateral (23.3%), and pneumatization of the pterygoid process (11.7%). Pneumatization of the lesser wing was the least prevalent type of lateral extension observed in 5.0% of the studied population. Body type was predominant on the right SS in males at 44.4% (Figure 6). When the incidence of the sella subtypes of sphenoid pneumatization in Black South Africans was compared to other ethnic groups found in South Africa (Indians & Whites), there was a significant difference; with the greater wing type being prevalent amongst Black South Africans, p = **0.016***. (Table 2)

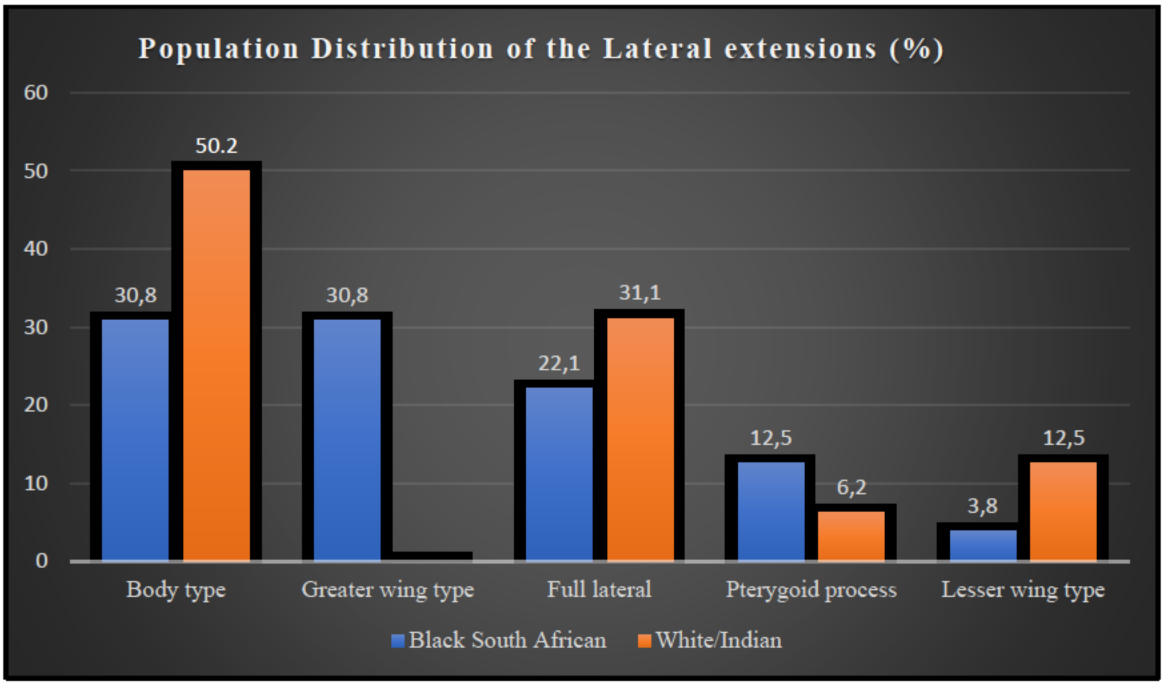

Figure 6: Bar graph showing population distribution of lateral extensions within the South African adult population.

Pneumatization of the lesser wing of the sphenoid was the least prevalent. There was no statistically significant difference in the incidence of the sella subtypes of SS pneumatization in terms of laterality and sexual dimorphism.

Table 2: Lateral extensions of SS n (%)

	Right		Left		Right		Left	
	M	**F**	**M**	**F**	**B**	**W/I**	**B**	**W/I**
Sphenoid Body	12(44.4)	10(30.3)	9(33.3)	9(27.3)	17(32.7)	4(57.1)	15(28.8)	2(28.6)
Greater wing type	6(22.2)	10(30.3)	6(22.2)	8(24.2)	16(30.8)	0(0.0)	14(26.9)	0(0.0)
Lesser wing type	2(7.4)	1(3.0)	1(3.7)	1(3.0)	2(3.8)	1(14.3)	2(3.8)	0(0.0)
Full lateral	6(22.2)	4(12.1)	8(29.6)	(824.2)	9(17.3)	1(14.3)	12(23.1)	4(57.1)
Pterygoid process	1(3.7)	5(15.2)	2(7.4)	5(15.2)	6(11.5)	0(0)	7(13.5)	0(0.0)
p-value	0.340		0.962		0.072		0.099	

2.5.3. Posterior pneumatization

Pneumatization extending posteriorly beyond the dorsum sellae into the clivus was also classified. This was in reference to the classification method for extended pneumatization introduced by Wang *et al*. (2010a). (Figure 7)

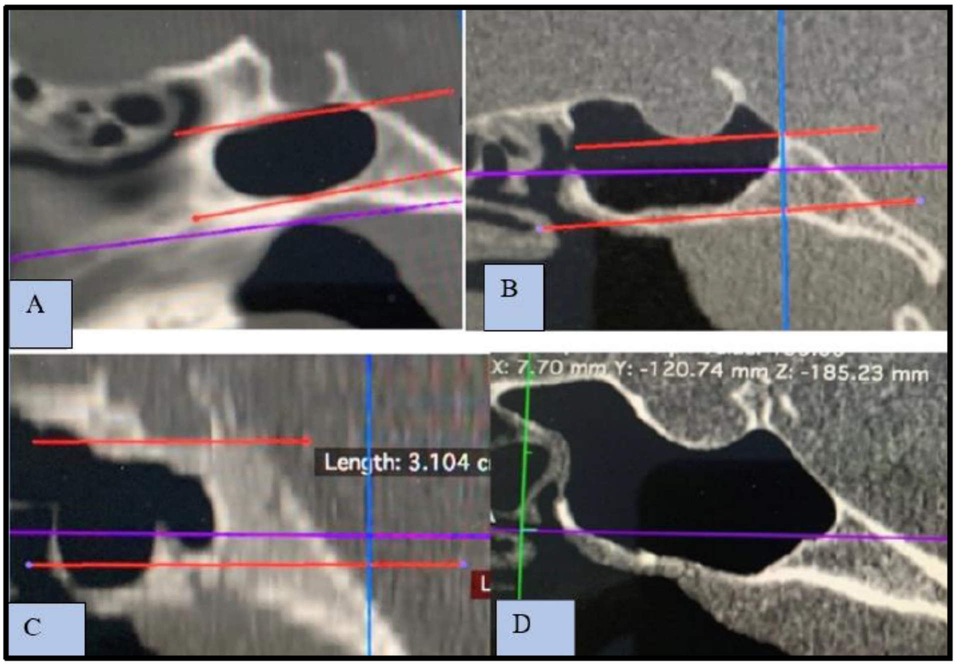

Figure 7: Sagittal CT scans showing different types of Posterior extensions of SS.

Key: A = subdorsum type, B = dorsum type, C = occipital type, D = clival type, red lines = reference lines for inferior and superior border of the sella turcica

The most prevalent type of posterior pneumatization of the SS was the dorsal type observed on 60.0% of the 126 sinuses. Clival, subdorsal, and occipital types were observed in 27.5%, 7.5%, and 5.0%, respectively (Figure 8). The dorsal type was predominant in males on the right SS at 77.8%. Variations in the incidence of posterior pneumatization of the SS between males and females were statistically significant, p = **0.033***.

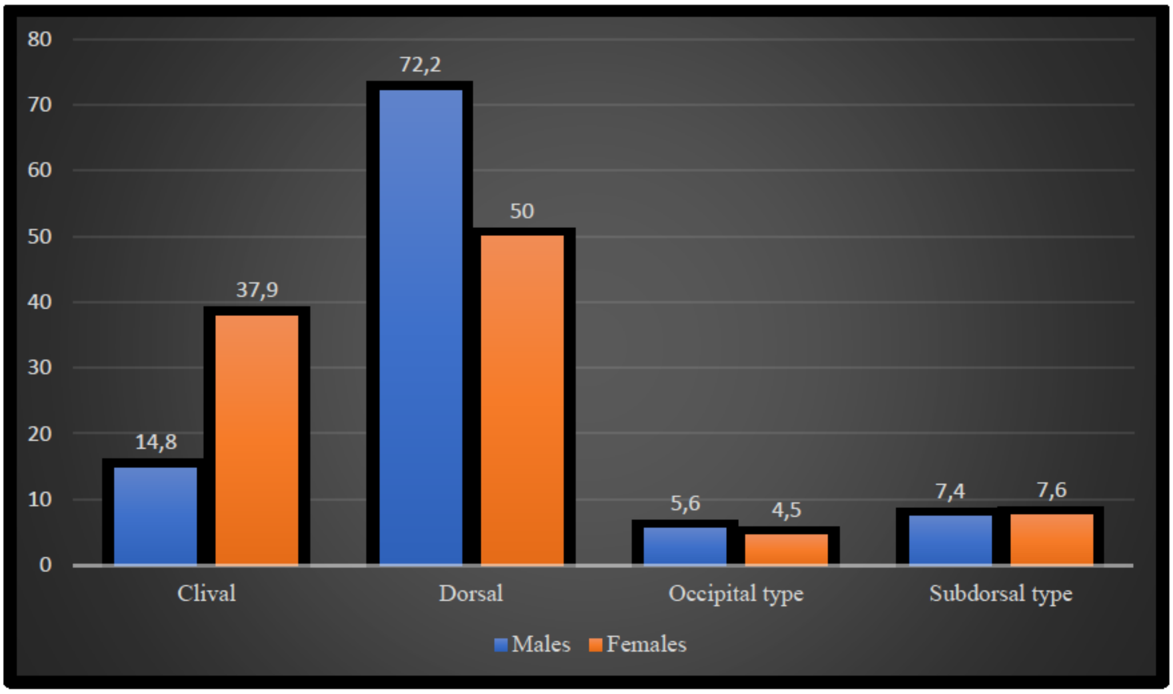

Figure 8: Bar graph showing the incidence posterior pneumatization of the SS (%).

There was a significant difference in the posterior pneumatization of the SS in terms of laterality. Pneumatization of the clivus was more prevalent in females on the right SS at 39.4%; p-value = 0.043. The subdorsal type and occipital type was only observed prevalent in Black South Africans. However, this was not statistically significant (Table 3)

Table 3: Posterior pneumatization of SS n (%)

	Right		Left		Right		Left	
	M	**F**	**M**	**F**	**B**	**W/I**	**B**	**W/I**
Dorsal	21(77.8)	15(45.5)	18(66.7)	18(54.5)	32(61.5)	4(57.1)	31(59.6)	5(71.4)
Clival	3(11.1)	13(39.4)	5(18.5)	12(36.4)	12(23.1)	3(42.9)	15(28.8)	2(28.6)
Subdorsal	2(7.4)	3(9.1)	2(7.4)	2(6.1)	5(9.6)	0(0.0)	4(7.7)	0(0.0)
Occipital	1(3.7)	2(6.1)	2(7.4)	1(3.0)	3(5.8)	0(0.0)	2(3.8)	0(0.0)
p-value	**0.043***		0.436		0.625		1.00	

2.5.4. Protrusion of ICA or ON

Group 1 (no protrusion of ICA/ON) was frequently observed (54.2%), followed by group 4 (protrusion of ICA & ON) (19.2%) and group 2 (protrusion of ICA) (18.3%). The least prevalent to protrude into the sinus was the ON, group 3 (8.3%). Group 3 was more prevalent in males (13.0%) and only 4.5% in females (Table 4).

Table 4: Protrusion of ICA &/ ON n (%)

	Right		Left		Right		Left	
	M	**F**	**M**	**F**	**B**	**W/I**	**B**	**W/I**
Group 1	15(55.6)	18(54.5)	14(51.9)	18(54.5)	30(57.7)	2(28.6)	29(55.8)	2(28.6)
Group 2	4(14.8)	7(21.2)	4(14.8)	7(21.2)	9(17.3)	2(28.6)	9(17.3)	2(28.6)
Group 3	3(11.1)	2(6.1)	4(14.8)	1(3.0)	4(7.7)	1(14.3)	4(7.7)	1(14.3)
Group 4	5(18.5)	6(18.2)	5(18.5)	7(21.2)	9(17.3)	2(28.6)	10(19.2)	2(28.6)
p-value	0.875		0.459		0.306		0.349	

2.5.5. Sphenoid sinus volume (SSV)

Females presented a higher SSV 243(72.5-837) cm^3 and 98.5(21.0-456) cm^3 in males ($p > 0.05$). Black South Africans also presented a higher SSV compared to other South African ethnicities (Indians and Whites), 240(69.2-801) cm^3 and 46.4(16.9-61.7) cm^3, respectively (Table 5).

Table 5: Sphenoid Sinus Volume (SSV) according to sex (cm^3)

	Right		Left		Total SSV	
	M	**F**	**M**	**F**	**M**	**F**
Median (Q_1-Q_3	8,70-226	19,5-363	25,4-344	24.0-488	21.0-456	72.5-837
Min-Max	1,20-1480	0.500-701	0.200-1140	0,600-1060	2.20-2620	10.3-1490
p-value	0.701		0.771		0.092	

2.5.6. Intra-observer bias

SSV measurements yielded an ICC value of 0.93, which indicated excellent reliability.

2.5.7. Inter-observer bias

SSV measurements between the first, second, and third observers yielded an ICC value of 0.89, indicating excellent reliability and repeatability.

2.6. Discussion

Imaging plays a significant role in the preoperative assessment of the SS. It is commonly understood how significant variability in pneumatization is and how it affects surgery. Therefore, it is imperative that radiologists understand the SS pneumatization patterns (Güldner *et al.,* 2012). When SS are investigated, the focus tends to be on the pneumatization of the sinus around the sella turcica. Extra-pneumatic extensions are often neglected. However, these pneumatization directions are regarded as a necessary component for the extended transsphenoidal approach (Wang *et al.,* 2010a). The South African population consists of diverse population groups. Black South Africans make up the majority of the population (79.8%), White (8.7%), and Indian (2.5%) constitute a significantly smaller proportion of the population statistics (Khalfani and Zuberi, 2001; L'Abbé *et al*., 2011; Aladeyelu *et al*., 2024).

2.6.1. Classification

The SS in humans is highly varied (Štoković *et al.,* 2016). Morphological variation in the anatomy and pneumatization of the SS have been documented across different populations globally (Wang *et al.,* 2010a; Gibelli *et al.,* 2019*;* Andrianakis *et al.,* 2020*;* Ominde *et al.,* 2021; Keerthi *et al.,* 2022). There are variations in the pneumatization patterns of the SS between different population groups. Empirical evidence suggests these variations are population-specific and sexually dimorphic (Ominde *et al.,* 2021). Previous studies have classified the SS in different population groups (Wang *et al.,* 2010a; Lu *et al.,* 2011; Rennie *et al.,* 2017; Andrianakis *et al.,* 2020; Ominde *et al.,* 2021*;* Sagar *et al.,* 2023). Data on the South African adult population is, however, limited. Surgical planning requires a thorough understanding of the anatomical characteristics of various populations.

This study classified the SS into four groups in relation to the sella turcica, conchal, pre-sella, sella, and post-sella. All four types of SS were present in the South African population. The main type of SS identified in the current study was the post-sella type (44.4%). These findings were in contrast with the Nigerian population, in which the predominant type was the sella type (Ominde *et al.,* 2021*)*. Furthermore, these findings differ from the results presented by Rennie *et al.* (2017) on the young South African population (≤ 25 years); the main type identified in that age cohort was the sella type. Though some authors do not distinguish between the sella and post-sella type pneumatization (Sagar *et al.,* 2023), it is, however, anatomically sound to view these as separate entities as in the post-sella type, the pneumatization progress more posteriorly beyond the dorsum sellae of the sella turcica as to compared to the sella type.

Patients with a post-sella variation are more likely to experience cerebrospinal fluid (CSF) rhinorrhea, so in order to reduce the chance of post-surgical CSF rhinorrhea, it is imperative to disclose their existence (Hiremath *et al.,* 2018). The post-sella type was more prevalent in White/Indian South Africans (57.1 % R; 71.4%L), while the conchal type was only identified in Black South Africans. The prevalence of the conchal type was more significant in South Africans (4.4%) compared to the Turkish (1.4%), Australian (1%), and Hispanic (0.6%) populations. This accentuates the SS variability between different populations even more. An extensive knowledge of the anatomy and variations of the paranasal sinuses is necessary for otorhinolaryngologists to treat the disease successfully and prevent complications (Orhan *et al.,* 2010).

2.6.2. Lateral extensions

Pneumatization of the SS ranges from minimal to extensive (Kinnman, 1977), spreading to nearby anatomical structures such as the ON and ICA. Wang *et al*. (2010) introduced a new classification in which various pneumatized extensions of the SS were classified into lateral recess and clival recess. The distribution of these pneumatized extensions differs across population groups (Ominde *et al.,* 2021), stressing the need for detailed anatomical knowledge for each population. After a thorough review of the literature, it is evident that there are no reports on this in the South African population.

Table 6: Comparison of prevalence of lateral extensions (%)

Study	Population	Body Type	Lesser wing	Greater wing	Pterygoid process	Full lateral	Methodology
Lu *et al.* (2011)	Chinese	_	0.8	_	22.3	11.4	CT
Özer *et al.* (2018a)	Turkish	32.6	16.66	6.94	9.02	34.72	CT
Degaga *et al.* (2020)	Ethiopian	_	_	16.5	15	_	CT
Andrianakis *et al.* (2020)	Australian	24	0	_	_	11	Cadaveric
Ominde *et al.* (2021)	Nigerian	_	_	17.9	42	_	CT
Treviño-Gonzalez *et al.* (2021)	Hispanic	_	_	57.5	26.7	_	CT
Sagar *et al.* (2023)	Indian	_	_	12.3	23.6	_	CT
Current study	South African	33.3	5.0	26.7	11.7	23.3	CT

In the current study, the body type of sphenoid pneumatization was most prevalent (33.3%); this differs from the Turkish population, in which the predominant type was full lateral pneumatization (Table 6). This body type of pneumatization was frequently observed on the right SS in male patients (44.4%). Full lateral pneumatization, pneumatization of the greater wings of the sphenoid bone, pneumatization of the pterygoid process, and pneumatization of the lesser wing were also identified at 23.3%, 26.7%, 11.7%, and 5.0%, respectively. These findings were comparable to those of other populations globally (Wang *et al.*, 2010; Gibelli *et al.*, 2019; Andrianakis *et al.*, 2020; Ominde *et al.*, 2021; Keerthi *et al.*, 2022). Pneumatization of the lesser wing was the least prevalent (5.0%); this was similar to the Chinese population (Lu *et al.*, 2011) but in contrast with the Turkish population (Özer *et al.*, 2018b). No pneumatization of the lesser wing was reported in the Australian population (0%) (Andrianakis *et al.,* 2020). When the incidence of the lateral extensions in Black South Africans was compared to other ethnic groups found in South Africa (Indians & Whites), there was a significant difference (p=0.0016), with the greater wing type being prevalent amongst the Black South African population group. This suggests that these pneumatization patterns indeed vary between different ethnic groups, further emphasizing the need for extensive anatomical knowledge on these variations for specific population groups to provide normative data for proper pre-surgical planning. Variations in the SS's pneumatization extensions may make it easier to enter adjacent regions and influence the surgical strategy chosen for lesions that border the sinus (Wang *et al.,* 2010).

2.6.3. Posterior pneumatization

Table 7: Comparison of prevalence of posterior extensions (%)

Study	Population	Subdorsal	Dorsal	Occipital	Clival	Methodology
Lu *et al.* (2011)	Chinese	_	_	_	_	CT
Wang et al. (2010a)		63.2	23.5	1.5	11.8	CT
Özer *et al.* (2018a)	Turkish	_	_	_	_	CT
Degaga *et al.*(2020)	Ethopian	_	_	_	_	CT
Andrianakis *et al.*(2020)	Australian	_	_	_	19	Cadaveric
Ominde *et al.* (2021)	Nigerian	7.4	5.4	1.0	_	CT
Treviño-Gonzalez *et al.* (2021)	Hispanic	_	_	_	_	CT
Sagar *et al.* (2023)	Indian	_	_	_	_	CT
Current study	South African	7.5	60.0	5	27.5	CT

In contrast to the non-pneumatized clivus, the clival extension of the SS is more suited for transnasal entry into the posterior cranial fossa (Keerthi *et al.,* 2022). Pneumatization of the posterior wall or clival recess was identified in this study. The most prevalent type of posterior pneumatization in the present study was the dorsal type pneumatization of the dorsum sellae

(60.0%); this contrasts with the findings of Wang *et al.* (2010), whereby the subdorsal type was prevalent (Table 7). In the current study, subdorsal pneumatization was only identified in 7.5%. Clival type was identified in 27.5%, while occipital type of SS pneumatization was the least prevalent at 5.0%. The prevalence of all the clival recess was higher in South Africa compared to the Nigerian population (Ominde *et al.,* 2021). Though authors have reported on the pneumatized extensions of the SS in different populations (Lu *et al.,* 2011*;* Özer *et al.,* 2018a; Degaga *et al.,* 2020; Andrianakis *et al.*, 2020; Treviño-Gonzalez *et al.,* 2021; Sagar *et al.,* 2023), there is still little information on the pneumatization of the posterior wall/ clival recess.

The clival type (pneumatization exhibiting both dorsal and occipital type) was more prevalent in Indian/White South Africans (37.5%) and 26.0% in Black South Africans. The subdorsal type was only identified in Black South Africans. The posterior pneumatization patterns were compared between sexes, and the results were statistically significant ($p = 0.03$), which was unique to this study. The clival type of sphenoid pneumatization was more prevalent in females, 37.9%, and 14.8% in males. Furthermore, this was prevalent mainly on the right SS ($p =0.043$).

In contrast to the non-pneumatized clivus, the clival extension of the SS is more suited for transnasal entry into the posterior cranial fossa (Keerthi *et al*., 2022). For clival chordoma and other craniovertebral junction lesions, the transnasal technique is more appropriate for biopsies and resections. Due to the possibility of bony dehiscence and neurovascular structures protruding into the sinus, there is an increased risk of post-procedure CSF rhinorrhea if pneumatization is extensive (Hiremath *et al.,* 2018). Furthermore, the dural layer of brainstem components is tightly associated with the sphenoid region of the clivus. Damage to the carotid protuberance, dorsal meningeal artery, and sixth cranial nerve, which are situated medial to the paraclival internal carotid artery occurs more frequently when using the transclival approach (Keerthi *et al.,* 2022). Given that the clival type of posterior pneumatization is common amongst female South Africans, employment of the transnasal approach in the treatment of cranial base pathologies is a safer option as opposed to the transclival approach.

2.6.4. Protrusion of Internal Carotid Artery (ICA) or Optic Nerve (ON)

Numerous important anatomical structures surround the SS, including the ICA and ON. Some of the recess, prominences, and imprints brought about by neurovascular coursing, when SS are sufficiently pneumatized, serve as crucial surgical landmarks for identifying these essential structures and preventing damage (Lu *et al.,* 2011). With extensive pneumatization of the SS, the surrounding neurovascular structures can protrude into the sinus (Sagar *et al.,* 2023). Protrusion of ICA and ON into the SS cavity has been documented in different populations (Unal *et al.,* 2006; Anusha *et al.,* 2014; Gibelli *et al.,* 2019; Erdur, 2023). Gibelli *et al*. (2019) classified the protrusion of the ICA or/and ON into four groups: Group 1 as no protrusion of either the ICA or ON, Group 2 as protrusion of the ICA, Group 3 as protrusion of ON and Group 4 as protrusion of both ICA & ON. The present study identified the protrusion of these neurovascular structures according to the four groups.

Table 8: Protrusion of ICA & ON in different populations

Study	Population	ON (%)	ICA (%)	Methodology
Unal *et al.* (2006)	Turkish	31	30.3	CT
Tan *et al.* (2007)	Asian	69	67	CT
Araujo *et al.* (2008)	Brazilian	36,9	48.8	Cadaveric material
Tomovic *et al.* (2013)	African American	24.6	24.6	CT
Lupascu *et al.* (2014)	Romanian	65	57	CT
Gibelli *et al.* (2019)	unknown	13.8	18.5	CT
Erdur *et al.* (2023)	unknown	8.8	22.9	CT
Current study	South Africa	8.3	18.3	CT

Group 1 was the most prevalent, identified in 54.2%, followed by group 4 (19.2%) and group 2 (18.3). Group 3 was the least prevalent (8.3%). These findings are similar to those of other populations (Gibelli *et al.,* 2019; Erdur, 2023). Prevalence of the protrusion of the ICA was low in South Africans compared to Turkish patients (Table 8). Group 3 was more prevalent among male South Africans (13.0%) and only 4.5% among females. Protrusion of the ON was reported to be incredibly high in Asian patients (Tan and Ong, 2007), which is in contrast with the current study in a South African population. Variations in the prevalence of the ON and ICA between different population groups are evident in the literature; hence, normative data must be available for each specific population to decrease surgical risks (Hewaidi and Omami, 2008b).

In cases where the SS is involved, endoscopic sinus surgery may have an adverse effect that could result in blindness as a result of damage to the ON (Anusha *et al.,* 2014). A damaged artery would result in severe bleeding, which would make surgery challenging. The danger of damage during surgery is increased for an ICA that is dehiscent in its bony wall or projecting into the SS (Anusha *et al.,* 2014). Extensive pneumatization of the SS results in thin or absent bone covering the carotid arteries, optic nerves, and vidian nerves. Consequently, the structures above are susceptible to iatrogenic damage (Rahmati *et al.,* 2016). There was no association between volume and protrusion of the ON and ICA in the current study; this could be a result of the fact that the most prevalent group was group 1 (no protrusion of ICA or ON). However, protrusion of these neurovascular structures is often associated with lateral extensions of the SS (Wang *et al.,* 2010).

2.6.5. Sphenoid sinus volume (SSV)

Table 9: Sphenoid sinus volume across different populations in relation to sex

Authors	Population	Volume in males	Volume in females	Methodology
Karakas and Kavakli (2005)	Turkish	$8.53 \pm 4.19cm^3$	$7.88 \pm 2.99cm^3$	CT
Emirzeoglu *et al.* (2007)	Turkish	$1.50\text{-}18.60cm^3$	$0.30\text{-}20.30cm^3$	CT
Gibelli *et al.* (2018)	Italian	$10.01 \pm 5.10cm^3$	$7.92 \pm 3.18cm^3$	CT
Andrianakis *et al.* (2020)	Australian	$5.27 \pm 2.49cm^3$	$4.32 \pm 2.22cm^3$	Cadaveric
Ramos *et al.* (2021)	Brazilian	$11.36 \pm 4.29mm^3$	$7.48 \pm 2.33mm^3$	CT
Banihashem Rad *et al.* (2023)	Iranian	$14.12 \pm 4.11cm^3$	$7.48 \pm 2.33cm^3$	CBCT
Tuang *et al.* (2023)	South Asian	10.19 (3.75-18.72) cm^3	12.22 (4.93-21.09) cm^3	CT
Current study	South Africa	98.5(21.0-456) cm^3	243(72.5-837) cm^3	CT

In forensic medicine, sex determination is a crucial component (Al Shehri *et al*., 2015). It is necessary to create specific anthropometric criteria for various populations in order to conduct various investigations on sexual dimorphism in human bones (Al Shehri *et al*., 2015). This component of this study was included due to the lack of similar studies on the SSV in sex determination in the South African adult population. Rennie *et al.* (2017) reported that, on the volume of the paranasal air sinuses in South African sub-adults, males presented with higher SSV in their cohort. An essential consideration in this investigation was the lack of pathologic alterations in the paranasal sinuses. The volume of the SS was expressed in medians as the data was not evenly distributed. Females presented a higher SSV of 243(72.5-837) cm^3 and 98.5(21.0-456) cm^3 in males ($p > 0.05$); this was in contrast with the Brazilian, Northeast Iranian, and South East Asian populations (Table 9) in which males presented with significantly larger SSV than females. The volume of the SS found in the current study population is smaller than what was reported in South African sub-adults (Rennie *et al*., 2017). There are several factors that could be impacting this variation from studies reported in various populations, including age, demographics, and the measurement technique (Yonetsu *et al.,* 2000; Demiralp *et al.,* 2019).

Black South Africans presented a higher SSV compared to other South African ethnicities (Indians & Whites), 240(69.2-801) cm^3 and 46.4(16.9-61.7) cm^3, respectively. It is crucial to be able to identify the sex of unknown skeletal remains, and techniques for doing so on the different human skeleton bones have been thoroughly studied. Numerous scholars have highlighted the necessity of gathering population-specific data for measurement-based techniques, given the wide variations in body size across different populations (Steyn and İşcan, 2008). The investigation displayed a statistically insignificant difference in the total SSV between the sexes ($p = 0.09$), suggesting that the SSV could not be used as an adjunctive measurement to determine sex. This was consistent with the findings of (Oliveira *et al.,* 2017) and (Nejaim *et al.,* 2019), who concluded that SSV could not be used for sex determination in their study populations.

2.7. Conclusion

The SS displays significant population-specific variations in its extensive pneumatization, protrusion of the ICA and/ ON, and SSV within the diverse South African population and globally. Furthermore, there were significant anatomical variations in posterior pneumatization of the SS between males and females and in terms of laterality. Protrusion of ON was more prominent in males. Females presented with larger SSV than males; this was a unique finding; however, it was not statistically significant, hence SSV cannot be used for sex determination in the South African population. Anatomical knowledge gained from this study can be applied in surgical procedures involving the SS for pre-surgical assessments and planning to avoid complications during surgery and ensure satisfactory postoperative outcomes. This study had a limitation of sample size, which included the uneven distribution of population groups. Future studies should investigate the relationship between extended SS pneumatization and common SS diseases (benign tumors, inflammatory disease, and rhabdomyosarcoma).

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CHAPTER 3: SYNTHESIS

The knowledge accumulated from this study on the pneumatization and pneumatized extensions of the sphenoid sinus (SS) and protrusion of the internal carotid artery (ICA) or/and optic nerve (ON) into the sinus cavity is essential for accurate pre-operative evaluation and surgical planning for transsphenoidal approaches and transnasal techniques (Lu *et al.,* 2011*;* Keerthi *et al.,* 2022). Studies have reported significant variations on these traits globally (Lu *et al.,* 2011; Özer *et al.,* 2018a; Degaga *et al.,* 2020; Andrianakis *et al.,* 2020; Ominde *et al.,* 2021; Treviño-Gonzalez *et al.,* 2021; Sagar *et al.,* 2023). These population-specific anatomical variations might be due to ethnicity, geographic location/environmental interactions, or methodology used in assessing the different population groups (Ominde *et al.,* 2021).

When the SS was classified into four types: conchal, pre-sella, sella, and post-sella type in terms of pneumatization around the sella turcica, the results were relatively similar to those of other populations, with the post-sella type being the most prevalent in the South African population (44.2%); followed by the sella (32%), pre-sella (20%) and conchal type (4%). However, it is worth noting that the prevalence of these pneumatization patterns varied within the diverse South African population. Though the conchal type was the least prevalent, it was mainly identified in Black South Africans, whereas the post-sella type was more prevalent in White/Indian South Africans (57.1 % R; 71.4%L). Cerebrospinal fluid (CSF) rhinorrhea is more common in patients with post-sella variations; hence, disclosing their existence is essential to lowering the risk of post-surgical CSF rhinorrhea (Hiremath *et al*., 2018). No significant differences were observed in terms of laterality and sex in the pneumatization of the SS around the sella turcica.

Pneumatization of the SS is not only limited to the sella turcica; when the sinus is extensively pneumatized, it progresses both laterally and posteriorly, pneumatizing the structures therein (Wang *et al*., 2010a). Numerous studies have been conducted on the highly variable SS. However, demographic information on the pneumatized extensions of the SS is still lacking, as authors tend to focus on the pneumatization of the sinus around the sella turcica (Wang *et al*., 2010a). With the increase in the implementation of extended transsphenoidal, endoscopy, and transnasal approaches, the need for this information has become crucial (Lu *et al*., 2011).

The South African population presented with different types of lateral extension in pneumatization of the SS. Body type, pneumatization of the greater wings of the sphenoid bone, lesser wings, pterygoid process, and full lateral pneumatization were all observed at 33.3%, 26.7%, 5.0%, 11.7%, and 23.3%, respectively. While pneumatization of the lesser wing was absent in the Turkish population (Özer *et al.,* 2018b), it was the least prevalent pneumatized lateral extension observed in the South African population. This is similar to the Chinese population (Lu *et al*., 2011) but in contrast with what is reported on the Turkish population. (Özer *et al*., 2018b) Significant ethnic variations in the distribution of the pneumatized lateral extensions were observed within the South African population ($p < 0.05$). Pneumatization of the greater wings of the sphenoid bone was significantly more prevalent among Black South Africans. This implies that there are differences in these pneumatization patterns amongst various ethnic groups, which emphasizes the necessity for in-depth anatomical understanding regarding these variations for a given population group in order to provide normative data for appropriate pre-surgical planning. Variations in the pneumatization extensions of the SS may facilitate entry into neighboring regions and affect the surgical approach selected for lesions bordering the sinus (Wang *et al.,* 2010).

There is currently not much data available regarding the pneumatization of the posterior wall and clival recess, despite publications on the pneumatized extensions of the SS in several populations (Lu *et al.,* 2011; Özer *et al.,* 2018b; Degaga *et al.,* 2020; Andrianakis *et al.,* 2020; Treviño-Gonzalez *et al.,* 2021; Sagar *et al.,* 2023). The dorsal type was frequently observed (60.0%) when posterior extensions in pneumatization of the SS were evaluated in the South African population. This was in contrast with the findings of Wang *et al.* (2010), whereby the most prevalent type was the subdorsal type at 63.2% (Wang *et al*., 2010). In the present study, subdorsal type was only observed in 7.5% of the sample. Clival and occipital types were also identified at 27.5% and 5.0%, respectively. These findings were comparable to those reported in other population groups. In comparison to the population of Nigeria (Ominde *et al.,* 2021), the South African population had a higher prevalence of all clival recess. Pneumatization displaying both dorsal and occipital types, or the clival type, was more common in Indian/White South Africans (37.5%) and Black South Africans (26.0%). The subdorsal type was found primarily among Black South Africans. Statistically significant results were accumulated when posterior pneumatization patterns were compared between males and females ($p<0.05$). In females, the clival type of SS pneumatization was prominent at 37.9%, while in males, it was 14.8%. Moreover, the right SS was the primary site of prevalence (p =

0.043). For the transnasal entry into the posterior cerebral fossa, the clival extension of the SS is more favorable than the non-pneumatized clivus (Keerthi *et al.,* 2022).

The sphenoid area of the clivus is closely related to the dural layer of brainstem components (Keerthi *et al.,* 2022). Using the transclival technique increases the risk of damage to the carotid protuberance, dorsal meningeal artery, and sixth cranial nerve, which are located medial to the paraclival carotid artery (Keerthi *et al.,* 2022). The transnasal approach is more suitable for biopsies and resections of clival chordoma and other lesions of the craniovertebral junction (Hiremath *et al.,* 2018). However, if pneumatization is severe, there is a greater risk of post-procedure CSF rhinorrhea due to the likelihood of bony dehiscence and neurovascular structures extending into the sinus (Hiremath *et al.,* 2018). Detailed anatomical knowledge from this study can be applied in pre-surgical examinations and planning to avoid such unfavorable post-surgical outcomes.

Endoscopic sinus surgery may have a negative consequence if the SS is involved, which could lead to optic nerve injury and blindness (Anusha *et al.,* 2014). There could be considerable bleeding from an injured artery, leading to complications during surgery (Anusha *et al.,* 2014). Neurovascular protrusions into the sinus can occur when the SS become extensively pneumatized (Sagar *et al.,* 2023). The literature clearly shows differences in the occurrence of the protrusion of ON and ICA into the SS among various population groups (Unal *et al*., 2006; Anusha *et al*., 2014; Gibelli *et al*., 2019; Erdur, 2023). Four categories were established by Gibelli *et al*. (2019) to categorize the protrusion of the ICA or/and ON: Group 1 consisted of neither the ICA nor the ON protrusion, group 2 of the ICA protrusion, group 3 of the ON protrusion, and group 4 of the ICA and ON protrusion. The protrusion of these neurovascular structures was detected in the current investigation based on the four groupings.

With 54.2% of cases, group 1 was the most common, followed by groups 4 (19.2%) and 2 (18.3). The least common group was Group 3 (8.3%). These results align with what was reported in other populations (Gibelli *et al.,* 2019; Erdur, 2023). Compared to Turkish patients (30.3%), South Africans had a lower prevalence of the ICA's protrusion (Unal *et al.,* 2006). Group 3 was more common among South African males (13.1%) than females (4.5%). Tan and Ong (2007) observed that protrusion of the ON was extremely high in Asian patients, a finding inconsistent with the current investigation in a South African population. The absence of an association between the protrusion of the optic nerve (ON) and internal carotid artery (ICA) in the study population suggests that the most common group did not have protrusion of either structure. Typically, when these structures protrude, they are linked to lateral extensions of the SS (Wang *et al*., 2010b). The internal carotid arteries, optic nerves, and vidian nerves are covered in thin or non-existent bone due to extensive SS pneumatization. As such, the structures mentioned above are vulnerable to iatrogenic injury (Rahmati *et al*., 2016). Data presented by this study on the South African population is essential for pre-surgical planning in this area.

Sphenoid sinus volume (SSV) has not previously been tested as a sex determination technique in the South African population, even though a study into sexual dimorphism in human bones necessitates the development of specific anthropometric criteria for distinct populations (Al Shehri *et al*., 2015). In the current study on the South African population, the SSV was higher in females when compared to males, however, with no significant difference. This was not the case in populations from Brazil, Northeast Iran, or Southeast Asia (Ramos *et al.,* 2021; Rad *et al.,* 2023; Tuang *et al.,* 2023), where males had significantly larger SSVs than females. Demographics and the assessment method may influence this variation from research conducted in different population groups (Yonetsu *et al.,* 2000; Demiralp *et al.,* 2019). In comparison to other South African population groups (Whites and Indians), Black South Africans presented greater SSVs.

The current study's analysis revealed a statistically insignificant difference ($p = 0.09$) in the total SSV between the sexes, indicating that SSV cannot be utilized as a complementary measurement to ascertain sex. This is in line with the conclusions of (Oliveira *et al.,* 2017) and (Nejaim *et al.,* 2019), who found that in their study populations, SSV could not be utilized to determine sex. Determining the sex of unexplained skeletal remains is vital, and methods for doing so on the various human skeleton bones have been extensively researched. Given the enormous variability in body size across different groups, several scholars have emphasized the need for collecting population-specific data for measurement-based methodologies (Steyn and İşcan, 2008). Therefore, data obtained from this study is an essential addition to the literature given that no similar study on the volume of the SS has been reported on the South African adult population.

3.1. Conclusion

There are several variations in the pneumatization and pneumatized extensions of the SS among adult South Africans. These variations include the protrusion of ICA and ON into the SS cavity. Features unique to this population were also noted; females presented higher SSV than males, and significant anatomical variations in the posterior pneumatization of the SS between males and females were obtained. It was also concluded that the SSV could not be used as a sex-determination tool in the study population. The data obtained from this study should be considered in pre-operative assessments for transsphenoidal surgery and other pathologies.

3.2. Limitations

The primary study limitation was an uneven distribution of population groups and sexes in the study sample. Due to the uneven distribution of population group, we could not compare the findings on Black South African to White and Indian South Africans separately furthermore, we did not have any colored South Africans in the current study population.

3.3. Recommendations for future studies

It is recommended that pneumatization of the SS be further invested in South African population on a larger sample, inclusive of all the different population groups found in South Africa. Future research ought to look at the connection between common SS disorders (rhabdomyosarcoma, inflammatory disease, and benign tumors) and extended pneumatization of the SS and the incidence of these disorders between the different population groups found in South Africa.

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APPENDIX A:

UNIVERSITY OF KWAZULU-NATAL PERMISSION

UNIVERSITY OF KWAZULU-NATAL
INYUVESI YAKWAZULU-NATALI

02 March 2023

To whom it may concern

This letter serves to inform that the School of Laboratory Medicine and Medical Sciences grants **N Magcaba (218005084)** permission to conduct the study referenced **BREC/00004712/2022** titled: **Pneumatization of the sphenoid sinuses in a select South African Population: An investigation using CT scans.** This permission is only valid for the time period and conditions stipulated in the BREC application.

Sincerely

[redacted]

Dr A Khathi

Academic Leader Human Body Form and Function Theme

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Department of Human Physiology
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APPENDIX B:

FULL ETHICAL APPROVAL

UNIVERSITY OF KWAZULU-NATAL
INYUVESI YAKWAZULU-NATALI

09 June 2023

Miss Nomthandazo Magcaba (218005084)
School of Lab Med & Medical Sc
Westville

Dear Miss Magcaba,

Protocol reference number: BREC/00004712/2022
Project title: Pneumatization of the Sphenoid Sinuses in a Select South African Population: An investigation using CT-Scans
Degree: MMedSc

EXPEDITED APPLICATION: APPROVAL LETTER

A sub-committee of the Biomedical Research Ethics Committee has considered and noted your application.

The conditions have been met and the study is given full ethics approval and may begin as from 09 June 2023. Please ensure that any outstanding site permissions are obtained and forwarded to BREC for approval before commencing research at a site.

This approval is valid for one year from 09 June 2023. To ensure uninterrupted approval of this study beyond the approval expiry date, an application for recertification must be submitted to BREC on RIG on the appropriate BREC form 2-3 months before the expiry date.

Any amendments to this study, unless urgently required to ensure safety of participants, must be approved by BREC prior to implementation.

Your acceptance of this approval denotes your compliance with South African National Research Ethics Guidelines (2015), South African National Good Clinical Practice Guidelines (2020) (if applicable) and with UKZN BREC ethics requirements as contained in the UKZN BREC Terms of Reference and Standard Operating Procedures, all available at http://research.ukzn.ac.za/Research-Ethics/Biomedical-Research-Ethics.aspx.

BREC is registered with the South African National Health Research Ethics Council (REC-290408-009). BREC has US Office for Human Research Protections (OHRP) Federal-wide Assurance (FWA 678).

The sub-committee's decision will be noted by a full Committee at its next meeting taking place on 11 July 2023.

Yours sincerely,

[redacted]

Prof D Wassenaar
Chair: Biomedical Research Ethics Committee

Biomedical Research Ethics Committee
Chair: Professor D R Wassenaar
UKZN Research Ethics Office Westville Campus, Govan Mbeki Building
Postal Address: Private Bag X54001, Durban 4000
Email: BREC@ukzn.ac.za
Website: http://research.ukzn.ac.za/Research-Ethics/Biomedical-Research-Ethics.aspx

APPENDIX C:

ETHICS EXTENSION

UNIVERSITY OF KWAZULU-NATAL
INYUVESI YAKWAZULU-NATALI

20 June 2024

Miss Nomthandazo Magcaba (218005084)
School of Laboratory Medicine & Medical Science
Westville

Dear Miss Magcaba,

Protocol reference number: BREC/00004712/2022
Project title: Pneumatization of the Sphenoid Sinuses in a Select South African Population: An investigation using CT-Scans
Degree: MMedSci

RECERTIFICATION APPLICATION APPROVAL NOTICE

Approved: **09 June 2024**
Expiration of Ethical Approval: **08 June 2025**

I wish to advise you that your application for recertification for the above study has been **noted and approved** by a subcommittee of the Biomedical Research Ethics Committee (BREC). The start and end dates of this period are indicated above.

If any modifications or adverse events occur in the project before your next scheduled review, you must submit them to BREC for review. Except in emergency situations, no change to the protocol may be implemented until you have received written BREC approval for the change.

The committee will be notified of the above approval at its next meeting to be held on 09 July 2024.

Yours sincerely

[redacted]

....

Ms A Marimuthu
(for) Prof S Singh
Chair: Biomedical Research Ethics Committee

Biomedical Research Ethics Committee
Chair: Professor S Singh
UKZN Research Ethics Office Westville Campus, Govan Mbeki Building
Postal Address: Private Bag X54001, Durban 4000
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Website: http://research.ukzn.ac.za/Research-Ethics/Biomedical-Research-Ethics.aspx

APPENDIX D:

FUNDING & CONFERENCE ATTENDANCE

- N. Magcaba, E.C.S. Naidu, O.O. Azu, C.O. Rennie
  Pneumatization of the sphenoid sinuses in a South African population: a radiologic study. Accepted for poster presentation in th 21st Congress of the International Federation of Association of Anatomist (IFAA 2024) in South Korea
- UKZN Postgraduate scholarship: 2022
- NRF Postgraduate scholarship (masters): 2022-2023

APPENDIX E:

TURNITIN REPORT

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