Pneumatization of the temporal bone, its petromastoid part and related vasculature in a South African population from early childhood to early adulthood: an anatomical and radiological study

By

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

In fulfillment of the requirement for the degree of Doctor of Philosophy in Health Sciences (Clinical Anatomy)

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PREFACE

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 July 2019 to December 2022, under the supervision of Dr. Carmen Olivia Rennie, Dr. Andile Lindokuhle Sibiya and Dr. Wonder-Boy Eumane Mbatha for the award of Doctor of Philosophy Degree in Health Sciences (Clinical Anatomy).

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Okikioluwa Stephen Aladeyelu **Date**

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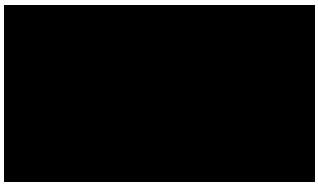

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Dr. Andile Lindokuhle Sibiya **Date**

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Dr. Wonder-Boy Eumane Mbatha **Date**

DECLARATION 1: PLAGIARISM

I, ALADEYELU, Okikioluwa Stephen, with student number **219076039,** declare that:

1. This thesis is the product of my research work.
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3. This thesis does not contain another person's writing data, pictures, or information unless explicitly acknowledged as being sourced from other persons or researchers.

However, where other written sources have been quoted:

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DECLARATION 2: PUBLICATIONS

PUBLICATION 1

Aladeyelu OS, Olaniyi KS, Olojede SO, Mbatha WE, Sibiya AL, Rennie CO. Temporal bone pneumatization: A scoping review on the growth and size of mastoid air cell system with age. PLoS One. 2022 Jun 3;17(6):e0269360. doi: 10.1371/journal.pone.0269360. PMID: 35657972; PMCID: PMC9165849. **(Published).**

PUBLICATION 2

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I carried out the study design, experimental imaging, fieldwork, data curation, analysis, and interpretation of results regarding the articles above. The co-authors contributed to the imaging analysis, data curation, editing, proofreading, and study supervision.

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Okikioluwa Stephen Aladeyelu

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Date

DEDICATION

This work is dedicated to God Almighty, for He is good because His mercies endure forever in my life. I also dedicate it to my late father, Prince Samuel Adeola Aladeyelu.

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LIST OF ABBREVIATIONS AND ACRONYMS

3D	Three dimensional
CT	Computed tomography
EAC	External acoustic canal
HJB	High jugular bulb
HRCT	High-resolution computed tomography
IAC	Internal acoustic canal
ICA	Internal carotid artery
JB	Jugular bulb
LSCC	Lateral semicircular canal
ME	Middle ear
MIJ	Malleoincudal junction
OM	Otitis media
SS	Sigmoid sinus
TBP	Temporal bone pneumatization
TB	Temporal bone

ABSTRACT

Introduction: The pneumatization of the temporal bone is important in various clinical settings. These include serving as a prognostic factor in middle ear surgeries and acting as a shock absorber in patients sustaining lateral skull trauma. The size and growth rate of its air cell system have been associated with middle-ear pathology. The degree of temporal bone pneumatization is highly relevant when planning temporal bone-related surgeries and has been hypothesized to influence anatomical variations of temporal bone-related vessels. This study aimed to investigate the size of temporal bone pneumatization (air cell volume) with age, the association between temporal bone pneumatization and the morphologies of some temporal bone-related vessels, as well as their morphometrical relationship with ear regions, and to propose a simple and concise classification of the degree of temporal bone pneumatization using reference structures and landmarks.

Materials and Methods: A retrospective review of 496 temporal bone computed tomography (CT) images of 248 head and neck/brain CTs of patients from public hospitals in KwaZulu-Natal, South Africa, was conducted. The sample consisted of 133 males and 115 females, 0 to 35 years old (median age 13.0 years) of three population groups (202 South African Black, 28 South African Indian, and 18 South African White). The age range of 0 to 35 years was further divided as follows: 0-2 (infant); 3-5 (young child); 6-9 (middle child); 10-14 (early adolescent); 15-18 (middle adolescent); 19-25 (young adult stage I); 26-35 (young adult stage II). High-resolution CT images with fine slices of ≤ 0.625 mm were analyzed using IntelliSpace Portal (ISP) Version 11.1 viewer software. The volume of temporal bone pneumatization was achieved using three dimensional (3D) volumetric rendering technique. At the same time, the morphologies of the sigmoid sinus, jugular bulb, and internal carotid artery and their morphometrical relationships with ear regions were analyzed using the measuring tools on the ISP. Additionally, an inter-observer assessment was conducted among otologists to classify the degree of temporal bone pneumatization utilizing temporal bone CT images at two levels (landmarks): the malleoincudal junction and the lateral semicircular canal using sigmoid sinus as a reference.

Results:

Size (volume) of temporal bone pneumatization with age: The volume of temporal bone pneumatization increased significantly ($p<0.001$) with age up to the adult stage I (19-25 years), followed by a significant decline in young adult stage II (26-35 years). Females showed a significant early increase compared to males. Regarding population groups, Black South Africans (SA) showed a higher increase in volume with age than the SA Whites and Indian population groups.

Influence of pneumatization on temporal bone-related vessels: Four degrees of pneumatization (hypo, moderate, good, and hyper) were analyzed. Hyper-pneumatization was observed to be more common. Vascular variants such as high jugular bulb, jugular bulb dehiscence, and internal carotid artery dehiscence were observed and significantly associated ($p<0.01$) with hyper-pneumatization. Also, as pneumatization increases, sigmoid sinus and jugular bulb distances to ear regions were observed to increase significantly ($p<0.01$, $p<0.05$). The sigmoid sinus and its variant shapes were also observed but were not significantly associated with the degrees of pneumatization (right- $p= 0.070$; left- $p= 0.645$).

Classification of degree of pneumatization: In the survey conducted among cohort otologists, the percentage of participants that correctly rated temporal bone CT images taken at the level of lateral semicircular canal according to their respective degrees of pneumatization was significantly higher ($p < 0.05$) regardless of their year of experience compared to those that correctly rated corresponding images taken at the level of malleoincudal junction. A 76% positivity in their agreement with the use of sigmoid sinus in evaluating mastoid pneumatization was observed.

Discussion and Conclusion: This study concludes that the pneumatization of a healthy temporal bone is expected to show a significant linear increase from infant up until at least the early adult stage I (19-25 years) in the South African population. The high incidence of high JB, JB dehiscence, and internal carotid artery dehiscence, and the increase in distances of sigmoid sinus and JB to ear regions reported in this study population due to increased pneumatization validates temporal bone pneumatization as a factor that influences jugular bulb variants and internal carotid artery dehiscence as well as the distances of sigmoid sinus and jugular bulb to ear regions. The study also concludes that using the lateral semicircular canal as a landmark on axial CT, and evaluating air cells around the sigmoid sinus was suitable in classifying the degree of temporal bone pneumatization into hypo-, moderate, good, and hyper-pneumatization. This study proposes this classification system as an easier and quicker method for clinical applications.

Keywords: Temporal Bone, Pneumatization, Air Cells, Computed Tomograph, Vasculature

CHAPTER ONE
INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction and Background to the Study

One of the anatomical complexities of the temporal bone (a pair of bones located on the lateral aspect of the human skull [Standring, 2008]) is its pneumatization (i.e., the presence or development of air cells) which has been the subject of considerable discussion to which various opinions and theories have been expressed (Osama, 2018). Kang *et al.* (2019) identified temporal bone pneumatization as having a potential protective effect in temporal bone fractures, further preventing damage to the auditory apparatus and other traumatic injuries. Fractures to the temporal bone have brought about serious psychological distress and had devastating impacts on many people's lives, with about 69 million individuals estimated to suffer traumatic brain injury (Dewan *et al.,* 2019; www.psychologtoday.com/za/basics/trauma%3famp). According to World Head Injury Awareness Day on 20th March 2016, head injuries and temporal bone fractures are relatively common in South Africa, with 89,000 new traumatic brain injuries reported yearly. This was bolstered in the study by Makolane *et al.* (2019), who reported a prevalence of 15.2% (32 out of 210 patients) in the Tshwane district of Gauteng province.

In clinical practice, the temporal bone and its pneumatization are significantly relevant in various situations. These include surgical planning for bone conduction implants, active middle ear (ME) implants, and even cochlear implantation when assessing the space required for implant placement or predicting access to the ME via trans-mastoid and retro-facial approaches (Holmquist, 1970; Proud & Duff, 1978; Galal *et al.,* 2021). These are required for patients with partial or severe hearing loss, in which about 5% of the world's population suffers from (Schmucker *et al.,* 2019). The degree of pneumatization has also been associated with surgical considerations of many temporal bone fractures, injuries, or traumatic insults (Koc *et al.,* 2003; Ilea *et al.,* 2014). This is because air cells are usually exposed during ear-related surgeries required to treat injuries sustained from these fractures (Yamakami *et al.,* 2003). The exposure of air cells is accompanied by various potential complications such as sensorineural hearing loss, tinnitus, facial nerve paralysis, and cerebrospinal fluid (CSF) otorrhea (Ilea *et al.,* 2014; Shew *et al.,* 2018). Understanding the degree of temporal bone pneumatization and possible classifications is very important. Although very few authors have described different classifications (Virapongse *et al.,* 1985; Han *et al.,* 2007; Jadhav

et al., 2014), their various limitations (to be discussed in the literature review) have resulted in a lack of consensus among surgeons and otolaryngologists, which may be a cause for concern in a few otologic surgeries such as primary mastoidectomies and postoperative care of skull base surgeries (Singh *et al.,* 2017).

In addition, the various positioning of temporal bone-related vasculature is also influenced by the degree of pneumatization, as highlighted by Singh *et al.* (2019). Good knowledge of these vascular structures and their possible anatomical variations is essential during surgical procedures (Ichijo *et al.,* 1996; Aslan *et al.,* 1997). For instance, the sigmoid sinus (SS) is one of the most familiar landmarks used during trans-mastoid and posterolateral skull base approaches (Comert *et al.,* 2018). The location and size of SS vary significantly according to laterality. Also, some of these vascular variants, such as high-riding jugular bulb (JB) and JB dehiscence, pose dangers by eroding the middle and inner ear causing tonal or pulsatile tinnitus, vertigo, and hearing loss (Kawano *et al.,* 2000; Friedmann *et al.,* 2010). These contribute to difficulties in diagnosis, complexities, and vital pitfalls encountered in temporal bone and ear-related surgeries (Vachata *et al.,* 2010; Inal *et al.,* 2015; Osama, 2018; Osch *et al.,* 2019).

Furthermore, temporal bone pneumatization has been implicated in the pathophysiology of chronic ear infections and ME pathology such as otitis media (OM); one of the global burdens of diseases and a major cause of hearing loss and disorders with highest incidence rate in Sub-Saharan Africa and South Asia (Morris & Leach, 2009; Vos *et al.,* 2015; DeAntonio *et al.,* 2016; Tesfa *et al.,* 2020). Recent studies in South Africa have shown a local prevalence of hearing loss between 17.5% and 19.88%, higher than the global average prevalence, with OM being the major risk factor locally (Louw *et al.,* 2018; Joubert & Botha, 2019). Early studies in South Africa revealed the prevalence of OM and other ME pathologies to vary between 7.2% and 38% (Halama *et al.,* 1986; Nel *et al.,* 1988; Cilliers *et al.,* 1988; Cruickshanks *et al.,* 1998). However, present studies have shown an increased incidence rate, ranging between 31.4% and 51%, especially among younger children (Biagio *et al.,* 2014; Phanguphangu, 2016).

According to the genetic (hereditary) theory, the size of air cells in temporal bone pneumatization is genetically determined during the period of embryonic development (Diamant, 1940;), while environmental theory suggests that it is determined by the degree of pathological involvement of the ME during childhood (Palva & Palva, 1966; Turgut & Tos, 1992; Han *et al.,* 2007). There have

been inconsistencies in the literature regarding the expected norms for the development of temporal bone pneumatization, particularly in the size of air cells, the rate of growth, and completion age (Diamant, 1940; Lee *et al.,* 2005; Hill, 2011). Although Schillinger (1939) stated that there is a continuation of pneumatization during the whole lifetime, few studies have utilized different methodologies in describing the development of temporal bone pneumatization. Myerson *et al.* (1934) and Diamant (1940) revealed that mastoid aeration and pneumatization growth pattern of "Coloured" and "White" cadaveric skulls in New York terminates at puberty. With plain lateral X-ray, Chatterjee *et al.* (1990) observed that pneumatization continues into early adulthood with initial rapid growth during the juvenile period, and thereafter, the process slows down in an Indian population. Lee *et al.* (2005), utilizing the three-dimensional (3D) multiplanar volumetric rendering (MPVR) technique of computed tomography (CT) images in a Korean population, observed pneumatization to have steady growth through the third decade of life before declining slowly, then rapidly after the seventh decade of life. Discrepancies in these studies may be due to different methods or techniques used, as well as differences in population groups of the study populations (Hill, 2011).

Advancements in temporal bone imaging have contributed to a greater understanding of normal anatomy, pathology, treatment, and surgical planning (Clarke & Booth, 2017). According to Todd *et al.* (1987), Park *et al.* (2000), and Han *et al.* (2007), CT has the best advantage in demonstrating detailed imaging of the temporal bone, its pneumatization, related vessels, and other soft tissues with excellent resolution. Hence, utilizing high-resolution computed tomography (HRCT) images, this study sets out to; investigate the pattern of pneumatization that exist within the South African population; provide in-depth information on the volume of air cells as regards to age and normal growth rate of temporal bone pneumatization from childhood to early adulthood; propose a simple and concise classification of temporal bone degree of pneumatization (at a glance) that could be standardized amongst otologic, and head and neck surgeons; and highlight possible correlations between anatomical variations of some related vasculature in the petromastoid part and degree of pneumatization.

1.2 Literature Review

1.2.1 Anatomy of the Temporal Bone

Temporal bones are paired bones located in the lateral aspect of the skull (Standring, 2008). Each temporal bone consists of four components: a) the squamous part, which is the antero-superior part of the bone; b) the petromastoid part, which is relatively large; c) the tympanic part, which is a curved plate below the squamous part and anterior to the mastoid process; d) the styloid process, which is a slender and pointed bone which projects antero-inferiorly from the inferior aspect of the temporal bone [Figure 1a & 1b]. The petromastoid part consists of the petrous, which is made up of compact bone and houses the auditory apparatus, and the mastoid, which is trabeculae and has a process filled with a system of interconnecting air-filled cells. [Figure 2] (Standring, 2008).

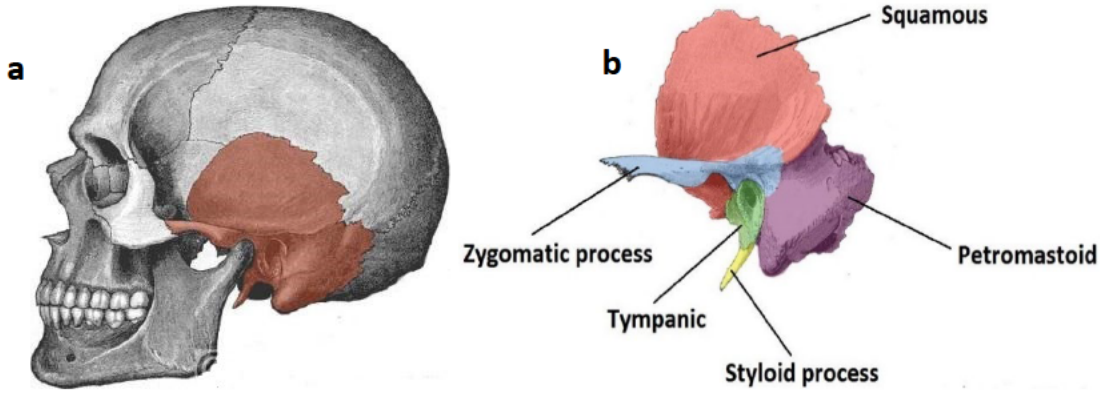

Figure 1: Diagram showing temporal bone: a) as part of the skull bones (brown); and b) its different parts *(adapted from* https://teachmeanatomy.info/head/osteology/temporal-bone/*)*

The mastoid air cells vary considerably in number, form and size. At birth, the mastoid consists of a single antrum cell connected to the ME by a small channel (Klein, 2015). Usually, they interconnect and are lined by a mucosa with squamous non-ciliated epithelium, continuous in the mastoid antrum and tympanic cavity [Figure 2a]. Though the mastoid antrum is well-developed at birth, the mastoid air cells are merely minute antral diverticula at this stage. As the mastoid develops in the second year, the cells gradually extend into it, and by the fourth year, they are well-formed, although their most significant growth occurs at puberty (Standring, 2008).

Furthermore, within the temporal bone are fissures and foramina, by which vessels and nerves transit in and out of the skull [Figure 2b]. As the temporal bone continues to increase in size (as

well as other skull bones), these openings/spaces increase in diameter as well as the vessels and the pneumatization of the temporal bone (Mortazavi *et al.,* 2013).

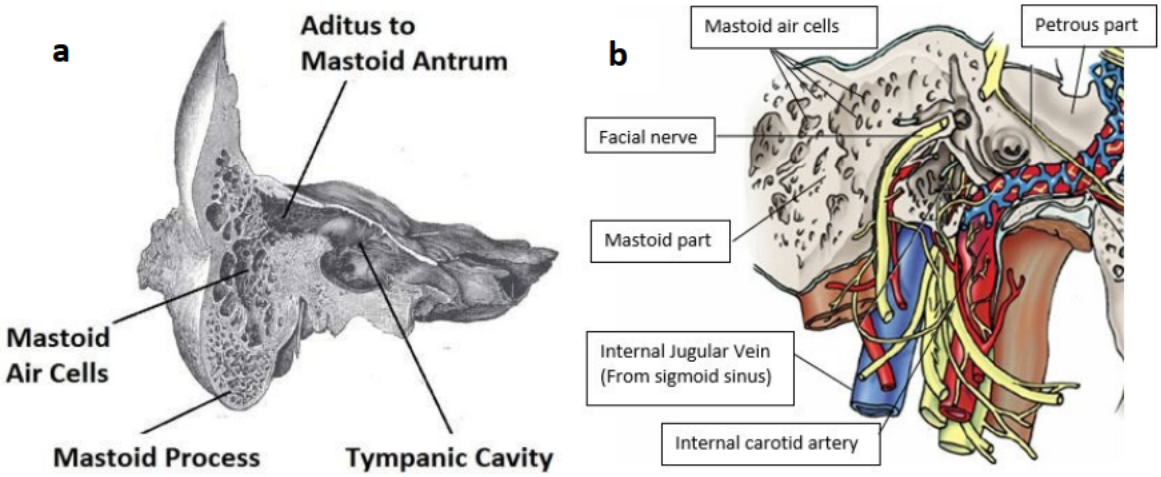

Figure 2: Diagram showing; a) the mastoid process with mastoid air cells and antrum and petrous, b) vessels and nerves in relation to foramina and fissures in the temporal bone *(adapted from* https://teachmeanatomy.info/head/osteology/temporal-bone/*& Mortazavi et al., 2013)*

1.2.2 Temporal Bone Pneumatization

1.2.2.1 Overview of Pneumatization of the Temporal Bone

Pneumatization is the presence or development of air-filled cavities or air cells in a bone (Standring, 2008). It is the process whereby epithelium infiltrates the developing bone and forms epithelial-lined air cell cavities (Hill, 2011). Standard textbooks have described the mastoid as mostly pneumatized, with the extension of air cells into the petrous and other parts of the temporal bone and related parts of the skull bones (Standring, 2008; Howard, 2010; Schmalfuss, 2018). However, Lee *et al.* (2015) suggested that the pneumatization of the petrous apex may be an independent process from the mastoid and other parts of the temporal bone. Factors influencing these are not established but may be genetically controlled (hereditary or ancestry) (Diamant, 1940; Arora *et al.,* 1973; Chatterjee *et al.,* 1990), or condition of the mucous membrane, development of growth centers in bone, eustachian tube function or inter-current infection (Koc *et al.,* 2003), or related to the degree of pathological involvement of the ME in childhood (Lee *et al.,* 2015).

The extent and arrangement of the air cells vary widely, from a minimal air cell system to most parts of the temporal bone. Allam (1969) and Virapongse *et al.* (1985) gave a simple description

of temporal bone pneumatization by zoning these air cell systems into; a) mastoid pneumatization, b) petrous pneumatization, and c) accessory pneumatization (extending beyond the limit of the mastoid and petrous).

a. Mastoid Pneumatization: The mastoid region consists of two key areas of pneumatization: the mastoid antrum (the central tract and most prominent) and the peripheral areas. The mastoid air cells in the peripheral areas relate to one another and with the antrum. These air cells are subdivided according to the areas of pneumatization in the mastoid: the antrum proper, the periantral cell area, the tegmental cell area, the sinodural cell area, the perisinus cell area, the central cell area, the perifacial cell area, and the mastoid tip cell area (lateral and medial) (Allam, 1969). [Figure 3a]

b. Petrous Pneumatization: This covers the perilabyrinthine region and petrous apex.
i. The perilabyrinthine region is further subdivided into supralabyrinthine and infralabyrinthine areas, which lie superior and inferior to the labyrinth (Allam, 1969). The supralabyrinthine area consists of the postero-superior cell tract, the postero-medial cell tract, and the subarcuate cell tract. The infralabyrinthine area consists of two tracts: the hypotympanic cell tract and the retro-facial cell tract.
ii. The petrous apex is further subdivided into the peritubal and apical areas. The peritubal area surrounds the osseous portion of the eustachian tube supplied by varying numbers of air cells from two tracts: the antero-superior cell tract and the antero-lateral cell tract (Allam, 1969). The apical area, richly pneumatized, receives supply from three principal tracts: the hypotympanic tract, the peritubal tract, and the perilabyrinthine tract (Allam, 1969). [Figure 3b]

c. Accessory Pneumatization: This refers to the extension of air cells beyond the limits of the mastoid and petrous regions to involve the other portions of the temporal bone (such as the styloid process, squamous part, and zygomatic process) and even adjacent cranial bones (e.g., occipital bone), thus, forming the accessory cell areas (Allam, 1969). These regions may be classified as follows: the zygomatic cell area due to an anterior extension of either the epitympanum or the periantral air cells into the zygomatic process; the squamous cell area as a result of a superior extension of the tegmental air cells into the squamous part; the occipital cell area due to a posterior extension of the perisinus air cells into the occipital bone; and the styloid cell area occurring due to an extension of the mastoid air cells into a hollow styloid process (Virapongse *et al.,* 1985). [Figure 3a]

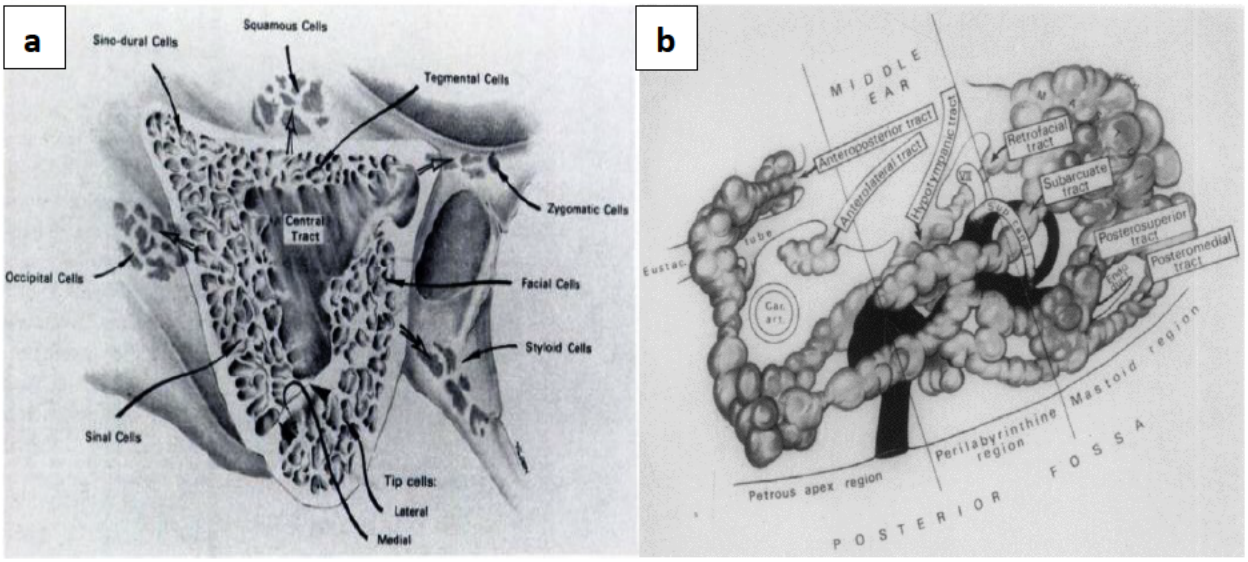

Figure 3: Diagram showing a normal pattern of pneumatization of: a) mastoid region with open arrows indicating the extension of air cells into corresponding accessory regions; and b) perilabyrinthine region and petrous apex regions with various air cell tracts *(adapted from Allam, 1969)*

1.2.2.2 Developmental Anatomy

Between the 22nd – 24th weeks of intrauterine life, the mastoid antrum (the only visible air cell) begins to develop (Virapongse *et al.,* 1985; Hill, 2011). During late fetal life or at birth, the mastoid antrum (the large central air cell) is fully developed (as a mere minute antral diverticula). It is either pneumatized or filled with embryonic connective tissue (Cheatle, 1907; Hill, 2011). The outer antral wall, formed by the squama, comprises a thin layer of compact bone and an inner layer of fine cells. After birth, air cells begin to enlarge and become readily visible. As this enlargement continues, air cells spread throughout the mastoid (Virapongse *et al.,* 1985; Hill, 2011) [Figure 4]. In adult life, the normal mastoid bone may give different structural appearances such as pneumatized- which forms most of the mastoids; diploic- which contains marrow rather than air cells; sclerotic-which is composed of very dense bone; or mixed- which contains both bone marrow and air cells.

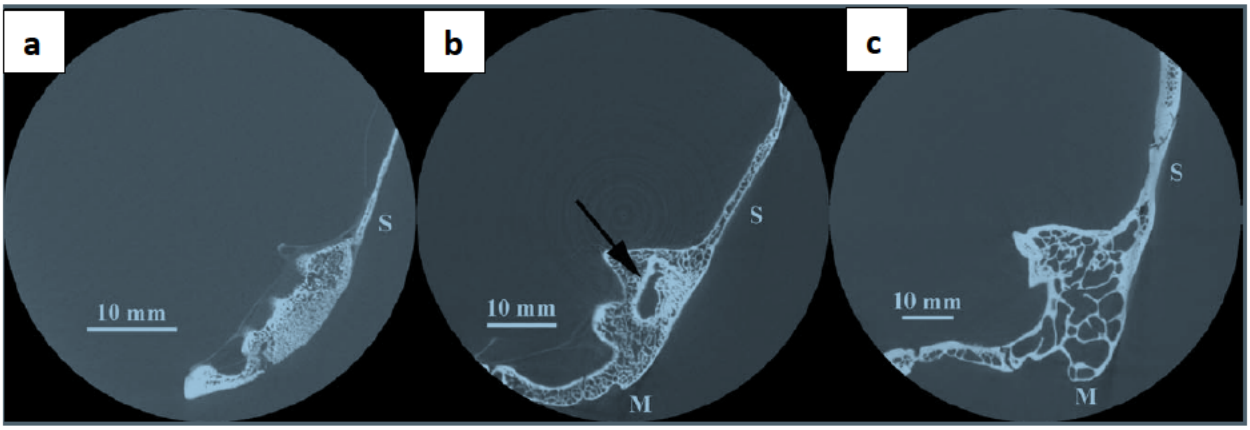

Figure 4: Diagram showing slices of the mid-mastoid region showing the progression of pneumatization, specifically: a) a neonate, b) a 1-year-old, and c) an adult. Black arrow: the thickened bone surrounding the air cells in one of the scans; S: squamous portion; M: mastoid process *(adapted from Hill, 2011)*.

There is no agreement on the development of temporal bone pneumatization, as several authors have different descriptions and suggestions. Virapongse *et al.* (1985) described complete pneumatization in three stages: "*the infantile stage- occurring from birth to two years of age (air cells begin to appear and are readily visible by two years); transitional stage- from two to five years (squamomastoid/mastoid undergoes gradual enlargement with the migration of air cells toward the periphery); and adult stage (attainment of this stage results in cessation of pneumatization).*" This description was stated as a normal development in which the pneumatization can appear well pneumatized (with many air cells) or diploic (containing more bone marrow than air cells). When it appears sclerotic, it becomes abnormal development.

Cinamon (2009) gave a more explicit description after reviewing various studies on temporal bone pneumatization using the surface area of the air cells. It was suggested that the antrum is well developed at birth (1-1.5 cm^2) and the mastoid air cells to be about 3.5-4 cm^2 at one year. A linear growth follows this till the age of 6 years (1-1.2 cm^2 per year); after that, a slow increment up to adult size at puberty (~12 cm^2). The study of Isono *et al.* (2003) among a Japanese population also supported this, identifying that the mastoid air volume could reach about 80% of the volume of adult size at early puberty. At late puberty, it has a mean adult value of 5.79 ml. Isono *et al.* (2003) also suggested that mastoid air volume increases with age.

However, the study of Lee *et al.* (2005) among Korean adults gave a different description. The study stated that *"mastoid aeration increases rapidly from birth until early in the second decade. Thereafter, the growth in size continues at a slow rate, reaching a maximum in the third decade".*

Furthermore, Hill (2011), in an ontogenetic study, statistically evaluated age-related changes in the bony organization of pneumatized spaces in various regions of the temporal bone. This study revealed that the temporal bone is not well pneumatized in infants. The surface area and volumes of pneumatized spaces doubled before age 4. There was a twofold to threefold increase in size between 9 years and adults. [Figure 5]

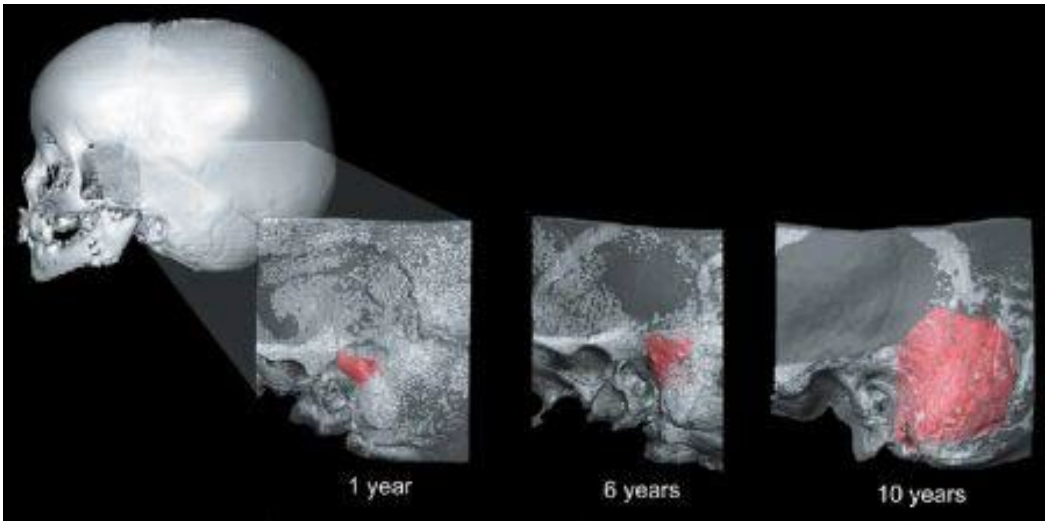

Figure 5: Diagram showing three-dimensional reconstructions of the temporal bone for ages 1 year, 6 years, and 10 years. The red portions delineate the air cell network within the temporal bone, showing a significant increase in the pneumatized spaces *(Adapted from Hill, 2011)*.

1.2.3 Review of studies on the size and growth rate of temporal bone pneumatization and air cell system: surface area and volumetric studies

Over the years, measuring the size of temporal bone pneumatization and air cells has been carried out using cadaveric bone specimens, radiographs, and CT images. (Diamant, 1940; Chatterjee *et al.,* 1990; Lee *et al.,* 2005; Hill, 2011). In radiographs, the planimetric method has been commonly used to measure the surface area of air cells (Arora *et al.,* 1973; Chatterjee *et al.,* 1990). Other methods include the water-weight method and the pressure transducer method (Hill, 2011). Advanced techniques such as volumetric rendering have made it possible to easily measure a more accurate volume of temporal bone pneumatization (Lee *et al.,* 2005). However, studies have

utilized some of these methods to investigate the size of temporal bone pneumatization, but very few are age-related studies (Diamant, 1940; Kawamura *et al.,* 1963; Rubensohn, 1965; Arora *et al.,* 1973; Qvarnberg, 1981; Chatterjee *et al.,* 1990; Isono *et al.,* 2003; Lee *et al.,* 2005; Hill, 2011). The studies are summarized in Tables 1 and 2. The age-related studies gave information on the size and growth of air cells with age. However, the majority of these studies utilized the planimetric method of measurement. These studies were able to consider the surface area of air cells only and reported that pneumatization terminates at puberty [Table 1]. While the studies by Isono *et al.* (2003), Lee *et al.* (2007), and Hill (2011) considered the volumes of air cells and reported that air cells continue to grow after puberty [Table 2].

Amongst these studies, Chatterjee (1990) analyzed the size variation of the mastoid air cell system in an Indian population of different age groups. One hundred human subjects aged six months to 60 years were used. The age group was further subdivided into 1 to 5 years, 5+ to 10 years, 10+ to 15 years, 15+ to 20 years, and above 20 years. The mean area of the mastoid air cell system was measured planimetrically on X-rays [Table 1]. The study found that the rate of development of the mastoid air cell system was very rapid from age one up to ten years, and then it slowed down in both sexes.

Furthermore, the size of the mastoid air cell system in the age group 1+ to 5 years was almost equal to that of Swedish children and larger in Japanese children in the studies of Robensohn (1965) and Kawamura *et al.* (1963), respectively. The area of pneumatization between the age group 5+ to 10 years was comparatively less in the North Indian skull in the study of Arora *et al.* (1973). Still, it was the same as in the Western population (Diamant, 1940). This study did not compare other age groups, as no data was available. Also, discrepancies in the age group of the studies compared with the report of Chatterjee *et al.* (1990) may be due to methods, genetic, or ethnic backgrounds. Considering that volumetric measurements likely give the foremost comprehensive insight to appreciate the estimate of air cells (Cinamon, 2009), the planimetric measurement used to analyze the surface area of air cells could be a common limitation in all of these studies.

Lee *et al.* (2005) considered an age-related study among a Korean population (sample size= 102; age range: 6-84 years). The study utilized a 3D MPVR technique [Figure 7]. The mean volumes of mastoid pneumatization for Korean children (0-9 years) and adults (19-44 years) were 3813.85 mm^3 and 7095.2 $mm^{3,}$ respectively. The study showed that mastoid pneumatization rapidly

increases from birth until the second decade of life, with a slow growth rate until the third decade of life (i.e., 30 years). Afterward, there is a tendency for decline with a slow reduction in volume followed by a rapid decrease late in the seventh decade of life.

Furthermore, this study did not show a statistically significant difference between sex, but the growth of female mastoid pneumatization was interestingly more rapid than in males. In addition to the limitation in considering only the mastoid region, the interval in age grouping was 10 years (i.e., 0-9, 10-19, etc.). The interval in the age group was considered too large and not accurate enough to statistically evaluate age-related changes in the volume of air cells in the temporal bone (Hill, 2011).

Hill (2011) analyzed 28 temporal bones from cadaveric skulls. The skulls were scanned on either side using X-ray CT systems. An image cropping system was used to extract regions and volumes of interest (i.e., ROI and VOI). Both the petrous and mastoid parts were analyzed. Age grouping was from infant to adulthood [infant (neonate–2yearrs); young child (2–4years); middle age (4–8years); adolescent (9–18years); and adult (> 25years)]. The study revealed that the volume of temporal bone pneumatization changed with age. Although the temporal bone is not well-pneumatized in infants as it is limited to the mastoid antrum, the surface area and volume of pneumatized spaces doubled before four years of age. Also, a twofold to threefold increase in air cell size between nine years of age and adulthood. The mean volume of pneumatization for the infant was 232.76 mm^3. There was no statistical significance in the volume of the young and middle age group compared to infants. Adolescent and adult age groups showed mean volumes of 3199.84 mm^3 and 4545.44 mm^3, respectively. The volumes estimated in this study were said to be lower when compared to the mean volumes estimated in the study by Koc *et al.* (2003), Lee *et al.* (2005), Han *et al.* (2007), and Kim *et al.* (2010), that conducted their studies among the Turkish, Korean, South Korean and Korean population groups, respectively, utilizing volumetric surface rendering technique [Table 2] [Figure 6 & 7]. Besides, the sample size of Hill (2011) was comparatively very small and was conducted in the Columbian population group [Table 2]

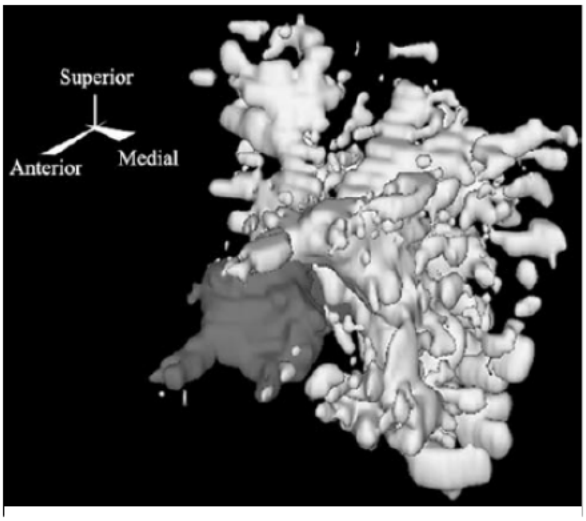

Figure 6: 3D reconstruction by surface rendering. **Pneumatization of a right temporal bone considering the mastoid air cell system (white shading), excluding the eustachian tube, middle ear, and external auditory canal (grey shading)** *(Adapted from Lee et al., 2005)*

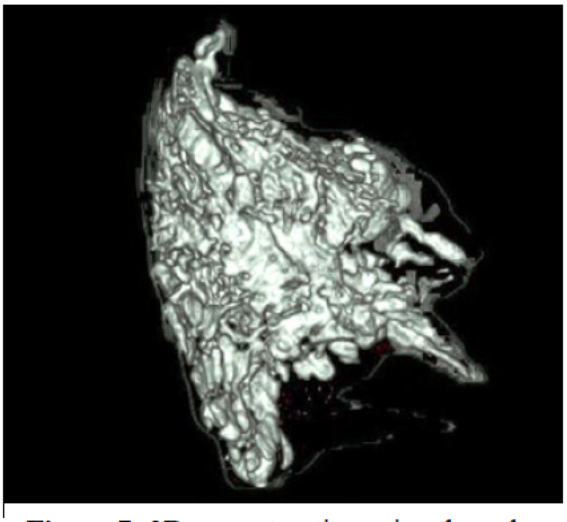

Figure 7: 3D reconstruction using the volume rendering technique. **Pneumatization of the right side of the temporal bone is composed of the middle ear, petrous apex, and mastoid air cells.** *(Adapted from Han et al., 2007)*

Table 1: Previous studies analyzing the surface area of temporal bone pneumatization and air cell system

Author (Date)	Country (Population)	Sample Size	Age (Years)	Methodology	Age grouping	Temporal bone pneumatization (mean area of air cells)	Size of temporal bone air cell area with age (M- male; F- female)
Diamant (1940)	Sweden (Swedish Children; pre-antibiotic era)	180	1 to 15 years	-Prospective study -X-ray planimetry	5 years	12.04 ± 0.37 cm^2	• Size (cm^2) with respect to age: 1 – 5 yrs = 5.80 (M); 6.97 (F) 5 – 10 yrs = 9.68 (M); 10.49 (F) 10 – 15 yrs = 9.47 (M); 14.2 (F) 15 – 20 yrs = ?? (M); 11.03 (F)
Kawamura *et al.* (1963)	Japan (Japanese Children)	116	1 – 6 years	-Retrospective -X-ray measurements.	1 year	4.71 cm^2	• Size (cm^2) with respect to age: 1yrs= 3.06; 2yrs= 4.33; 3yrs= 4.56; 4yrs= 4.10; 5yrs= 5.53; 6yrs= 6.68
Rubensohn (1965)	Sweden (Swedish Children)	430	1 – 15 years	-Retrospective -Mastoid X-ray measurements.	1 year	9.32 cm^2	• Size (cm^2) with respect to age: 1yrs= 4.7; 2yrs= 4.8; 3yrs= 6.5; 4yrs= 7.2; 5yrs= 8.6; 6yrs= 9.1; 7yrs= 10.9; 8yrs= 11.4; 9yrs= 12.7; 10yrs= 10.1; 11yrs= 9.9; 12yrs= 11.0; 13yrs= 11.4; 14yrs= 12.7
Arora *et al.* (1973)	Indian (North Indian Children)	100	5 to 15 years	-Retrospective -Roentgenographic planimety	5 years	10.91±0.46cm^2	• Size (cm^2) with respect to age: 5 – 10 yrs = 7.66 (M); 9.09 (F) 10 – 15 yrs = 9.30 (M); 10.02 (F)
Wolfowitz (1974)	South Africa (South African "Bantu-speaking Blacks")	–	17 – 90 years	-Retrospective -Dried cadaver planimetry	–	–	–
Qvarnberg (1981)	Finland (Finish Children)	232	Birth to 16 years	- Retrospective -X-ray planimetry	1 year	9.66 cm^2	• Size (cm^2) with respect to age: 0-5months= 2.9; 6-11months= 3.3; 1yrs= 3.7; 2yrs= 5.2; 3yrs= 6.7; 4yrs= 7.9; 5yrs= 9.8; 6yrs= 10.7; 7yrs= 10.6; 8yrs= 10.7; 9yrs= 12.2; 10yrs= 12.0; 11yrs= 12.0; 12yrs= 12.0; 13yrs= 12.0; 14yrs= 12.0

Chatterjee *et al.* (1990)	Indian (West Bengal: Bengalee People)	100	6 months to 60 years	-Cross-sectional retrospective study -Xray planimetry	5 years	12.05 ± 0.67 cm^2 (male) 11.45 ± 0.70 cm^2 (female)	• Size (cm^2) with respect to age: 1 – 5 yrs = 7.38 (M); 7.19 (F) 5 – 10 yrs = 11.51 (M); 9.69 (F) 10 – 15 yrs = 11.89 (M); 11.47 (F) 15 – 20 yrs = 12.54 (M); 13.87 (F) Above 20 yrs = 16.93 (M); 14.76 (F)
Park *et al.* (2000)	Korea	15	20 – 35 years	-Axial CT	–	167.0 cm^2 (Range= 74.78 cm^2 – 330.01 cm^2)	–

Table 2: Previous studies analyzing the volume of temporal bone pneumatization and air cell system

Author (Date)	Country (Population)	Sample Size	Age (Years)	Methodology	Age grouping	Temporal bone pneumatization (mean volume of air cells)	Size of temporal bone air cell volume with age (M- male; F- female)
Todd *et al.* (1987)	–	30	Adults	Lateral radiographs	–	7.95 ml	–
Colhoun *et al.* (1988)	–	26	Adults	HRCT images	–	9.5 cm^3	–
Isono *et al.* (1999)	Japan	26	Adults	CT film	–	5.97 ml	–
Park *et al.* (2000)	Korea	15	20 – 35 years	Axial CT 1	–	10.43 cm^3 (Range= 6.25 cm^3 – 20.52 cm^3)	–
Luntz *et al.* (2001)	Israel	69	(Adult)	3D reconstruction of ultra-HRCT	–	6.61 cm^3 (Range= 1.3 cm^3 – 12.7 cm^3)	–
Vabrec *et al.* (2002)	–	–	> 14 years	3D CT volumetric reconstruction	–	5.56 ml	–
Isono *et al.* (2003)	Japan	80	1 – 18 years	HRCT images (2 mm)	–	5.97 ml (Adults only)	–
Koc *et al.* (2003)	Turkey (Turkish Population)	50	–	-Retrospective 3D-MPVR HRCT	–	7.9 cm^3 (4.0 cm^3 – 14.0 cm^3)	–
Lee *et al.* (2005)	Korea (Korean population)	102	6 – 84 years	-Retrospective 3D-MPVR CT images (2.5 mm)	10 years	3813.85 mm^3 (Children: 0-10yrs) 7095.20 mm^3 (Adult: 19-44yrs)	• Size (mm^3) with respect to age: 0 – 9 yrs = 4315.4 (M); 3312 (F) 10 – 19 yrs = 6963.9 (M); 7320.6 (F) 20 – 29 yrs = 8211.7 (M); 6748.6 (F) 30 – 39 yrs = 7321.1 (M); 6403.9 (F) 40 – 49 yrs = 6333.7 (M); 6306.1 (F) 50 – 59 yrs = 6580.9 (M); 5063.8 (F) 60 – 69 yrs = 4993.0 (M); 5092.3 (F) 70 – 79 yrs = 4961.3 (M): 2,759.5 (F) 80 – 89 yrs = 2012.6 (M); 2022.3 (F)

Han *et al.* (2007)	South Korean (Young Korean Adult)	92	≥ 20 years	-Retrospective 3D-MPVR CT (1 mm)	–	15.28 ± 5.34 cm^3	–
Molvaer *et al.* (2009)	–	55	–	Acoustic method (Fluid-filling induced vacuum)	–	6.5 cm^3 (2 – 22 cm^3)	–
Kim *et al.* (2010)	Korea (Korean adult)	60	18 – 63 years	-Retrospective -PNS 3D CT	–	6151.25 mm^3	–
Hill (2011)	Columbia, Missouri (Human Cadaveric temporal bone)	28	0 – 25 years	-Cross-sectional sampling -3D reconstruction	–	Adolescents = 3199.84 mm^3 Adults = 4545.44 mm^3	–
Jadhav *et al.* (2014)	University of Connecticut Health Centre	78	16-84 years	-Retrospective -Cone-beam CT	–	1337 ± 9 mm^3 (Infants only)	–

1.2.4 Classification of Temporal Bone Pneumatization

From the earliest study of Zuckerkandl (1879), the classification of temporal bone pneumatization has been based on its degree or extent of pneumatization, utilizing gross anatomical observations, serially sectioned specimens, or radiographs (Diamant, 1940; Allam, 1969). The term pneumatized, diploic, and sclerotic were used to distinguish different degrees of pneumatization. With the development of advanced imaging technology, assessing the degree of pneumatization of a temporal bone on CT scans has been used by otologic, head, and neck surgeons. Few studies have also utilized this imaging technique in devising and suggesting methods for classifying the temporal bone degree of pneumatization (Virapongse *et al.,* 1985; Koc *et al.,* 2003; Al-Faleh *et al.,* 2005; Han *et al.,* 2007; Jadhav *et al.,* 2014; Marchioni *et al.,* 2016. [Table 3].

Some of these classifications have limitations in clinical applications, most especially when performing middle-ear surgeries and some mastoidectomies (Virapongse *et al.,* 1985; Koc *et al.,* 2003; Al-Faleh *et al.,* 2005; Marchioni *et al.,* 2016). Although the classification system by Han *et al.* (2007) was more defined and utilized in various studies due to its specific landmark/reference structure, it could be time-consuming and, in most emergency surgeries, could be a burden for otologic surgeons [Figure 8]. The classification by Jadhav *et al.* (2014) also utilized reference structures but was only limited to the inner ear/petrous apex, and only one study has been reported to utilize this classification (Kang *et al.,* 2019) [Figure 9].

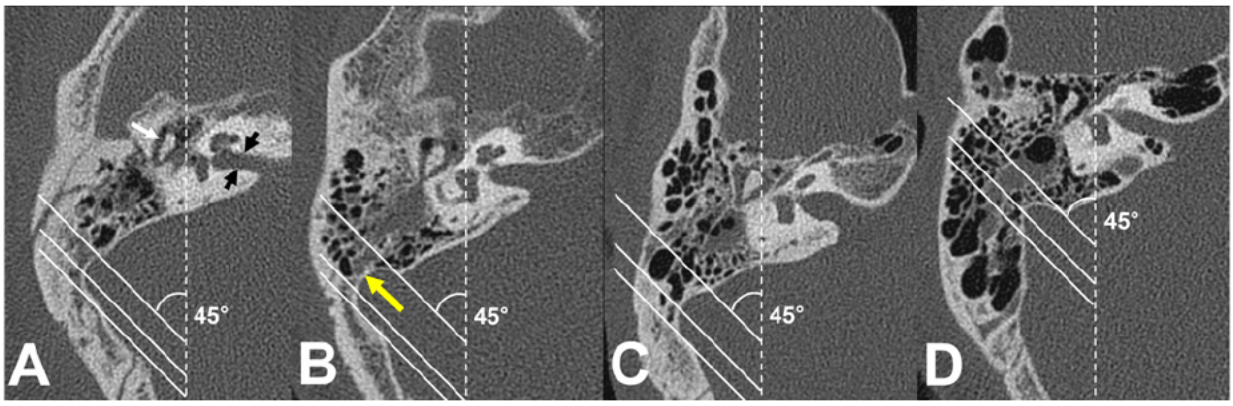

Figure 8: Diagram showing the suggested classification system degree of temporal bone pneumatization by Han *et al.* (2007) using sigmoid sinus [yellow arrow] as reference structures (at the appearance of the malleoincudal complex as ice-cream cone-shaped [white arrow] on axial CT image) *(Adapted from Kang et al., 2019).*

Description of Figure 8: At the axial section in which the malleoincudal complex appears like an ice-cream cone; three parallel lines were applied in the anterolateral direction angled at 45° with

each crossing the most anterior point of the SS at the junction with the petrous bone, the most lateral aspect along the transverse plane of the sigmoid groove, and the most common posterior point of the SS, respectively. With the application of these lines, the degree of pneumatization was classified into four groups: Hypo-pneumatization- pneumatization that extends to the line drawn at the most anterior aspect of the SS [A]; Moderate pneumatization- pneumatization that extends to the space between arbitrary lines drawn at the most anterior point and most lateral aspect of the SS [B]; Good pneumatization- pneumatization that extends to the space between the lines drawn at the most lateral region and the most posterior point of the SS [C] and; Hyper-pneumatization- pneumatization that extends postero-laterally beyond the line drawn at the posterior point of the SS [D]

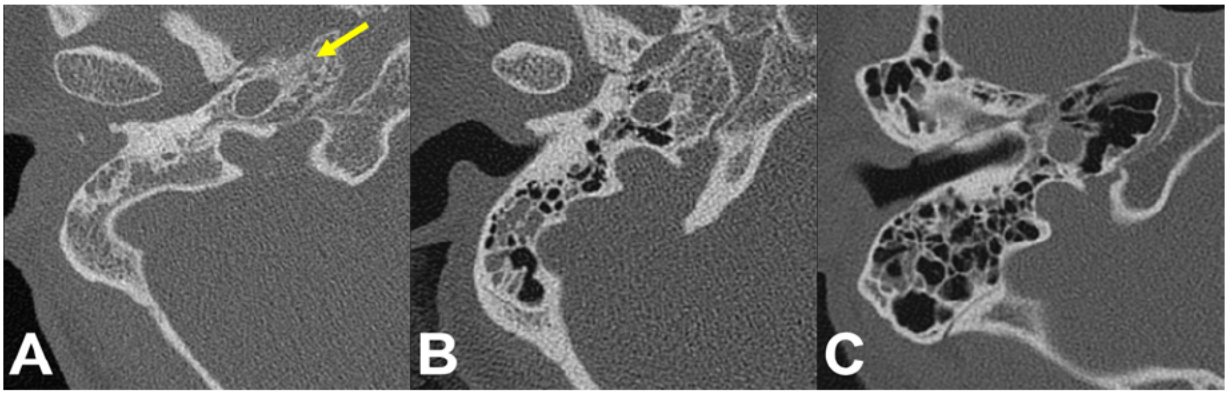

Figure 9: Diagram showing the devised classification system of the degree of temporal bone pneumatization by Jadhav *et al.* (2014) using the carotid canal [yellow arrow] as reference structures *(Adapted from Kang et al., 2019).*

Description of Figure 9: Using the carotid canal petrous segment of the temporal bobe as a reference structure, the degree of pneumatization was classified into three groups: Group 1- None (no pneumatization present in the petrous apex) [A]; Group 2- Mild pneumatization (focal pneumatization is found either medial or lateral to the carotid canal) [B]; and Group 3- Complete pneumatization (pneumatization is surrounding the carotid canal) [C].

Table 3: Summary of studies on devised and suggested classification systems of the temporal bone degree of pneumatization.

Author	Method	Classification System
Virapongse *et al.* (1985)	CT image	A scoring system based on number of air cells on CT slice that best demonstrate the region (4 Grades) Grade 1- 10 or fewer medium-sized cells Grade 2- 11 – 30 cells Grade 3- 31 – 50 cells Grade 4- 51 or more cells.
Koc *et al.* (2003)	3D-MPVR of CT image	Volume of mastoid air cells (3 Levels) Level 1- small pneumatization with an air cell system not exceeding 6. cm^3. Level 2- medium pneumatization with an air cell system of 6 to 10.cm^3. Level 3- large pneumatization with an air cell system exceeding 10. cm^3.
Al-Faleh and Ibrahim (2005)	Cone-beam CT (CBCT)	Surface evaluation of air cells around the mastoid process, glenoid fossa, and articular eminence Grade 0- pneumatization limited to the mastoid process. Grade 1- pneumatization between the mastoid process and glenoid fossa. Grade 2- pneumatization between the glenoid fossa's deepest part and the articular eminence's tip. Grade 3- pneumatization extending beyond the crest of the articular eminence.
Han *et al.* (2007)	HRCT (Axial)	Using the SS as a reference structure and malleoincudal complex as a landmark (4 Degrees) Group 1- Hypo-pneumatization Group 2- Moderate pneumatization Group 3- Good pneumatization Group 4- Hyper-pneumatization. [Figure 8]
Jadhav *et al.* (2014)	CBCT	On CBCT with reference to carotid canal (3 Degrees) Group 1- No pneumatization (None). Group 2- Mild pneumatization Group 3- Complete pneumatization. [Figure 9]
Marchioni *et al.* (2016)	CT (Sagittal)	Using the labyrinth, petrous apex, and internal auditory meatus as reference structures (3 Types) Type A- well-pneumatized temporal bone at the most inferior and medial portion of the petrous apex Type B- limited pneumatized bone below the labyrinth. Type C- no air cells at the petrous apex's most inferior and medial portion.

Table 4: Review of studies that have utilized different classification systems to investigate the degree of temporal bone pneumatization in different populations.

Author	Sample size	Population (Location)	Age (Years)	Methodology	Classification method(s)	Most common temporal bone degree of pneumatization
Virapongse *et al.* (1985)	100 patients	White (Non-Hispanic) (Connecticut, USA)	6 – 8	CT scans	Utilizing subjective evaluation of the approximate surface area of pneumatization and the number of air cells (Virapongse *et al.,* 1985)	Grade 2 & Grade 3 account for 84% of the population
Han *et al.* (2007)	92 patients	Young Korean Adult (South Korea)	≥ 20	CT scans in axial view	Utilizing reference structures (SS, labyrinth & carotid canal) (Han *et al.,* 2007)	Group 2 (Moderate pneumatization): 48 cases
Jadhav *et al.* (2014)	78 patients	University of Connecticut Health Centre	18 – 70	CBCT scans	Utilizing reference structures (labyrinth and carotid canal) (Han *et al.,* 2007; Jadhav *et al.,* 2014)	Group 2 (mild pneumatization): 57 cases
Bronoosh *et al.* (2014	225 patients	Iranian (Iran)	8 – 85	HRCT scans in axial view	Utilizing reference structures (SS, labyrinth & carotid canal) (Han *et al.,* 2007)	SS as reference Hyper-pneumatization: R= 30.0%; L= 31.7% Labyrinth & carotid canal as references Group 1: R= 42.3%; L= 43.4%
Demirel *et al.* (2014)	250 patients (127 males & 123 females)	Turkish Adult (Turkey)	–	CBCT scans in axial view	Utilizing surface evaluation of air cells around the mastoid process, glenoid fossa & articular eminence (Al-Faleh & Ibrahim, 2005)	Grade 1 & Grade 2 accounting for 74% of the population (67.33% male; 60.57% female)
Tan *et al.* (2018) ***Largest study so far**	299 patients (166 males & 133 females)	Singapore *Chinese= 221* *Malay= 47* *Indian= 31*	13	CT scans in axial and sagittal views	Utilizing reference structures (SS, labyrinth &carotid canal). (Han *et al.,* 2007 & Marchioni *et al.,* 2016)	SS as reference Hyper-pneumatization- 55.4% **(There is no significant association between age, sex and population group, and degree of pneumatization).** Labyrinth & carotid canal as reference Group 2- 54.8% **(There is a significant association between age and sex and degree of pneumatization but not in the population group).**

1.2.5 Overview of Temporal Bone Fracture and Trauma, Incidence Rate, and Clinical Significance of Temporal Bone Pneumatization

Temporal bone fractures are lesions in individuals/patients mostly with traumatic brain injury (Secchi *et al.,* 2012). Major causes may include heavy falls, car accidents, sports injuries, and physical assault (Secchi *et al.,* 2012). Currently utilized classification of temporal bone fractures is given as: i) otic capsule-violating fractures that course through the labyrinth (i.e., the cochlea, vestibule, and semicircular canals); ii) otic capsule-sparing fractures which do not involve the otic capsule (Secchi *et al.,* 2012; Most, 2020). The previous classification of temporal bone fractures can be given as follows: longitudinal fractures- which make up 70% to 90% of temporal bone fractures, extending through the ME and rupturing the tympanic membrane; transverse fractures- which make up 10% to 30% of temporal bone fractures, crossing the fallopian canal and otic capsule; and mixed fractures- which is a combination of the characteristics of longitudinal and transverse fractures (Secchi *et al.,* 2012).

The overall incidence rate of traumatic brain injury in 100,000 people in 2015 was as follows: North America- 1299, Africa- 801, Europe- 1012, Eastern Mediterranean- 897, and Southeast Asia 984 (Dewan *et al.,* 2019). In a systemic review by Dewan *et al.* (2019), 69 million individuals (ranging from 64 – 74 million) are estimated to suffer traumatic brain injury from all causes yearly. Road traffic accidents were the most common cause, the greatest in Africa and Southeast Asia (56%) and the lowest in North America (25%).

According to World Head Injury Awareness Day on 20th March 2016, head injuries were reported to be relatively common in South Africa and have devastatingly impacted many people's lives. Eighty-nine thousand new cases of traumatic brain injuries are reported every year. The most common causes are motor vehicle, bicycle, or vehicle-pedestrian accidents (50%), falls (heavy or moderate) accounting for 25%, and violence (which is also one of the four major epidemics faced in South Africa) accounting for 20% (Makolane *et al.,* 2019). Makolane *et al.* (2019) reported the prevalence of basal skull fracture to be 15.2% (32 out of 210 patients) in the Tshwane district of Gauteng province. The majority (80.5%) were under 40 years old, with a male-to-female ratio of 3:1. The middle cranial fossa was identified as the most frequently fractured compartment (18/32; 56.25%), with the petrous bone being the most fractured, both in isolation and in combination with

other bones (12/18; 66.67%). Major causes were vehicle-pedestrian accidents, falls, and violence (Makolane *et al.,* 2019).

Temporal bone pneumatization plays an important role in the absorption and dispersion of kinetic energy (serving as a shock absorber) in lateral skull-based fractures (Kang *et al.,* 2019). It can prevent further damage to the auditory apparatus. Kang *et al.* (2019) substantiated this by revealing that otic capsule-violating fractures were present only in temporal bone with reduced pneumatization. However, the air cell system of the temporal bone is believed to have an important role in surgical intervention in this region of the skull (Koc *et al.,* 2003).

Also, the degree of pneumatization of the petrous temporal bone has important surgical implications. For instance, the success of ME surgery depends on mastoid pneumatization, i.e., it is a prognostic factor (Allam, 1969). Patients with poor pneumatization are more prone to complications in this surgical procedure (Lee *et al.,* 2015). This is because mastoid cells are air reservoirs of the ME, thereby regulating ME pressure (Koc *et al.,* 2003). Additionally, Stieglitz *et al.* (2010) revealed that patients with higher mean air cell volume in the petrous bone undergoing retrosigmoid surgical removal of vestibular schwannoma had a significantly higher rate of postoperative cerebrospinal fluid (CSF) fistula. Air cells in the petrous temporal bone can also provide CSF otorrhea routes after skull base surgery for cerebellopontine angle tumors (Yamakami *et al.,* 2003).

1.2.6 Overview of Otitis Media (OM), Middle Ear (ME) Pathology and Hearing Impairments, Incidence Rate, and Clinical Significance of Temporal Bone Pneumatization

Temporal bone pneumatization has been implicated in the pathophysiology of chronic ear infections such as OM and ME pathology (Tan *et al.,* 2018). This is because the extent of pneumatization clinically correlates with the spread of infectious diseases that may bring about chronic ear diseases, leading to hearing dysfunction and hearing impairments/loss (Olusanya *et al.,* 2014). For instance, a poor pneumatized temporal bone (hypo-pneumatization) or the small air cell system predisposes to acute and chronic OM (Koc *et al.,* 2003).

Hearing is an essential sensation in human communication, and its impairment at any stage of one's life can compromise the communication process, thereby influencing the quality of one's life (Taylor *et al.,* 2012; Ramma & Sebothoma, 2016). Table 5 below shows the prevalence of

disabling hearing loss (hearing loss greater than 35dB in the better hearing ear) across regions of the world among children and adults *(adapted from WHO, 2012)*. Sub-Saharan Africa ***(*)*** accounts for the second-highest prevalence in children, with a high incidence in adult males and females.

Table 5: Prevalence of disabling hearing loss across regions of the world.

	Selected Regions	DHL in children		DHL in adults			
		Both sexes		Males		Females	
		millions	prevalence (%)	millions	prevalence (%)	millions	prevalence (%)
	High-income	0.8	0.5	19	4.9	18	4.4
	Central/Eastern Europe and Central Asia	1.1	1.6	14	9.0	16	8.8
*	Sub-Saharan Africa	6.8	1.9	17	7.4	13	5.5
	Middle East and North Africa	1.2	0.9	6	4.1	4	2.9
	South Asia	12.3	2.4	52	9.5	36	7.0
	Asia Pacific	3.4	2.0	19	8.7	15	6.8
	Latina America and Caribbean	2.6	1.6	15	7.6	13	6.0
	East Asia	3.6	1.3	41	7.4	30	5.6
	World	31.9	1.7	183	7.5	145	5.9
	MBD, WHO, 2012 DHL estimates DHL: Disabling Hearing Loss						

In South Africa, hearing impairment is the third-highest reported disability after visual impairment and physical disability (Statistics South Africa, 2012). World Health Organization (2011) also classified hearing loss as a poverty-related disease, one of the four major epidemics faced in South Africa. Most studies on the prevalence of hearing loss and disorders in South Africa have ascribed the major cause of hearing loss to ME infections such as OM and other ME pathologies (highlighted in Table 6 below).

Otitis media is the inflammation of the ME, which comprises a spectrum of diseases (Tesfa *et al.,* 2020). It has been ranked as the second-most common cause of hearing loss (Morris & Leach, 2009; DeAntonio *et al.,* 2016) and the fifth global burden of disease, with the highest incidence rate in Sub-Saharan Africa and South Asia (Vos *et al.,* 2015; Tesfa *et al.,* 2020).

Early studies conducted across South Africa to investigate the prevalence of OM and other ME pathologies among children and adults varied between 7.2% and 38% (Halama *et al.,* 1986; Nel *et al.,* 1988; Cilliers *et al.,* 1988). Incidence rates have been on the increase to date [Table 7]. Phanguphangu (2016) revealed a high prevalence (51%) of outer and ME pathologies in pediatrics. According to the study by Prescott and Kibel (1991), 59.7% of school children in the Western Cape have different types of ear and hearing disorders. The most recent study in Western Cape indicated a referral rate of 7.9% (Mahomed-Asmal *et al.,* 2016). Furthermore, ME infections/diseases could ultimately lead to conductive hearing loss (when sound cannot get through the outer and middle ear) in the school-aged and general populations (Mulwafu *et al.,* 2016).

Table 6: Prevalence of Hearing Loss and Disorder and Reported Causes in South Africa

Author	Location	Age (Years)	Sample	Prevalence	Causes
Prescott & Kibel (1991)	Western cape	School children	401	59.7% have different types of ear and hearing disorders	**Past acute OM (progressive to chronic), ME effusion**, obstructing wax plug,
Couper (2002)	KwaZulu-Natal	< 10	2036	More in children between 6 – 9 years	–
North-Marhiaseen & Singh (2007)	Western Cape	6 – 12	1101	7.9%	–
Pullen (2015)	Limpopo	Mean age 27.9	850	8.9% have hearing loss (≥ 65yrs with the highest)	**OM (more often)** impacted cerumen
Mahomed-Asmal *et al.* (2016)	Tshwane, Gauteng	Children	1070	2.2%	**Middle-ear effusion**, cerumen in the ear canal, **OM**
Ramma & Sebothoma (2016)	Cape town	1 – 60+	2494	12.5% have hearing loss (4.57% disabling hearing loss among ≥ 4 years)	**History of trauma,** age, gender (male), hypertension, a family history of hearing impairment
Louw *et al.* (2018)	Tshwane, Gauteng.	3 – 97	1236	17.5% have hearing loss (3 – 4yrs= 4.8%; 15 – 39yrs= 5.7%; ≥ 40yrs= 15%)	**ME disease**, high cost of ear and hearing services
Joubert & Botha (2019)	Elias Motsoaledi Local Municipal	15 – >65	1428	19.88%	**Ear disease** with cerumen and **OM reported most often**

Table 7: Incidence of Otitis Media (OM) and Other Middle-Ear (ME) Pathologies in South Africa

Author	Location	Sample	Outcome
Halama *et al.* (1986)	Vhuri-Vhuri village, Venda	267 children (< 15 years)	OM in children (8.2%)
Nel *et al.* (1988)	Pretoria	146 primary school children	ME pathology (7.2%)
Cilliers *et al.* (1988)	Pretoria	94 subjects (66 – 95 years)	Outer and ME pathology (38%)
Biagio *et al.* (2014)	WHWC, North of Johannesburg	140 children (2 – 16 years)	-OM: younger children (31.4%) and older children (16.7%). -OM effusion (16.5%)
Phanguphangu (2016)	Limpopo	1089 pupils	Outer and ME pathologies (51%)

1.2.7 Overview of Temporal Bone-Related Vascular Structures

Major vascular structures related to the temporal bone are mostly found passing through fissures and foramina in the petromastoid part and having different relationships with the auditory apparatus (Standring, 2008). These structures include the sigmoid sinus (SS), jugular bulb (JB), and internal carotid artery (ICA).

The SS i**s** an S-shaped dural venous sinus extending from the mastoid process to the jugular foramen beneath the temporal bone. It is a continuation of the transverse sinus, passing infero-medially in a groove on the mastoid process of the temporal bone (Shaikh, 2012).

The JB connects the SS and the internal jugular vein (Shaikh, 2012). It is somewhat enlarged to form the superior bulb arising from the first part of the internal jugular vein, which projects into the floor of the tympanum (Friedmann *et al.,* 2011).

The ICA is the terminal branch of the common carotid artery that most frequently arises between the C3 and C5 vertebral levels, where the common carotid bifurcates to form the internal carotid and external carotid arteries.[Figure 10]

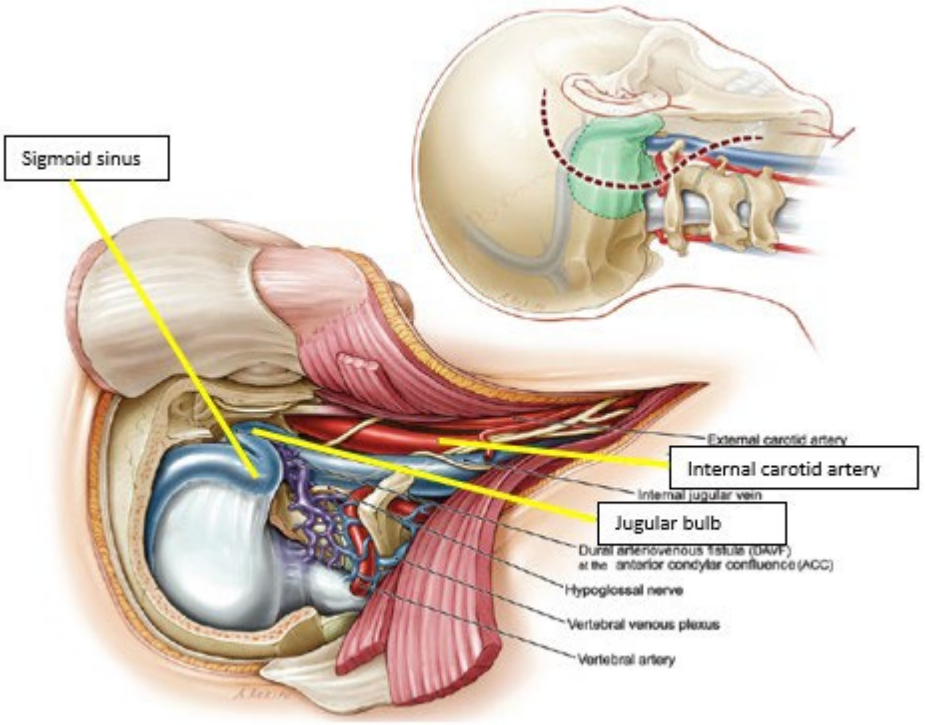

Figure 10: Diagram showing temporal bone-related vasculatures highlighted *(adapted* from Liu *et al., 2008)*

The pneumatization of the temporal bone is believed to significantly influence the anatomy of the vessels related to this region (Singh *et al.,* 2017). These vessels are important in planning and executing surgeries on petrous and mastoids (Sarmiento and Eslait, 2004). For instance, the SS has greatly assisted in preventing complications in cases where osteomas and cholesteatomas have destroyed traditional landmarks such as the posterior auditory canal wall or posterior semicircular canal (Sarmiento and Eslait, 2004). Besides, some of these related vessels are commonly encountered in routine clinical practice. They can pose dangers (i.e., pitfalls for surgeons) during related surgical procedures (Inal *et al.,* 2015), e.g., the JB and its variants, as well as anteriorly placed SS (Kawano *et al.,* 2000; Clarke and Booth, 2017).

1.2.7.1 Morphology and Anatomical Variants of the Sigmoid Sinus (SS)

The SS morphology varies in shape and location (Sarmiento and Esliat, 2004). Dai *et al.* (2007) noted that temporal bone pneumatization might be a contributing factor to this. Also, Singh *et al.* (2019) identified that the volume of mastoid pneumatization impacts the location of the SS, as a more properly placed SS was associated with a larger volume of mastoid air cells. Anatomical

variations of SS may result in aberrant variants such as SS diverticulum or dehiscence, which induce abnormal blood flow within the SS with resultant hearing symptoms (Wenjuan *et al.,* 2015). Different morphologies and anatomical variations of the SS have been described and classified. Ichijo *et al.* (1993) classified the SS into three types of shapes considering the SS- depth (D) and SS- width (W) of the lateral sinus: half-moon type, protrusive type, and saucer type, utilizing CT imaging in an axial plane.

Furthermore, the half-moon type of SS was ascribed to a healthy mastoid and seen as a regular type (most common) of SS [Table 8]. This was observed in the study by Sirikci *et al.* (2004) that the SS shape becomes more protrusive as the air cells diminish. Sarmiento and Eslait (2004) also classified the SS into three types according to the location in the mastoid: type 1, type 2, and type 3 (Trautmann's triangles), utilizing 96 cadaveric adult temporal bones from individuals with no history of ear disease by dissection, simulating a canal wall-up mastoidectomy with extension to expose the facial recess epitympanium and SS.

1.2.7.2 Morphology and Anatomical Variants of the Jugular Bulb (JB)

Jugular bulb variants in terms of size, location and relationship with nearby structures are multifactorial, which may depend on the degree of pneumatization of the temporal bone (Dai *et al.,* 2007; Friedman *et al.,* 2010; Inal *et al.,* 2015). Additionally, blood flow-related factors and changes to the semicircular canal orientation with age may contribute to JB varaints (Lyu *et al.*, 2016). There are several categories of JB variants/anomalies; high or high-riding JB, JB diverticulum, inner ear adjacent JB, and JB-related inner ear dehiscence. These JB anomalies are also responsible for some irrelevant buzzing in the ear, which, when consistent, may damage the ear and its function (Friedmann *et al.,* 2011).

Friedmann *et al.* (2011) and Park *et al.* (2015) identified a high JB (HJB) as a common JB variant that is not rare in a population. Kawano *et al.* (2000) confirmed this as their study's overall incidence of an HJB was 16%. An initial clinical study by Aslan *et al.* (1997) showed a higher incidence of HJB, as 23% of the population studied accounted for this [Table 8]. Low *et al.* (1995) conducted a study on the influence of population variation on the position of the JB among 58 Chinese and 60 Caucasians, and it was concluded that population variation did not have an influence on the height of the JB in a sagittal plane between the studied populations. However,

population influence can be possible when HJB is medially or laterally situated. Other studies on the incidence of JB variants are summarized in Table 8.

1.2.7.3 Morphology and Anatomical Variants of the Internal Carotid Artery (ICA)

An ICA variation, such as an ICA dehiscence, could present with pulsatile tinnitus (Cavusoglu *et al.,* 2016; Kizildag *et al.,* 2016). In a pathological study (University of Michigan Hospital, USA) by Silbergleit *et al.* (2000), aberrant ICA was found to be present in five patients of different age groups with a history of hearing symptoms. In the same study, a persistent stapedial artery was present, arising from an aberrant ICA and coursing through stapes via angiographic and surgical findings, respectively. Furthermore, a clinical study of Inal *et al.* (2015) observed ICA dehiscence to occur in unilateral and bilateral HJB among 20 adult patients in Kirikkale, Turkey [Table 8].

Persistent Stapedial Artery (PSA): The persistent stapedial artery is a rare vascular anomaly (with a histopathologic incidence of 2 in 1400 specimens) that may present as a pulsatile ME mass found incidentally during ME surgery (Yilmaz *et al.,* 2003). The prevalence of this anomaly is estimated to be 0.02 to 0.48% (Govaerst *et al.,* 1993; Silbergleit *et al.,* 2000). When a PSA is present, it can cause conductive hearing loss by limiting the movement of the stapes, thereby mimicking otosclerosis (Goderie *et al.,* 2017). In such cases, stapedectomy is carried out to improve hearing. No sex-based studies on the incidence of PSA have been carried out. However, only clinical studies have been conducted on its occurrence in some patients with a history or existing hearing symptoms (Silbergleit *et al.,* 2000; Yilmaz *et al.,* 2003). In most of these clinical studies, PSA occurs in most cases of hearing symptoms alongside aberrant ICA in different age groups (Silbergleit *et al.,* 2000).

Table 8: Morphological studies of temporal bone-related vascular structures

Author	Country/ Location	Age (years)	Sample	Method	Temporal bone-related Vascular Variants								
					Jugular Bulb (JB)					Sigmoid Sinus (SS)			Internal Carotid Artery (ICA)
					Normal JB	High JB	JB Dehiscence	Flat JB	High-riding JB	Half-moon	Protrusive	Saucer	ICA Dehiscence
Aslan *et al.* (1997)	Italy	Adults	30 temporal bones	Formalin-fixed skull (Dissection)	–	23%	–	–	–	–	–	–	–
Sirikci *et al.* (2004)	Turkey	17-67	58 patients	Axial CT	–	–	–	–	–	25(62%)	4(10%)	11(28%)	–
Vachata *et al.* (2010)	Czech Republic	Adults	200 temporal bones	Alcohol-fixed skull base & HRCT	68%	15.5%	–	15%	1.5%	–	–	–	–
Inal *et al.* (2015)	Turkey	30 – 86	40 ears	HRCT	13	27	–	–	–	–	–	–	–

1.3 Problem Statement

The temporal bone, despite being smaller in size when compared to other bones of the cranial vault, remains a complex anatomical structure (Osama *et al.,* 2018). One of its major complexity is the degree of pneumatization, which gives the temporal bone its resilient properties against fractures due to direct trauma on the lateral aspect of the skull (Kang *et al.,* 2019). Globally, traumatic head injuries and temporal bone fractures incidences keep increasing, bringing psychological distress to individuals involved (Dewan *et al.,* 2019; Psychology Today, 2020). In South Africa, there is an increase in head injuries and lateral basal skull fractures resulting from motor vehicle accidents, falls, and violence- one of the major epidemics faced by South Africans (Makolane *et al.,* 2019). Despite the increasing rate of temporal bone fracture and trauma, literature has revealed no information regarding the pattern of pneumatization of the temporal bone in this population. Tan *et al.* (2018) stated that the pattern and degree of pneumatization vary among individuals or different population settings with possible factors including age, sex, genetics, environment, nutrition, and diseases. Although Wolfowitz (1974) described the pneumatization of the skull among the South African *"Bantu-speaking Blacks,"* information on the pneumatization of the temporal bone is still lacking.

Furthermore, the success of surgical procedures following direct trauma to the lateral base of the skull and ME surgery is highly dependent on the degree or extent of pneumatization, which also serve as a prognostic factor (Allam, 1969; Koc *et al.,* 2003). It could also give where the position of related vasculatures, such as the SS and JB (Singh *et al.,* 2019). Aberrant positions that could become pitfalls for surgeons (i.e., there is an element of association between pneumatization and the morphological and morphometrical variations of temporal bone-related vasculature) (Dai *et al.,* 2007; Singh *et al.,* 2017; Singh *et al.,* 2019). Currently, there is no standardized method of classifying the extent or degree of temporal bone pneumatization, resulting in a lack of consensus among otologic, head, and neck surgeons. Although few authors have tried to devise some classification systems, literature has shown that most classifications are limited in their aspects (Singh *et al.,* 2017). Furthermore, previous studies have also highlighted the paucity of data in ascertaining the association between different degrees of pneumatization of the temporal bone and anatomical variations of its related vessels and their relationship with ear regions.

However, the genetic and environmental theories of pneumatization described the relationship between temporal bone pneumatization and ear infections such as OM to be *"a chicken and egg"* tale (i.e., dependent of each other) affecting the size of the temporal bone air cell system, which is a determinant of its degree of pneumatization (Turgut & Tos, 1992; Han *et al.,* 2007). Otitis media, on the other hand, remains one of the global burdens of disease (Tesfa *et al.,* 2020; WHO, 2021), with an increasing incidence rate in South Africa, ranging between 31.4% and 51% (Biagio *et al.,* 2014; Phanguphangu, 2016). The onset of ME infections, such as OM, has been linked to the development of temporal bone pneumatization (Aoki *et al.,* 1990; Koc *et al.,* 2003). This is because a normal ME mucosa is a determinant for normal pneumatization (Wittmaack, 1931; Palva & Palva, 1966). What, then, is expected to be the normal size of air cells as regards age and growth? Information concerning the size of temporal bone air cells is still lacking within a South African Population.

Knowledge of the size of air cells could be achieved by measuring the area (i.e., surface area) or volume. It is worth noting that the size and growth rate of temporal bone air cells has been reported to differ in some populations. Although volumetric analysis is more detailed when compared to area measurement of air cells (Koc *et al.,* 2003), most of these studies utilized surface area measurements to describe the size of air cells in different cohort age groups, reporting the growth of air cells to terminate at early puberty or late puberty. However, the study of Lee *et al.* (2005) that utilized the 3D volumetric rendering technique of CT images with a slice thickness of 2.5 mm reported a continuous growth of air cells till the third decade of life. In other volumetric studies, the thinnest slice ever used is 1 mm. Precision in quantifying air cells requires very thin slices such as ≤ 0.6 mm. Hence, volumetric analysis utilizing very thin slices, which likely gives the foremost comprehensive insight to appreciate the estimate of mastoid air cells, is still not fully analyzed with age postnatally.

1.4 Justification of Study

The extent and anatomic distribution of pneumatization have relevance to the pathophysiology of chronic ear infections, surgical management of ear diseases, and surgical intervention of traumatic skull and temporal bone fractures (Howard, 2010). Aside from the protective properties of temporal bone pneumatization, one important factor to be considered by otologists and head and neck surgeons in temporal bone-related surgeries such as mastoidectomies and some lateral skull

base surgeries is the degree of temporal bone pneumatization, which also serve as a prognostic factor (Koc *et al.,* 2003; Cinamon, 2009). It also has surgical implications for temporal bone-related fractures, injuries and trauma (Lee *et al.,* 2015). This is because air cells are usually exposed during these surgeries, usually accompanied by various complications, especially skull-base surgeries (Yamakami *et al.,* 2003). For instance, patients with poor pneumatization are more prone to complications in ME surgeries.

Furthermore, temporal bone pneumatization positively correlates with the risk of OM with effusion and tympanoplasty success rates (Sade & Fuchs, 1997; Baklaci *et al.,* 2022). It could also give favorable positioning of related vasculatures, such as the SS and JB, that could become pitfalls for surgeons (Friedman *et al.,* 2010; Inal *et al.,* 2015; Singh *et al.,* 2017). However, caution needs to be taken in patients with hyper-pneumatized mastoid as surgeons could easily *"be at the mercy"* of these vasculatures and their possible variants *"that does not easily forgive"* when suddenly encountered during bone drilling and other otologic surgeries.

1.5 Research Question

1. What is the size of air cells (in volume) of temporal bone pneumatization from early childhood to early adulthood in the South African population?
2. What pattern/degree of temporal bone pneumatization exists among the South African population?
3. Is there any association between the degrees of temporal bone pneumatization and incidences of temporal bone-related vascular variants and the relationship of these vessels with the ear regions in the study population?
4. What reference structure and landmark can best be used for simple and concise classification of temporal bone pneumatization on a CT?

1.6 Research Objectives

1.6.1 General Objectives

The study aimed to assess the pneumatization of the temporal bone, investigating the size (volume) of air cells developmentally (postnatal), its degree of pneumatization, and anatomical variations of some related vasculature using HRCT imaging and 3D volumetric rendering techniques in the South African population.

1.6.2 Specific Objectives

1. To conduct a scoping review on temporal bone pneumatization and size and growth of the mastoid air cell system with age.
2. To investigate the size of temporal bone pneumatization (in volume) with age and the growth rate of air cells at different stages of human development postnatally in the South African population, according to sex, laterality, and population groups.
3. To investigate the incidence of morphological and morphometrical variations of some temporal bone-related vasculature within the South African population according to age, sex, and laterality.
4. To investigate the pattern/degree of temporal bone pneumatization in the study population and how it influences the morphology of some related vasculatures in the petromastoid part of the temporal bone and their morphometric relationship with ear regions.
5. To review and propose a simple and concise classification of the degree of temporal bone pneumatization using reference structures and landmarks among otologists in the South African population.

1.7 General Overview of Research Methodology

1.7.1 Study Population

This study was a retrospective review of CT scans of patients aged between 0 to 35 years (according to Lee *et al.* [2005], which reported the growth of air cells to continue until age 30). A total of 11,378 head and neck CT scans in the last 5 years were retrieved and reviewed, from which only 248 scans (496 sides: right and left) were suitable and selected for this study. The CT scans/images were obtained from the Picture Archiving and Communication Systems (PACS) at Inkosi Albert Luthuli Central Hospital (IALCH) and Greys Hospital KwaZulu-Natal Province, South Africa.

The age range of 0 to 35 years was further conveniently subdivided into seven levels: 0-2 years (infant); 3-5 years (young child); 6-9 years (middle child); 10-14 years (early adolescent); 15-18 years (middle adolescent); 19-25 years (young adult stage I); 26-35 years (young adult stage II). Age categorization was similar to that reported by Hill (2011); according to age-related changes in the bony organization of pneumatized spaces in various regions of the temporal bone. Population grouping was also achieved by dividing patients into three population groups; Black South

Africans, White South Africans, and Indian South Africans. Generally, of the South African population, Black South Africans make up about 79.8%, White South Africans make up about 8.7%, and Indian South Africans make up about 2.5% (Khalfani and Zuberi, 2001; L'Abbie *et al.,* 2011)

1.7.2 Ethical Considerations

Ethical approval for this study was obtained from the Biomedical Research Ethics Committee of the University of KwaZulu-Natal with approval number **BREC/00002263/2020** [Appendix A]. In addition, ethical clearance was sought from the Department of Health, Kwazulu-Natal, with reference number **KZ_202102_026** [Appendix B]. Permissions were also obtained from hospital sites and radiology departments [Appendix C].

This study also maintained 100% confidentiality and anonymity by documenting only patients' age, sex, and population grouping. Other health information obtained was strictly used for this study only. A password access control was created on the workstation used for this study to protect all images' information and data. A plan to destroy images and electronic data obtained from the radiology department of these hospitals five (5) years after the study had been completed was put in place.

1.7.3 Inclusion Criteria

The inclusion criteria were the following: a) scans of patients between the age range 0 – 35 years; b) High-resolution multidetector CT images acquired with ≤ 0.6 mm collimation; c) images without observable signs of abnormal pathological processes in the temporal bone or temporal region; d) absence of bony destruction, fluid, or mass in any of the temporal bone air spaces; e) temporal bone images with no history of ME infection such as OM and any other pathology; and f) clear visualization of the mastoid, middle, inner ear region, and petrous apex.

1.7.4 Exclusion Criteria

Scans of patients above age 36, scans of patients that have undergone temporal bone or ME surgeries, and CT images with abnormal pathological conditions, bony destruction, or image distortion were excluded from this study.

1.7.5 Core Technology

Computed tomography scanning offers the greatest structural definition of any available imaging modalities using X-ray technology and advanced computer analysis to create detailed body pictures (Mariam, 2020). This cross-sectional scanning method allows for the visualization at different levels or slices of the temples or sides of the skull bone using a rotating X-ray beam. The advent of HRCT scanning has stirred up the diagnostic imaging of the temporal bone. When a patient is scanned, a volume of data is captured. This captured data allows for linear measurements, volumetric surface rendering, multiplanar reconstruction, 3D reconstruction, and visual analysis at coronal, sagittal, and axial planes at any level. The CT images used for this study were from these modern CT scanners, which can produce numerous slices from a single patient scan at 0.625 mm thickness or less. These scanners can also extract the air cells from the temporal bone in other quantify them (volumetrically) without further radiation exposure. The relationship between major vessels of the temporal bone can also be visualized at any of the planes. The CT program software also allows for measurement between related vessels.

1.7.6 Scanning Protocol

Temporal bone CT images were taken using a Multi-Detector row Computed Tomography (MDCT) Scanners (Lightspeed CT, GE Healthcare Medical System, Milwaukee, Wisconsin, USA; and SOMATOM Definition Flash CT Scanner, Siemens Healthineers, Forcheim, Germany, both of 64 and 128 slice configuration, respectively). 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 axial view was reconstructed parallel to the orbito-meatal line using slice thickness of 0.625 mm, detector coverage of 20mm, and a PITCH of 0.5. The voxel size of images is isotropic.

1.7.7 Method of Data Collection

Temporal bone CT scans from the Picture Archiving and Communication Systems of the selected hospitals used for this study were retrieved. The retrieved scans were transferred using digital imaging and communication in medicine (DICOM) to a workstation IntelliSpace Portal (ISP) Version 11.1 (Philips Image and Information Management software, Nederland) [Figure 11]. Further screening was done on each scan to select scans that meet the inclusion criteria. The ISP

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 [Appendix D]. A three-sectioned questionnaire was also designed to conduct a randomized survey among cohort otologists in KwaZulu-Natal Province. The questionnaire was subjected to face and content validation [Appendix E]. Further details are described in Manuscript Four (Chapter 5).

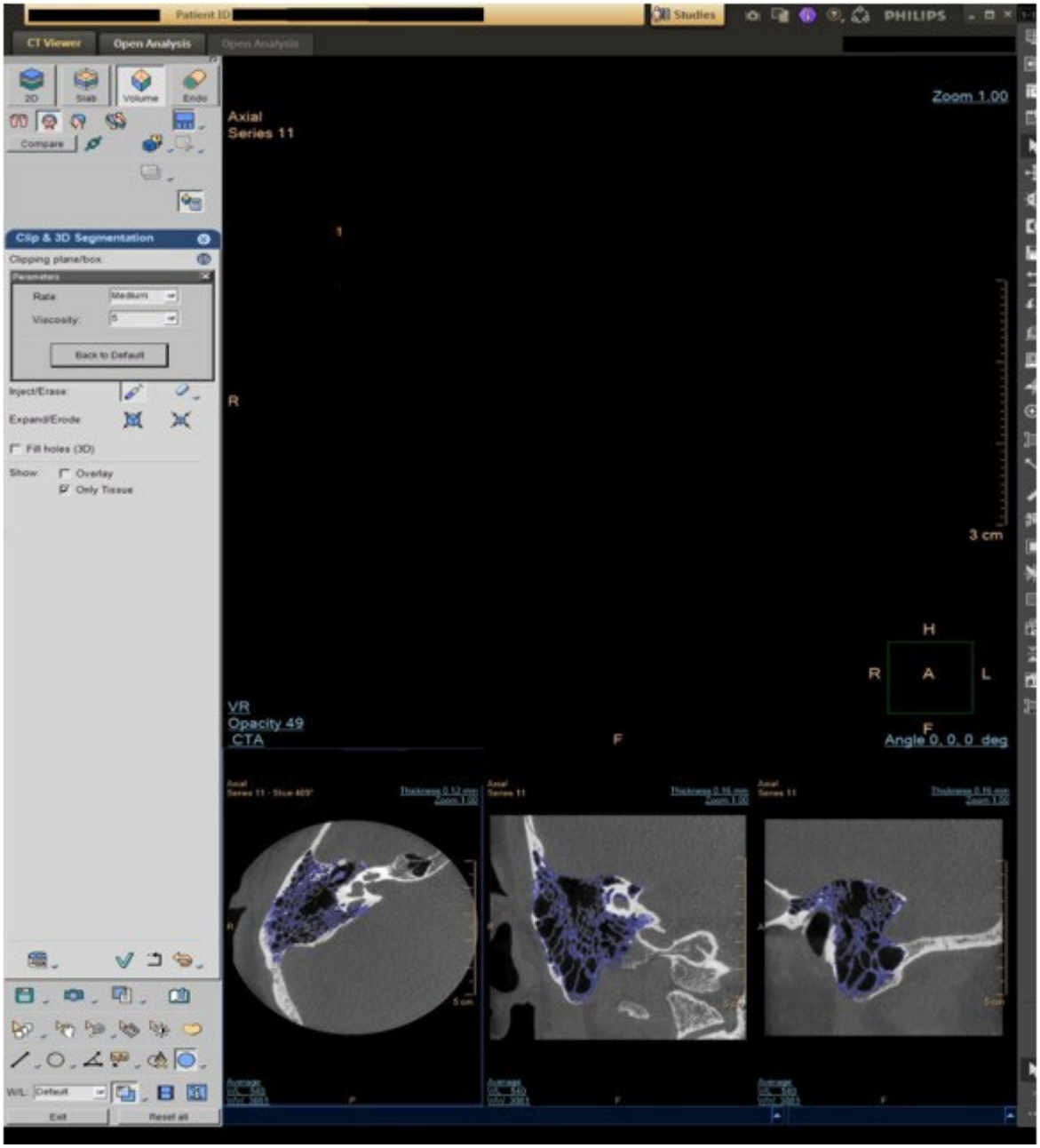

Figure 11: IntelliSpace Portal (ISP) [Version 11.1]

1.7.7.1 Volumetric analysis of temporal bone air cells

The clip and 3D segmentation process ISP viewer software (version 11.1) on the Workstation was used to achieve 3D models and calculate the volume of each temporal bone air cells. With a surface rendering algorithm of the lowest limit window level of -1,024 hU and the uppermost limit window level of -318 hU, the axial image was double-clicked to be enlarged. Next, 3D models were created using a smart segmentation process on ISP viewer software. The ISP then provided a calculator that automatically calculates the volume of each 3D reconstructed temporal bone pneumatization from the mastoid process to the petrous apex, including the ME.

1.7.7.2 Morphometric analysis of temporal bone-related vasculature to ear regions

Using measuring tools on ISP viewer software (version 11.1), the distance between temporal bone-related vasculature (i.e., SS and JB) and ear regions (i.e., IAC, ME, and EAC) was obtained using anatomical landmarks that best define the shortest distance between them. The points of measurement were standardized based on surgical relevance. Axial images at the level or about the level of the lateral semi-circular canal (LSCC) were used (visible landmarks of ear regions are best identified around this level). Further details are described in Manuscript Three (Chapter 4). (Image description available in Manuscript Three- Chapter 4).

1.7.7.3 Morphological observation of temporal bone-related vascular variants

On the ISP viewer software (version 11.1), anatomical variants of the SS, JB, and ICA were analyzed (Image description available in Manuscript Three- Chapter 4).

i) Jugular bulb (JB): The following variants of the JB were identified according to Vachata *et al.* (2010), Inal *et al.* (2015), and Lee *et al.* (2015).

- Flat jugular bulb (FJB): the absence of the dome (rising bulb), no bulb
- High jugular bulb (HJB): when the bulb's dome is above the tympanic membrane's annulus.
- JB Dehiscence: HJB extending into the ME cavity due absence of the sigmoid plate.

ii) Sigmoid sinus (SS): The morphology of SS was identified according to the method of Ichijo *et al.* (1993) and Dai *et al.* (2007) by comparison between the SS depth (SS-D) and SS width (SS-W) as follows;

- Half-moon type: SS-D = ½SS-W
- Protrusive type: SS-D > ½SS-W
- Saucer type: SS-D < ½SS-W

iii) Internal carotid artery (ICA): The morphology of ICA was identified according to the method of Clarke and Timothy (2017).

- ICA dehiscence: dehiscence of ICA into the ME (On the axial view showing focal dehiscence of the carotid canal)

1.7.7.4 Degree of pneumatization

In the present study, the degree of pneumatization was classified using SS as a references structure on axial CT images taken at two levels (as landmarks): the level of malleoincudal junction (MIJ) according to Han *et al.* (2007) and the level of LSCC according to the proposed classification system of this study.

i) Classification at MIJ level using SS as a reference according to Han *et al.* (2007): At the axial section in which the malleoincudal complex appears like an ice-cream cone shape; three parallel lines were applied in the anterolateral direction angled at 45°, with each crossing the most anterior point of the SS at the junction with the petrous bone, the most lateral aspect along the transverse plane of the sigmoid groove, and the most common posterior point of the SS, respectively [Figure 12]. With the application of these lines, the degree of mastoid pneumatization was classified into four groups: Hypo-pneumatization- pneumatization that extends to the line drawn at the most anterior aspect of the SS [Figure 12a]; Moderate pneumatization- pneumatization that extends to the space between arbitrary lines drawn at the most anterior point and most lateral aspect of the SS[Figure 12b]; Good pneumatization- pneumatization that extends to the space between the lines drawn at the most lateral region and the most posterior point of the SS [Figure 12c] and; Hyper-pneumatization- pneumatization that extends postero-laterally beyond the line drawn at the posterior point of the SS [Figure 12d].

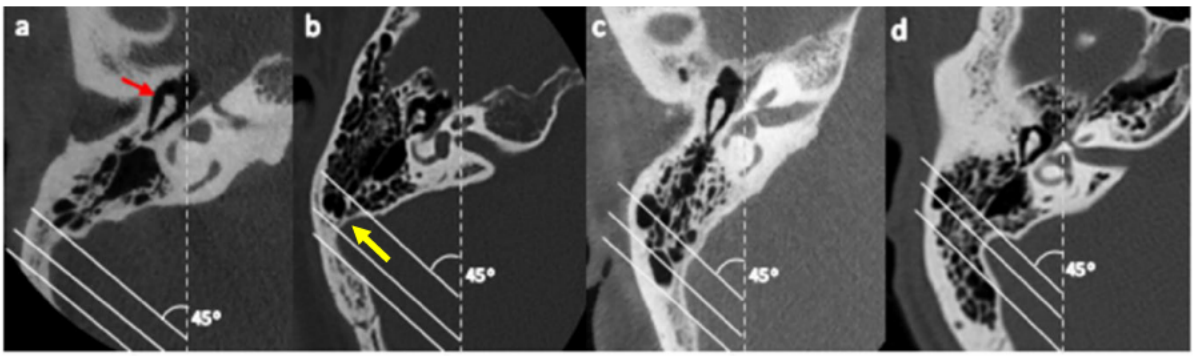

Figure 12: Degrees of pneumatization using SS (yellow arrow) as a reference structure according to Han et al. (2007). On the axial section where the malleoincudal complex (red arrow) appeared as an ice-cream-cone shape. Three parallel lines drawn angled at 45˚ to the anteroposterior axis (dotted line). a) hypo-pneumatization, b) moderate pneumatization, c) good pneumatization, d) hyper-pneumatization.

ii) Classification at LSCC level using SS as a reference according to this study's proposed classification system: On the axial CT image at the level of the LSCC, the lateral convex or semicircular-shaped line/border of the SS was divided into three equal segments by two imaginary dots (grey dots); superior-lateral 1/3 (black arrow), lateral 1/3 (blue arrow), and inferolateral 1/3 (green arrow) [Figure 13]. The degree of mastoid pneumatization was classified as follows: Hypo-pneumatization- when no air cells are found around any of the three segments of the lateral convex border of the SS [Figure 13a]; Moderate pneumatization- when air cells are found only in relation to the superior-lateral 1/3 segment and limited to this segment [Figure 13b]; Good pneumatization- when air cells are found in relation to both the superior-lateral 1/3 and the lateral 1/3 segments [Figure 13c]; Hyper-pneumatization- when air cells are found in relation to all three segments and even extend further after the inferolateral 1/3 [Figure 13d]. In addition, this classification system was verified by comparing each degree of mastoid pneumatization in the proposed classification system with the corresponding degree of pneumatization in the classification system proposed by Han *et al.* (2007).

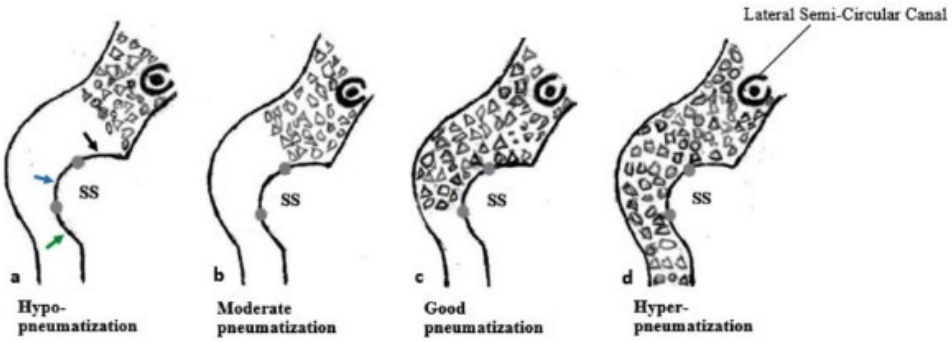

Figure 13: Diagram showing the proposed classification system. SS- sigmoid sinus. Grey dots- 2 imaginary dots. Black arrow- superior-lateral 1/3 segment. Blue arrow- middle-lateral 1/3 segment. Green arrow- inferolateral side 1/3 segment.

1.7.8 Scientific Validity

High-resolution computed tomography scanning has stirred up the temporal bone's diagnostic imaging. It offers detailed visualization of its bony components, organs/tissues, and related vessels and nerves. Raw data from multiplanar CT acquisitions were loaded on ISP viewer software (version 11.1). 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 temporal bone. Axial reformats were made in the plane parallel to the anterior and posterior limbs

of the LSCC. Images of 0.6 mm thickness and 0.5 mm inter-slice gap were generated. Coronal images of 0.6 x 0.5 mm were made in a plane perpendicular to the axial plane. Sagittal reformats were made perpendicular to the coronal images. Specific landmarks based on clinal relevance were adopted for specific morphological observations, morphometric analysis, and classification systems. A pilot study was conducted on 20 temporal bone CT images in order to ascertain these specific landmarks. Inter-observer reliability testing was carried out for morphological observations, morphometric analysis, and classification systems using 50 randomly selected temporal bone CT images (both left and right) by a first, second, and third observer to achieve accuracy and repeatability of the technique used in this study. The results for each inter-observer reliability testing are provided in their corresponding manuscripts.

1.7.9 Data Analysis

The R Statistical computing software of the R Core Team, 2020, version 3.6.3. was used to analyze data. All results were presented in descriptive and inferential statistical forms. Comparisons were made between each age level regarding air cell volume according to sex and population groups. Degree of pneumatization and anatomical variations of temporal bone-related vessels were compared as regards sex, laterality as well as the association between degrees of pneumatization and anatomical variants of these vessels. The accuracy of inter-observer assessment was also analyzed. Average, percentage, median, and interquartile ranges were computed from the data. The Wilcoxon test, Kruskal Wallis, Dunn test, Chi-Square test, and Fisher's exact test for all inferential statistics. A P-value less than 0.05 was considered statistically significant. This study's statistical methods and analysis were conducted in consultation with the university statistician.

1.8 Overview of the Thesis

This thesis is written and submitted in manuscript form. As per the College of Health Sciences' guidelines, this thesis comprises of six (6) chapters and appendices as follows:

Chapter 1: This provides information on the background to the study, reviewed literature, problem statement and research gap, study justification, research questions, research objectives, general overview of research methodology, overview of the thesis, and references.

Chapter 2: This chapter contains the first manuscript from the study and presents results for objective 1. This is a scoping review of studies conducted on the size of temporal bone

pneumatization with age identifying what is known and yet to be known as regards the size of air cells at different stages of human postnatal growth from early childhood to early adulthood. This manuscript was authored by **Okikioluwa Stephen Aladeyelu,** Kehinde Samuel Olaniyi, Samuel Oluwaseun Olojede, Wonder-Boy Eumane Mbatha, Andile Lindokuhle Sibiya, and Carmen Olivia Rennie, and has been published in **PLoS ONE (Impact Factor 3.752; Q1). PubMed ID: 35657972; https://doi.org/10.1371/journal.pone.0269360**

Chapter 3: This chapter contains the second manuscript from this study and presents results for objective 2. It reports the size of temporal bone pneumatization with age and the normal distribution of air cell volumes in different stages of human growth postnatally. This manuscript was authored by **Okikioluwa Stephen Aladeyelu,** Samuel Oluwaseun Olojede, Sodiq Kolawole Lawal, Matome Nadab Matshipi, Andile Lindokuhle Sibiya, Carmen Olivia Rennie, Wonder-Boy Eumane Mbatha, and has been published in **Folia Morphologica (Impact Factor 1.195; Q2). PubMed ID: 36896646; https://doi.org/10.5603/FM.a2023.0016**

Chapter 4: This chapter contains the third manuscript from this study, presenting results for objectives 3 and 4. It reports different degrees of temporal bone pneumatization and how they influence the morphology and morphometry of temporal bone-related vessels, such as the JB, SS, and ICA. This manuscript was authored by **Okikioluwa Stephen Aladeyelu,** Samuel Oluwaseun Olojede, Sodiq Kolawole Lawal, Wonder-Boy Eumane, Mbatha, Andile Lindokuhle, Sibiya, and Carmen Olivia Rennie, and has been published in **Scientific Reports (Impact Factor 4.998; Q1). PubMed ID: 36737493; https://doi.org/10.1038/s41598-023-29295-4**

Chapter 5: This chapter contains the fourth manuscript produced from this study and presents results for objective 5. It reviewed and conducted an interobserver assessment of temporal bone pneumatization using SS as a reference structure in order to propose a simple and concise classification of the degree of temporal bone pneumatization. This manuscript was authored by **Okikioluwa Stephen Aladeyelu,** Carmen Olivia Rennie, Kurt Schlemmer, Sodiq Kolawole Lawal, Wonder-Boy Eumane Mbatha, and Andile Lindokuhle Sibiya and has been published in **Surgical and Radiologic Anatomy (Impact Factor 1.425; Q2). PubMed ID: 37024734; https://doi.org/10.1007/s00276-023-03130-x**

Chapter 6: This chapter contains the synthesis, conclusion, recommendation, suggestions for future research, limitations, a summary of findings and contribution to knowledge, and references.

Appendices: This contains the ethical and hospital approvals, data collection sheet, questionnaire, and informed consent form

Finally, as per the format required by the University of KwaZulu-Natal, aspects of the sample demographics and methods had to be reported in each manuscript. However, the specific methodology employed for each aspect of the study is contained in the respective manuscripts in order to address the objectives. All manuscripts were prepared according to the guidelines of the respective journals.

REFERENCES

Acuin, J. (2004). Chronic Suppurative Otitis Media: Burden of Illness and Management Options. Geneva: WHO. Retrieved July 17, 2020, from http://www.who.int/pbd/deafness/activities/hearing_care/otitis_media.pdf.

Al-Faleh, W. & Ibrahim, M.E. (2005). A tomographic study of air cell pneumatization of the temporal components of the TMJ in patients with temporomandibular joint disorders. *Egyptian Dental Journal,* 51: 1835–1842.

Allam, A.F. (1969). Pneumatization of the temporal bone. *Annal of Otology Rhinology and Laryngology,* 78: 49–64.

Anson, B.J. & Donaldson, J.A. (1981). *Surgical Anatomy of the Temporal Bone,* (3rd ed.). Philadelphia: W.B. Saunders: 122–123.

Aoki, K., Esaki, S., Honda, Y. & Tos, M. (1990). Effect of middle ear infection on pneumatization and growth of the mastoid process. An experimental study in pigs. *Acta Otolaryngologica,* 110(5-6): 399–409.

Arora, M.M.L., Sain, U. & Sodhi, J.S. (1973). Mastoid pneumatization in children—a roentgenographic planimetric study. *Indian Journal of Otolaryngology,* 25:87–90.

Aslan, A., Falcioni, M., Russo, A., De Donato, G., Balyan, F.R., Taibah, A. & Sanna, M. (1997). Anatomical considerations of high jugular bulb in lateral skull base surgery. *The Journal of Laryngology and Otology,* 3: 333–336.

Austin, D.F. (1977). On the function of the mastoid. *Otolaryngology Clinics of North America,* 10:5 41–547.

Baklaci, D., Bilgin, E., Çelik, E.K., Kılıç, A., Erdem, D. & Eliçora, S.S. (2022). Effects of mastoid and middle-ear volume on graft success and hearing outcomes in pediatric tympanoplasty. *Journal of Laryngology and Otology*, 136(5): 404 – 409.

Balzeau, A, Girmaud-Herve, D. & Semah, F. (2006). Characteristics and variation of the temporal bone pneumatization in Asian Homo errectus. *EurASEAA\ Bougon papers,* 21–27.

Basraoui, D., Elatiqi, K. & Jalal, H. (2018). Computed Tomography of the Petrous Bone: Particularities in Children. *Advances in Molecular Imaging,* 8: 15–24.

Bast, T.H. & Anson, B.J. (1949). The temporal bone and the ear, (1st ed). Springfield IL: Thomas, pp. 315–336.

Bast, T.H. & Forrester, H.B. (1939). Origin and distribution of air cells of the temporal bone. *Archives of Otolaryngology,* 30: 183–205.

Biagio, L., Swanepoel, D.W., Laurent, C. & Lundberg, T. (2014). Paediatric otitis media at primary healthcare clinic in South Africa. *South African Medical Journal,* 104(6): 431–435.

Bozorg, G.A., Bouccara, D., Julien, N., Rihane, S., Chaigne, P. &Sterkers, O. (1995). Surgical treatment of vertigo induced by jugular bulb diverticulum. *Revue de Laryngologie-Otologie-Rhinologie (Board),* 116: 31–37.

Brodie, H.A. & Thompson, T.C. (1997). Management of complications from 820 temporal bone fractures. *American Journal of Otology,* 18(2): 188–197.

Bronoosh, P., Shakibafard, A., Mokhtare, M.R. & Rad, T.M. (2014). Temporal bone pneumatisation: A computed tomography study of pneumatized articular tubercle. *Clinical Radiology,* 69: 151–156.

Cavusoglu, M., Duran, S., Elveric, E. & Ozsoy, A. (2016). Aberrant internal carotid artery in the temporary bone: a case report. *Journal of Radiology and Imaging Technology,* 2(1): 1–3.

Chatterjee, D., Ghosh, T.B. & Ghosh, B.B. (1990). Size variation of mastoid air cell system in Indian people at different age groups: a radio-graphic planimetric study. *Journal of Laryngology and Otology,* 104: 603–605.

Cheatle, A.H. (1907). The infantile types of mastoid with ninety-six specimen. *Journal of Laryngology,* 22: 256.

Cilliers, N.J., van der Merwe, A., Hurter, M. & Nel, O. (1988). The manifestation of middle ear pathology in an elderly group. *South African Journal of Communication Disorder,* 35(1): 37–44.

Cinamon, U. (2009). The growth rate and size of the mastoid air cell system and mastoid bone: A review and reference. *European Archives Oto-Rhino-Laryngology,* 266(6): 781–786.

Clarke, R. & Booth, T. (2017). CT and MR Imaging of the Pediatric Temporal Bone: Normal Variants and Pitfalls. *Current Radiology Reports,* 5(34): 1–17.

Colhoun, E.N., O'Neill, G., Francis, K.R. & Hayward, C. (1988). A comparison between are and volume measurements of the mastoid air spaces in normal temporal bone. *Clinical Otolaryngology,* 13: 59–63.

Comert, E., Kilic, C. & Comert, A. (2018). Jugular bulb anatomy for lateral skull base approach. *The Journal of Craniofacial Surgery,* 29(7): 1969–1972.

Congdon, E.D. (1922). Transformation of the aortic-arch system during the development of the human embryo. *Contributions to Embryology,* 14: 47–110.

Connor, S.E.J., Leung, R. & Natas, S (2008). Imaging of the petrous apex: a pictorial review. *British Journal of Radiol*ogy, 81(965): 427–435.

Couper, J. (2002). Prev\alence of childhood disability in rural KwaZulu-Natal. *South African Medical Journal,* 92(7): 649–552.

Cureoglu, S., Schachern, P.A. & Paparella, M.M. (2003). Temporal Bone Histopathology Case of the Month Persistent Stapedial Artery. *Otology & Neurotology,* 24: 833–834.

Dai, P-D., Zhang, H-Q., Wang, Z-M., Sha, Y., Wang, K-Q. & Zhang, T-U. (2007). Morphological and positional relationships between the sigmoid sinus and the jugular bulb. *Surgical and radiologic Anatomy,* 29:643–651

DeAntonio, R., Yarzabal, J-P., Cruz, J.P., Schmidt, J.E. & Kleijnen, J. (2016). Epidemiology of otitis media in children from developing countries: A systematic review. *International Journal of Pediatric Otorhinolaryngology,* 85: 65–74.

Demirel, O., Kaya, E. & Ucok, C.O. (2014). Evaluation of mastoid pneumatization using cone-beam computed tomography. *Oral Radiology*, 30: 92–97.

Dewan, M.C., Rattani, A., Gupta, S., Baticulon, R.E., Hung, Y- C., Punchak, M., Agrawal, A., Adeleye, A.O., Shrime, M.G., Rubiano, A.M., Rosenfeld, J.V. & Park, K.B. (2019). Estimating the global incidence of traumatic brain injury. *Journal of Neurosurgery*, 130: 1080–1097.

Diamant, M. (1940). Otitis and pneumatization of the mastoid bone. *Acta Otolaryngologica,* 41.

Eagleton, W.P. (1935). A new classification of bones forming the skull. *Transactions- American Academy of Ophthalmology and Otolaryngology,* 21–58.

Friedmann, D.R., Eubig, J., McGill, M., Babb, J.S., Pramanik, B.K. & Lalwani, A.K. (2011). Development of the jugular bulb: a radiologic study. *Otology and Neurology,* 32(8): 1389–1395.

Friedmann, D.R., Thuy, L.B., Pramanik, B.K. & Lalwani, A.K. (2010). Clinical spectrum of patients with erosion of the inner ear by jugular bulb abnormalities. *Laryngoscope*, 120: 365–372.

Galal, A., Caruso, A., Lauda, L., Eldin, O.G., Baki, F. & Sanna, M. (2021). Effect of sigmoid sinus position on the difficulty and approaches to cochlear implantation surgery. *The Journal of International Advanced Otology*, 17(1):23–29.

Goderie, T.P.M., Alkhateeb, W.H.F., Smit, C.F. & Hensen, E.F. (2017). Surgical Management of a Persistent Stapedial Artery: A Review. *Otology & Neurotology,* 38: 788–791.

Govaerst. P.J., Marquet, T.F., Cremers, W.R. & Offesiers, F.E. (1993). Persistent stapedial artery: does it prevent successful surgery? *Annal of Otology Rhinology and Laryngology,* 102: 724–728.

Halama, A.R., Voogt, G.R. & Musgrave, G.M. (1986). Prevalence of otitis media in children in a black rural community in Venda (South Africa). *International Journal of Pediatric Otorhinolaryngology,* 11(1): 73–77.

Han, S.J., Song, M.H., Kim, J., Lee, W.S. & Lee, H.-K. (2007). Classification of temporal bone pneumatization based on sigmoid sinus using computed tomography. *Clinical Radiology,* 62: 1110–1118.

Harnsberger, R., Hudgens, P., Wiggins, R. & Davidson, C. (2006). Dehiscent jugular bulb. In: Harnsberger R, Diagnostic Imaging: Head and Neck. (3rd ed.). Salt Lake City: Amirsys/Elsevier Saunders, Utah, 18–22.

Hashemi, J., Rajati, M., Rezayani, L. & Bahadori, A. (2014). Temporal bone measurements: A comparison between rendered spiral CT and Surgery. *Iranian Journal of Radiology,* 11(3): e9400

Hill, C. A. (2011). Ontogenetic change in temporal bone pneumatization in humans. *Anatomical Record,* 294(7): 1103–1115.

Hitier, M., Barbier, C., Marie-Aude, T., Moreau, S., Courtheoux, P. & Patron, V. (2013). New treatment of vertigo caused by jugular bulb abnormalities. *Surgical Innovations,* 21(4): 365–371.

Holmquist, J. (1970). Size of mastoid air cell system in relation to healing after myringoplasty and to Eustachian tube function. *Acta Otolaryngologica,* (Stockh), 69:89–93.

Howard, W.F. (2010). Anatomy of the temporal bone, external ear, and middle ear. *In: Flint, P.W., Haughey, B.H., Lund, V.J., Niparkd, J.K., Richardson, M.A. Robbins, K.T. & Thomas, R.J.* (5th ed.). Philadelphia: Elvesier, pp 1841.

Ichijo, H., Hosokawa, M. & Shinkawa, H. (1993) Differences in size and shape between the right and left sigmoid sinuses. *European Archives of Otorhinolaryngology,* 250: 297–299.

Ichijo, H., Hosokan, M. & Shinkawa, H. (1996). The relationship between mastoid pneumatization and the position of the sigmoid sinus. *European Archives of Otorhinolaryngology, 253*: 421–424.

Ilea, A., Butnaru, A., Sfrângeu, S.A., Hedeşiu, M., Dudescu, C.M., Berce, P., Chezan, H., Hurubeanu, L., Trombiţaş, V.E., Câmpian, R.S. &Albu, S. (2014). Role of Mastoid Pneumatization in Temporal Bone Fractures. *American Journal of Neuroradiology*, 35(7): 1398–1404.

Inal, M., Muluk, N.B., Dag, E., Arikan, O.K. & Kara, S.A. (2015). The pitfalls and important distances in temporal bones HRCT of the subjects with high jugular bulb- Preliminary Review. *Advances in Clinical and Experimental Medicine*, 24(2): 315–325.

Ishman, S.L. & Friedland, D.R. (2004). Temporal bone fractures: traditional classification and clinical relevance. *Laryngoscope,* 114(10): 1734–1741.

Isono, M., Murata, K., Azuma, H., Ishikawa, M. & Ito, A. (1999). Computerized assessment of the mastoid air cell system. *Auris Nasus Larynx.,* 26: 139–145.

Isono, M., Ito, A., Nakayama, K., Miyashita, H., Saito, K. & Murata, K. (2003). Computerized assessment of developmental changes in the mastoid air cell system. *International Congress Series,* 1254: 487–491.

Jadhav, A.B., Fellows, D., Hand, A.R., Tadinada, A. & Lurie, A.G. (2014). Classification and volumetric analysis of temporal bone pneumatization using cone beam computed tomography. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology*, 117(3): 376–84.

Joubert, K. & Botha, D. (2019). Contributing factors to high prevalence of hearing impairment in the Elias Motsoaledi Local Municipal area, South Africa: A rural perspective. *South African Journal of Communication Disorders,* 66(1): 1–7.

Kang, T.K., Ha, R., Oh, J.H. & Sunwoo, W. (2019). The potential protective effects of temporal bone pneumatization: A shock absorber in temporal bone fracture. *PLoS ONE,* 14(5): e0217682.

Kawamura, S., Okabe, K., Mogi, S. & Terao, A. (1963). The normal development of the mastoid pneumatic cells. *Nippon Jibiinkoka Gakkai Kaiho,* 66: 909–912.

Kawano, H., Tono, T., Schachern, P.A., Paparella, M.M. & Komune, S. (2000). Petrous high jugular bulb: A histological study. *American Journal of Otolaryngology,* 21: 161–168.

Khalfani, A. K. & Zuberi, T. (2001). Racial classification and the modern census in South Africa, 1911–1996. *Race Sociology,* 4: 161–176.

Kim, J. Song, S.W., Cho, J-H., Chang, K-H. & Jun, B.C. (2010) Comparative study of the pneumatization of the mastoid air cells and paranasal sinuses using three-dimensional reconstruction of computed tomography scans. *Surgical and Radiologic Anatomy,* 32: 593–599.

Kizildag, B., Bilal, N., Yurttutan, N., Sarica, M.A., Gungor, G. & Bakayara, M. (2016). The relationship between tinnitus and vascular anomalies on temporal bone CT scan: a retrospective case-control study. *Surgical and Radiologic Anatomy,* 38: 835–841.

Klein, J.O. (2015). Otitis Externa, Otitis Media and Mastoiditis. *In: Bennett, J.E., Dolin, R. & Blaser, M.J. Mandell, Douglas and Bennetts Principles and Practices of Infectious Diseases.* New York: Elsevier Inc.

Koc¸ A., Ekinci, G., Bilgili, A.M., Akpinar, I.N., Yakut, H. & Han, T. (2003) Evaluation of the mastoid air cell system by high resolution computed tomography: three-dimensional multiplanar volume rendering technique. *The Journal of Laryngology and Otology*, 117**:** 595–598.

L'Abbé, E.N., Van, R.C., Nawrocki, S.P. & Becker P.J. (2011). An evaluation of non-metric cranial traits used to estimate ancestry in a South African sample. *Forensic Science International*. 209(1-3):195.e1-7

Lee, D.-H., Jun, B.-C., Kim, D.-G., Jung, M.-K. & Yeo, S.-W. (2005). Volume variation of mastoid pneumatization in different age groups: a study by three-dimensional reconstruction based on computed tomography images. *Surgical and Radiologic Anatomy,* 27: 37–42

Lee, D -H., Jung, M -K., Yoo, Y -H. & Seo, J -H. (2008). Analysis of unilateral sclerotic temporal bone: How does the sclerosis change the mastoid pneumatization morphologically in the temporal bone? *Surgical and Radiology Anatomy,* 30: 221– 227.

Lee, D -H., Kim, M -J., Lee, S. & Choi, H. (2015). Anatomical Factors Influencing Pneumatization of the Petrous Apex. *Clinical and Experimental Otorhinolaryngology,* 8(4): 339–344.

Lima, M.A.R., Farage, L., Cury, M.C.L. & Junior, F.B. (2013). Mastoid surface area-to-volume ratios in adult Brazilian individuals. *Brazilian Journal of Otorhinolaryngology,* 79(4): 446–453.

Low, W.K. Fenton, J.E., Fagan, P.A. & Gibson, W.P. (1995). The influence of race on the position of the jugular bulb. *Journal of Laryngology and Otology,* 109(7): 610–613.

Louw, C., Wet, S.D., Eikelboom, R.H. & Hugo, J. (2018). Prevalence of hearing loss at primary health care clinics in South Africa. *African Health Sciences,* 18(2): 313–320.

Luntz. M., Malatskey, S., Tan, M., *et al.* (2001). Volume of mastoid pneumatization: three-dimensional reconstruction with ultrahigh-resolution computed tomography. *Annals of Otology Rhinology and Laryngology,* 110: 486–490.

Lyu, H.Y., Chen, K.G., Yin, D.M., Hong, J., Yang, L. & Zhang, T.Y. (2016). The age-related orientational changes of human semicircular canals. *Clinical Experimental Otorhinolaryngology,* 9: 109–115.

Mokolane, N.S., Minne, C. & Dehnavi, A. (2019) Prevalence and pattern of basal skull fracture in head injury patients in an academic hospital. *South African Journal of Radiology,* 23(1): a1677. https://doi.org/10.4102/sajr. v23i1.1677

Marchioni, D., Soloperto, D., Colleselli, E., Tatti, M., Patel, N. & Jufas, N. (2016). Round window chamber and fustis: endoscopic anatomy and surgical implications. *Surgical and Radiologic Anatomy,* 38: 1013–1019.

Mahomed-Asmal, F., Swanepoel, D.W. & Eikelboom, R.H. (2016). Hearing loss in urban South African school children (grade 1 to 3). *International Journal of Pediatric Otolaryngology,* 84: 27–31.

Mariam I.R. (2020). *CT scan of temporal bone*. Retrieved from emedicine.medspace.com/article/ 875593-overcome on July 31, 2020.

McMurrich, J.P. (1923). *The development of the human body.* Philadelphia: Saunders, pp 1142.

Molvaer, O.I., Vallersnes, F.M. & Kringlebotn, M. (1978). The size of the middle ear and the mastoid air cell system measured by an acoustic method. *Acta Otolaryngologica,* 85: 24–32.

Morris, P.S. & Leach, A.J. (2009). Acute and chronic otitis media. *Pediatrics Clinics of North America,* 56(6): 1383–1399.

Most, S.P. (2020). Temporal bone fractures. Reviewed March 2020. Retrieved June 23, 2020, from https://www.msdmanuals.com/professional/injuries-poisoning/facial-trauma/temporal-bone-fractures.

Mutlu. C., Costa, S.S., Paparella, M.M. & Schachern, P.A. (1998). Clinical-histopathological correlations of pitfalls in middle ear surgery. *European Archives of Oto-Rhino-Laryngology,* 255: 189–194.

Myerson, M.C., Rubin, H. & Gilbert, J.G. (1934). Anatomic studies of the petrous portion of the temporal bone. *Archives of Otolaryngology,* 194–210.

Nel, M., Odendall, W., Hurter, M., Meyer, S. & van der Merwe, A., (1988). The occurrence and nature of hearing problems and middle ear pathologies with a group of black Africans urban children. *The South African Journal of Communication Disorders,* 35(1): 25–30.

Nelson, R. (1991). *Temporal bone surgical dissection manual*, (2nd ed.) Los Angeles: House Ear Institute.

Okudera, T., Huang, Y.P., Ohta, T. *et al.* (1994) Development of posterior fossa dural sinuses, emissary veins, and jugular bulb: morphological and radiologic study. *American Journal of Neuroradiology,* 15(10): 1871–1883.

Olusanya, B.O., Neumann, K.J. & Saunders, J. (2014). The global burden of disabling hearing impairment: a call to action. *Bull World Health Organization,* 92: 367–373.

Osama, A.M.K. (2018). Anatomical Characteristics of Temporal Bone on Computerized Tomography. *IOSR Journal of Dental and Medical Sciences,* 17(5): 88–96.

Osch, K.V., Allen, D., Gare, B., Hudson, T.J., Ladak, H. & Agrawal, S.K. (2019). Morphological analysis of sigmoid sinus anatomy: Clinical application to neurotological surgery. *Journal of Otolaryngology- Head and Neck Surgery,* 48:2.

Padget, D.H. (1948). The development of the cranial arteries in the human embryo. *Contributions to Embryology,* 32: 205–261.

Palva, T. & Palva, A. (1966). Size of the human mastoid air cell system. *Acta Otolaryngologica, (stockh),* 62: 237–251.

Park, J.H., Son, S.B., Hong, H.P. & Lee, H.S. (2012). A case of jugular bulb diverticulum invading the internal auditory canal. *Korean Journal of Audiology,* 16: 39–42.

Park, J.J., Shen, A., Keil, S., Kuhl, C. & Westhofen, M. (2015). Jugular bulb abnormalities in patients with Meniere's disease using high-resolution computed tomography. *European Archives of Oto-Rhino-Laryngology,* 272(8): 1879–1884.

Park, M.S., Yoo, S.H. & Lee, D.H. (2000). Measurement of surface area in human mastoid air cell system. *The Journal of Laryngology and Otology,* 114: 93–96.

Phanguphangu, M.C. (2016). Otoscopic examinations reveal high prevalence of outer and middle ear pathologies in pediatrics in Limpopo, South Africa. *Internal Journal of Audiology,* 56(4): 215–218.

Proetz, A.W. (1922). Observation upon the formation and function of the accessory nasal sinus and the mastoid cells. *Annals of Otology, Rhinology and Laryngology,* 31: 1083–1100.

Proud, C.O. & Duff, W.E. (1976). Mastoidectomy and epitympanotomy. *Annals of Otology, Rhinology and Laryngology,* 85(suppl 25): 289–292.

Psychology Today, (2020). *What is Trauma?* Retrieved February 21, 2020, from www.psychologtoday.com/za/basics/trauma%3famp.

Pulec, J.L. (1993). The facial nerve: how to find it. *Ear Nose Throat Journal,* 72: 677–685.

Pullen, D.L. (2015). Prevalence of hearing impairment and auditory pathology in the Limpopo Province, South Africa. Masters Thesis.

Qvarnberg, Y. (1981). Acute otitis media. A prospective clinical study of myringotomy and antimicrobial treatment. *Acta. Otolaryngologica,* (Stockh) Suppl 375: 1–157.

Ramma, L. & Sebothoma, B. (2016). The prevalence of hearing impairment within the Cape Town Metropolitan area. *South African Journal of Communication Disorders,* 63: 1–10.

Rathe, M., Govaere, F. & Forton, G. (2018). Unilateral pulsative tinnitus associated with an internal carotid eustachian tube dehiscence. *American Academy of Otolaryngology- Head and Neck Surgery,* 2(1): 1–2.

Rebol, J., Munda, A. & Tos, M. (2004). Hyper-pneumatization of the temporal, occipital and parietal bones. *European Archives of Oto-Rhino-Laryngology,* 261: 445–448.

Remington, L.A. (2012). *Clinical Anatomy and Physiology of the Visual System* (3rd edition). Retrieved December 7, 2020, from https://www.sciencedirect.com/topics/medicine-and-dentistry/internal-carotid-artery

Rennie, C.O., Haffajee, M.R. & Satyapal, K.S. (2017). Development of the paranasal air sinuses in a South African Population utilizing three-dimensional (3D) reconstruction model. *European Journal of Anatomy,* 21(3): 197–209.

Rubensohn, G. (1965) Mastoid pneumatization in children at various ages. *Acta Otolaryngologica,* (Stockh) 60: 11–14.

Sadé, J. & Fuchs, C. (1997). Secretory otitis media in adults: II. The role of mastoid pneumatization as a prognostic factor. *Annals of Otology, Rhinology and Laryngology*,106(1):37–40.

Saleh, E.A., Naguib, M., Aristegui, M., et al. (1995). Lower skull base: anatomic study with surgical implications. *Annals of Otology, Rhinology and Laryngology,* 104: 57–61.

Saraiya, P.V. & Aygun, N. (2009). Temporal bone fractures. *Emergency Radiology,* 16: 255–265.

Sarmiento, P.B. & Eslait, F.G. (2004). Surgical classification of variations in the anatomy of the sigmoid sinus. *Otolaryngology- Head and Neck Surgery,* 131:192–199.

Schillinger, R. (1939). Pneumatization of the mastoid. *Radiology,* 33: 54–69.

Schmalfuss, I.M. (2018). Petrous Apex. *In Chong. V, Skull Base Imaging (eds.).* Elsevier: Missouri, pp 233–245.

Schmucker, C., Kapp, P., Motschall, E., Loehler, J. & Meerpohl, J.J. (2019). Prevalence of hearing loss and using hearing aids among children and adolescents in Germany: a systematic review. *BMC Public Health,* 19: 1277.

Seibel, V.A., Lavinsky L. & Irion, K. (2006). CT-scan sheep and human inner ear morphometric comparison. *Brazilian Journal of Otorhinolaryngology,* 72(3): 370–376.

Secchi, M.M.D., Moraes, J.F.S. & Castro, F.B. (2012). Fractures of the temporal bone in patients with traumatic brain injury. *International Archives of Otorhinolaryngology,* 6(1): 62–66.

Shaikh, M.F., Mahboubi, H., German, M. & Djalilian, H.R. (2013). A Novel Approach for Surgical Repair of Dehiscent High Jugular Bulb. *Laryngoscope,* 123: 1803–1805.

Shambaugh, G.E. & Glassock, M.E. (1980) *Surgery of the ear,* (3rd edition). Philadelphia: Saunders, pp 24–25.

Shapiro, R. (1981). *Radiology of the normal skull*. Chicago: Yearbook Medical, 326–340.

Shew, M., Muellema, T., Harris, M., Li, M., Sykes, K., Staeker, H., Adunka, O.F & Lin, J. (2018). Petrous apex pneumatization: Influence on postoperative cerebropontine angle tumour cerebrospinal fluid fistula. *Annals of Otology, Rhinology and Laryngology,* 1–4.

Silbergleit, R., Quint, D.J., Mehta, B.A., Patel, S.C. Metes, J.J. & Noujaim, S.E. (2000). The Persistent Stapedial Artery. *American Journal of Neuroradiology,* 21: 572–577.

Singh, V., Chaitanya, D.C., Chauchan, B.K.S. & Kumar, I.D.V. (2017). A Comparative Study of Pneumatization of Temporal bone. *Journal of the Anatomical Society of India,* 66: 78–81.

Singh, A., Kumar, I.D.V., Sikka, K., Verma, H. & Thakar, A. (2019). Study of Sigmoid Sinus Variations in the Temporal Bone by Micro Dissection and its Classification- A Cadaveric Study. *International Archives of Otorhinolaryngology,* 23: e311–e316.

Sirikci, A., Bayazit, Y.A., Kervancioglu, S., Ozer, E., Kanlikama, M. & Bayram, M. (2004). Assessment of mastoid air cells size versus sigmoid sinus variables with tomography-assisted digital image processing program and morphometry. *Surgical and Radiologic Anatomy,* 26: 145–148.

South African National Deaf Association, (2005). *Deafness.* Retrieved December 17, 2019, from www.sanda.org.za.

Standring, S. (2008). *Gray's Anatomy: The Anatomical Basis of Clinical Practice.* Edinburg: Churchill Livingstone.

Statistics South Africa, (2010). *Recorded live births.* Retrieved December 17, 2019, from www.statssa.gov.za. P0305.

Statistics South Africa, (2012). *Census 2001: Prevalence of Disability in South Africa.* Retrieved December 17, 2019, from www.statssa.gov.za.

Stieglitz, L.H., Giordano, M., Gerganov, V. *et al.* (2010). Petrous bone pneumatization is a risk factor for cerebrospinal fluid fistula following vestibular schwannoma surgery. *Neurosurgery,* 67(2): 509–515.

Swanepoel, D., Storbeck, C. & Friedland, P. (2009). Early hearing detection and intervention in South Africa. *International Journal of Pediatric Otorhinolaryngology,* 73: 783–786.

Tan, D.A., Ng, J.H., Lim, S.A., Low, D.Y-M. & Yuen, H.W. (2018). Classification of temporal bone pneumatization of high-resolution computed tomography: Prevalence, patterns and implication. *Otolaryngology- Head and Neck Surgery,* 1: 1–7.

Tanghe, H. (2004). Vascular Temporal Bone Lesion. *In: Lemmerling, M. & Koolias, S.S. Radiology of the Petrous Bone.* New York: Springer, Page 159.

Taylor, S., Marchisio, P., Vergison, A., Harriague, J., Hausdorff, W.P. & Haggard, M. (2012). Impact of pneumococcal conjugate vaccination on otitis media: a systemic review. *Clinical Infectious Diseases,* 25(2): 161–167.

TeachMeAnatomy, (2020). https://teachmeanatomy.info/head/osteology/temporal-bone/

Tesfa, T., Mitiku, H., Sisay, M., Weldegebreal, F., Ataro, Z., Motbaynor, B., Marami, D. & Teklemariam, Z. (2020) Otitis media in sub-Saharan Africa: a systemic review and meta-analysis. *BMC Infectious Diseases,* 20: 225 (pp 1–12).

Todd, N.W., Pitts, R.B., Braun, I.F. & Heindel, H. (1987). Mastoid size determined with lateral radiographs and computerized tomography. *Acta Otolaryngologica*, 103(5-6): 226–231.

Tumarkin, A. (1957). On the mature and vicissitudes of the accessory air spaces of the middle ear. *Journal of Laryngology and Otology* 71: 65–99.

Turgut, S. & Tos, M. (1992). Correlation between temporal bone pneumatization, location of lateral sinus and length of the mastoid process. *Journal of Laryngology and Otology,* 106: 485e9.

Vachata, P. Petrovicky, P. & Sames, M. (2010). An anatomical and radiological study of the high jugular bulb on high-resolution CT scans and alcohol-fixed skulls of adults. *Journal of Clinical Neuroscience,* 17: 473–478.

Virapongse, C., Sarwar, M., Bhimani, S., Sasak, C. & Shapiro, R. (1985). Computed tomographic anatomy of the temporal bone: 1. Normal pattern and morphology. *AJR, America Journal of Roentgenology,* 145: 473–481.

Vasiliu, D. I. (1968). Contributions sur l'embryologenese de l'oreille et al pneumatization de la mastoid et du rocher. *International Audiology,* 7: 181–185.

Vos, T., Barber, R.M., Bell, B., Bertozzi-Villa, A., Biryukov, S., Bolliger, I., (2015). Global, regional, and national incidence, prevalence, and years lived with disability for 301 acute and chronic disease and injuries in 188 countries, 1990 – 2013: a systemic analysis for the global burden of disease study 2013. *Lancent,* 386(9995): 743–800.

Vrabec, J.T., Champion, S.W., Gomez, J.D., *et al.* (2002). Three-dimensional imaging method for measuring temporal bone aeration. *Acta Otolaryngologica,* 122: 831–835.

Warwick, R. & Williams, P.L. (1973). *Gray's Anatomy,* (35th ed.). Philadelphia: Saunders, pp. 1142.

Wenjuan, L., Zhaohui, L., Ning, Z., Pengfei, Z., Cheng, D. & Zhenchang, W. (2015). Temporal Bone Pneumatization and Pulsatile Tinnitus Caused by Sigmoid Sinus Diverticulum and/or Dehiscence. *BioMed Research International,* 1–4.

Williams, H.L. (1969). Developmental variations of the temporal bone that influence the evolution of chronic suppurative otitis media and mastoiditis and medical and surgical treatment of the syndrome. *Laryngoscope.,* 99: 827–859.

Wittmaack, K. (1931). Zur frage der Bedeutung der Mittelohrentzundungen des frushesten kindesalter fur sparter. *Archives Ohren Nasan Kehikofh,* 129: 207–250.

Wolfowitz, B.L. (1974). *Pneumatization of the skull of Southern African Negro.* Ph.D. Thesis.

World Health Organization. (2011). *Hearing Loss Estimates*. Retrieved February 17, 2020, from http://www.who.int/pbd/deafness/activities/epidemiology_economic_analysis/en/index.html.

World Health Organization, (2013). *Deafness and hearing loss.* Retrieved February 17, 2020, from https://www.who.int/news-room/fact-sheets/detail/deafness-and-hearing-loss.

World Health Organization, (2013). Millions of People in the World have a Hearing Loss that Can be Treated or Prevented. Retrieved February 17, 2020, from http://www.who.int.innopac.up.ac.za/pbd/deafness/

Yamakami, I., Uchino Y., Kobayashi, E. & Yamaura, A. (2003). Computed tomography evaluation of air cells in the petrous bone: relationship with postoperative cerebrospinal fluid rhinorrhea. *Neurologia Medico-Chirurgica. (Tokyo),* 24: 334–339.

Yilmaz, T., Bilgen, C., Savas, R. & Alper, H. (2003). Persistent Stapedial Artery: MR Angiographic and CT Findings. *AJNR American Journal of Neuroradiology,* 24: 1133–1135.

BRIDGING TEXT

From Chapter One to Chapter Two

The previous chapter revealed the general anatomy of TBP and its clinical importance. A general overview of the methodology employed for this research was also discussed. Furthermore, previous knowledge on what is known and yet to be known about the development of TBP, classification of temporal bone degree of pneumatization, and association with anatomical variations of related vasculature was highlighted. The literature revealed that the one key area that required more detailed elaboration was regarding the size of the temporal bone air system with age. This is of high clinical relevance because of controversies arising from the relationship between mastoid air cells and OM, a disease with high global burden, either as a cause or consequence (as described by the genetic and environmental theories). What then is the normal size of TBP with age? What is the normal growth pattern or growth rate of air cells?

The next chapter is a scoping review, highlights studies that have been conducted on the growth and size of mastoid air cells with age in order to identify what is known and yet to be known with regards to the size of air cells at different stages of human postnatal growth from early childhood to early adulthood.

The scoping review in chapter two, titled ***"Temporal bone pneumatization: A scoping review on the growth and size of mastoid air cell system with age,"*** was submitted to Plos One (Public Library of Science Journal) on 27th July 2021 and published on 3rd June 2022. (Manuscript and references were written according to journal format).

CHAPTER TWO

MANUSCRIPT ONE

Temporal bone pneumatization: A scoping review on the growth and size of mastoid air cell system with age

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Temporal bone pneumatization: A scoping review on the growth and size of mastoid air cell system with age

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Abstract

The interest in the mastoid air cell system arose from the association between temporal bone aeration and otitis media. Its size and growth have been considered when planning chronic and middle ear surgeries. The objective of this review was to explore the literature on the size of mastoid air cells with age, highlighting various growth rates reported and mapping out areas yet to be fully understood for further research. A three-step systematic search was conducted for available literature on the subject matter viz; Google Scholar, Medline, Cochrane Library, and PubMed. Eligibility criteria guided the study selection, and eligible studies were subjected to appraisal using screening and quantitative criteria of mixed-method appraisal tool. A data extraction form was developed to extract information from eligible studies. Nine studies met the eligibility criteria. 55.6% of the included studies were conducted among the east and south Asian population, 33.3% were conducted among Scandinavians, and 11.1% in South America. Age groupings varied among studies; 33.3% utilized 1-year age grouping, 33.3% utilized 5-year age grouping, 11.1% utilized 10-year age grouping. In reporting the size of mastoid air cells across age groupings, 66.7% utilized area, 22.2% utilized volume, while 11.1% utilized both area and volume. Findings from this review showed that the mastoid air cells' size with respect to age differs among populations of different origins. The most common measurements were the area of air cells. The highest growth rate was reported up to 30 years. Findings also show the influence of sex on the size of mastoid air cells and growth rate with age, as females were reported to have larger air cells with rapid growth until puberty. However, the male mastoid air cell system continues a steady growth after puberty and becomes larger. Information still lacks in the volume of air cells in pediatric pneumatization.

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Introduction

The temporal bone, a pair of bones located on the lateral skull that could be ignored because of its size but its anatomical complexity, could pose a challenge in interpreting anatomical details and diagnosis of various pathological conditions [1]. Each temporal bone consists of four parts: a squamous part, which is the antero-superior part of the bone; a tympanic part, which is a curved plate below the squamous part and anterior to the mastoid process; a styloid process, which is a slender and pointed bone which projects antero-inferiorly from the inferior aspect of the temporal bone; and a petromastoid part, which is relatively large consisting of the petrous and mastoid process [2, 3]. The petromastoid part houses the ear components, contains numerous openings and canals through which structures enter and exit the cranial cavity, and comprises a compact bone and trabeculae that are variably pneumatized [2, 4, 5].

Pneumatization is the presence or development of air-filled cavities or epithelial-lined air cells within cranial components that remain after the pneumatization process [6]. The pneumatization of temporal bone serves as a prognostic factor in middle ear surgery and could be considered once related surgeries are planned [7–9]. Temporal bone pneumatization has also been reported to give a protective function, acting as a shock absorber in patients with lateral skull-based fracture and traumatic brain injury [10, 11], which have had a devastating impact on many individuals, approximately 69 million individuals worldwide and affect a significant number of people in South Africa [12, 13]. However, minimal pneumatization of the temporal bone is a characteristic of otitis media [14, 15], which is one of the global burdens of disease [16–20], and significantly high in South Africa among younger children and older children with prevalence of 31.4% and 16.7% respectively [21, 22].

Temporal bone pneumatization is a process that begins during prenatal development (the mastoid antrum), achieved by transitioning the temporal bone into air cells which were first described by Schwartze and Eysell in 1873 and completed by Zuckerkandl in 1879 [9, 15, 23–25]. At about the 24th week of intrauterine life, the mastoid antrum is the only visible air cell, lined by a single flat layer of epithelium distinguished from bone by subepithelial connective tissue, which activity is largely responsible for air-cell formation [6, 26, 27]. The development of mastoid air cells (also called mastoid cells of Lenoir or air cells of Lenoir) is preceded by the formation of bone cavities that contain primitive bone marrow, which dedifferentiates into a loose mesenchymal connective tissue [23, 24, 28]. Invagination of the epithelial mucous membrane is followed by atrophy, leaving a thin residual lining membrane attached to the periosteum. "Retraction" of the lining membrane and the subepithelial bone resorption further enlarges air cells [24, 26, 28, 29].

After birth, the mastoid air cells are readily visible as hollowed-out spaces lined by flattened, non-ciliated squamous epithelium [30]. These air cells exhibit variability in size and extent [31]. At the superior and anterior parts of the mastoid process, air cells are large and irregular and contain air. Towards the inferior part of the process, they diminish in size, while those at the apex of the process are frequently quite small and contain marrow [27, 31–34]. As growth continues, mastoid air cells communicate with the middle ear via the mastoid antrum and the aditus ad antrum and extend variably to petrous parts and around the inner ear [27, 31, 35]. Air cells may also infiltrate the zygomatic, the squamous, the styloid, and the occipital regions, resulting in accessory pneumatization [34, 36]. Imperatively, there is a gradual reduction in air cells throughout life with additional loss in the elderly both at the base and more reduction at the apex [37].

Exposure of the middle ear to infections such as otitis media could affect the size of the mastoid pneumatization [15, 38]. This is because the mastoid air cell system development has been considered to be impeded by repeated and prolonged otitis media [39, 40]. Other factors that

could influence the mastoid air cell system include; genetics, environment, nutrition, and diseases [6, 9, 30]. Therefore, knowledge of the size of mastoid air cells with age is beneficial to researchers in Otorhinolaryngology and Clinical Anatomy.

In the past decades, various studies on temporal bone pneumatization and mastoid air cells have been conducted [6, 41]. However, very few have reported the size of the mastoid air cells concerning age. Therefore, this review is undertaken to explore available age-related studies on the size of the mastoid air cells, highlighting growth rate and size in terms of area and volume, and identifying possible variations regarding ethnicity and sex.

Methods

This is a scoping review of the available literature on the growth and development of the mastoid air cell system. This review employed the framework outlined by Arksey and O'Malley [42], with further recommendations by Levac and colleagues [43]. These include: identifying the research question; identifying relevant studies; study selection; charting the data; and collating, summarizing, and reporting the results.

Research question

The research question guiding this review was: "what are the age-related studies that have reported the size of the mastoid air cells in areas and volumes"? Two sub-questions were further used: (i) In which population and countries were these reported? (ii) What age range or groupings were used in reporting these studies?

Search strategies

A three-step systematic search of the literature was conducted on Google Scholar (Google Inc, Mountain View, California), PubMed and Medline (National Centre of Biotechnology Information, Bethesda, Maryland, United States), and Cochrane library (Access provided by University of KwaZulu-Natal Libraries) electronic databases. The keywords used for this search include temporal bone, pneumatization, mastoid bone, mastoid air cells, mastoid pneumatization, air cell growth, air cell size, and mastoid aeration. These keywords were used alone and in combination with Boolean operators (OR, AND) such as "temporal bone AND pneumatization" OR "mastoid bone AND mastoid air cells" OR "mastoid pneumatization AND air cell size" OR "Temporal bone AND air cell growth" OR "mastoid bone and mastoid aeration".

The first step search made use of keywords separately and in combination using Google Scholar and PubMed databases only. This was followed by analyzing the text words in the titles and abstracts of the retrieved papers and index terms used to describe the articles. A second search using identified keywords and index terms were used across all databases. The third step search was also conducted across all databases using a reference list of all identified articles.

Inclusion criteria

The following inclusion criteria were adopted during the literature search: All research and review articles, reports, and books available on temporal bone anatomy and its pneumatization; Research and review articles on mastoid air cell system, growth of air cells, and size documented between 1940–2021; Articles, reports and books available in English Language, articles already translated to the English language and articles that were available in dual languages.

Exclusion criteria

Research articles, reviews, and reports on temporal bone pneumatization and mastoid air cells before 1940 were excluded during study selection (age-related study on mastoid air cell systems was first reported in 1940 by Diamant). Studies on the classification of temporal bone pneumatization, pathology, and non-age-related studies on mastoid air cell systems were also excluded.

Study selection

A set of questions in line with the study's objective was used to assess the relevance of studies identified during the literature search. Study selection was done by two authors (OA and KO) who screened titles and abstracts of all retrieved studies to assess eligibility. When eligibility could not be determined, full articles were retrieved.

Quality appraisal

The quality appraisal of the eligible studies was conducted using screening criteria for all types of study and quantitative descriptive criteria of the Mixed Methods Appraisal Tool (MMAT)-Version 2018 [43]. This was used because this review involves studies with measurements. OS, KO & SO designed a form to assess the quality of eligible studies. The form consists of two screening questions for all study types and five criteria that apply to quantitative descriptive studies [Table 1]. CR, AS & WM reviewed this form. The appraisal was done by SL and OF, who are not part of this review authorship, to avoid bias. A score of 20% is given when an eligible study fulfills one quantitative criterion, 40% if it fulfills two criteria, 60% if it fulfills three criteria, 80% if it fulfills four criteria, and 100% if it fulfills all quantitative criteria.

Data extraction and analysis

A form was developed as a data extraction instrument by three authors (OA, SO) to extract key information such as author, date, title, the aim of the study, method, population, country of study, age range, age grouping, sample size, most significant outcome, and other important outcomes. The extraction form was subjected to review. CR and AS independently used this form to extract data from all eligible studies.

All data were compiled on a spreadsheet and imported into Microsoft Excel 2010. In addition, the content analysis of each paper included in this review was done, and a line graph was used to present the pattern and growth rate of mastoid air cells.

Table 1. Mixed Methods Appraisal Tool (MMAT), version 2018 indicators for screening questions and quantitative descriptive studies (adapted from Hong *et al.* [44]).

Category of study designs	Methodological quality criteria
Screening questions	*1. Are there clear research questions or objectives?*
	2. Do the collected data allow to address the research questions?
Quantitative descriptive studies	*1. The sampling strategy is relevant to address the research questions*
	2. The sample is a representative of the population study
	3. Appropriate and validated measurements
	4. Low risk of nonresponse bias
	5. Appropriate statistical analysis was done to answer the research question

Note: Studies were of acceptable quality when the first two screening questions for all study types and at least one of the indicators in the qualitative criteria were met.

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Results

Description of included studies

A total of 381 articles were identified during the literature search, including research papers, reviews, reports, and books. Ninety-three duplicates were removed. After screening titles and abstracts, 243 articles were excluded based on the following exclusion criteria; studies reported before 1940, studies reporting petrous pneumatization, studies reporting classification of temporal bone pneumatization, studies reporting pattern of pneumatization, and pathological-related studies. Finally, 45 full-text articles were reviewed for eligibility. Of them, 36 were excluded because they were non-aged related studies on the size of mastoid air cells and limited to degree of mastoid pneumatization. However, only 9 studies were considered to be eligible and included in this review (Fig 1).

Table 2 summarizes the included studies and their major findings, while Fig 2 shows the level of knowledge regarding the area and volume of air cells with age. Figs 3–5 show graphical representations (line graph) of patterns and growth rate of mastoid air cells regarding ethnicity and/or sex. The majority (55.6%) of the included studies were conducted among east and south Asian population [45–49], 33.3% were conducted among Scandinavians (North Europe) [41, 50, 51], while 11.1% in South America [4]. The majority (55.6%) of the included studies were conducted in high-income countries, while 44.4% were conducted in middle-income countries (upper & lower). The largest sample size used is 430 [50], and the lowest is 28 [6].

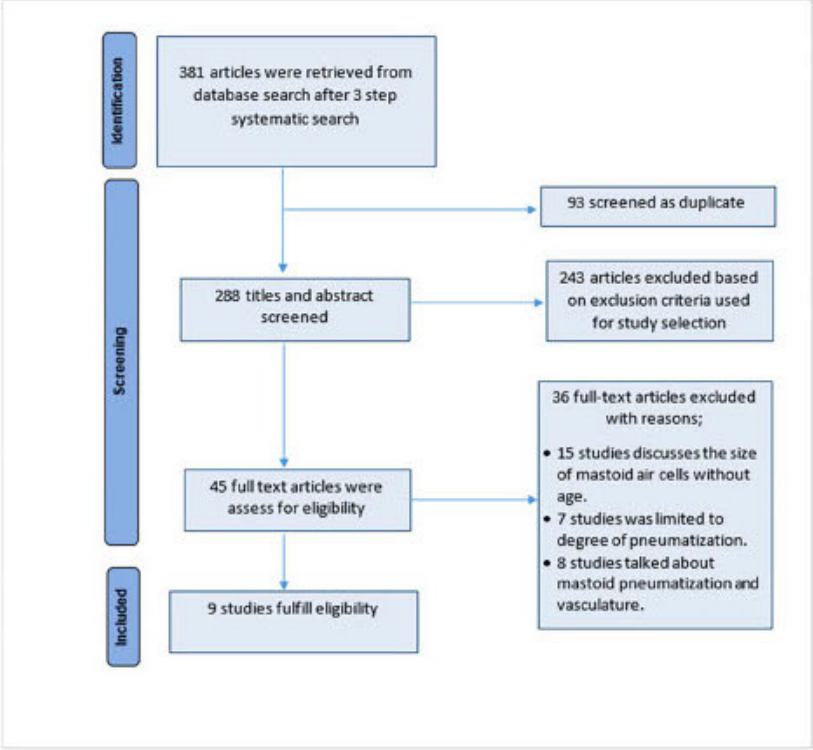

Fig 1. Flow diagram for study selection.

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Table 2. Table of characteristics of included studies.

Author (Date)	Country (Population)	Sample Size	Male (%)	Female (%)	Age	Aim of Study	Methodology	Major findings mastoid air cell growth	MMAT Score
Diamant, 1940	Sweden (Swedish Children; pre-antibiotic era)	180	43.9%	56.1%	1 to 15 years	To systematically study the mastoid air cells (otitis media and pneumatization of mastoid bone)	A prospective study from 1932 to 1938. Measurement was done by planimetry from lateral X-ray films. Age groupings: 5 years	• This prospective study found out that the area of mastoid air cells increases with age and terminates at puberty. • Mastoid Pneumatization in females was larger and increased significantly. • The mean size reported: 12.04 ± 0.37 cm^2	60%
Kawamura *et al.* 1963[b]	Japan (Japanese Children)	116	-	-	1–6 years	To study the normal development of the mastoid pneumatic cells	Lateral mastoid X-ray film measurements. Age grouping: 1 year	• A linear pattern of air cell growth was observed from age 1–6 years. • The mean size reported: 4.71 cm^2	60%
Rubensohn, 1965	Sweden (Swedish Children)	430	-	-	1–15 years	To investigate mastoid pneumatization in children at various ages.	Mastoid X-ray measurements. Age grouping: 1 year	• The mastoid air cells system continues to enlarge throughout the years, 1 to 15 years. • A linear pattern of air cell growth was observed from age 1–6 years. • The mean size reported: 9.32 cm^2	80%
Arora *et al.*, 1973	Indian (North Indian Children)	100	50%	50%	5 to 15 years	To measure mastoid Pneumatization in children	Roentgenographic planimetric measurements of North Indian skull. Age groupings: 5 years	• Area of mastoid Pneumatization increases with age by 2 cm^2 every 5 years, with females having larger pneumatization than males. • Pneumatization terminates in puberty. • The mean size reported: 9.02 cm^2	60%
Qvarnberg, 1981[b]	Finland (Finish Children)	232	-	-	Birth to 16 years	Mastoid air cell system and otitis media	Planimetric measurement of X-rays Age grouping: 1 year	• The mastoid air cells system continues to enlarge throughout the years, 1 to 15 years. • A linear pattern of air cell growth was observed from age 1–6 years. • The mean size reported: 9.66 cm^2	80%
Chatterjee *et al.*, 1990	Indian (West Bengal: Bengalee People)	100	50%	50%	6 months to 60 years	To measure the size of mastoid air cell system in normal subjects in various age groups or either sex and compare with findings with those reported in other countries	A Cross-sectional study using 2D radiographic planimetric measurements of lateral X-ray films. Age groupings: 5 years	• The mastoid air cell system development continues even after 20 years of age as mastoid air cells increase for both sexes, but males have larger pneumatization than females. • Mean size reported: • 12.05 ± 0.67 cm^2 (male) • 11.45 ± 0.70 cm^2 (female)	60%

(*Continued*)

Table 2. (Continued)

Author (Date)	Country (Population)	Sample Size	Male (%)	Female (%)	Age	Aim of Study	Methodology	Major findings mastoid air cell growth	MMAT Score
Isono *et al.* 2003	Japan	80	53.75%	46.25%	1–18 years	To describe the measurement of infants' mastoid air cell system and its developmental changes with age.	Volume measurement of High-Resolution Computed Tomography (CT) images of 2mm slice thickness. Age grouping: Not specified	• It was confirmed that the mastoid air volume increased with age. • By 9–10 years old, it had reached about 80% of the volume of an adult, • At late puberty (14–15 years), it had reached mean adult value. • The mean size reported: 5.97 ml	60%
Lee *et al.*, 2005	Korea (Korean population)	102	49%	51%	6–84 years	To report age-related variation of mastoid Pneumatization with the application of 3D computer-based volume measurement.	A retrospective study using 3D-MPVR on CT images of 2.5 mm slice thickness. Age grouping: 10 years	• Volumetric measurements of mastoid air cells revealed that mastoid aeration continues to grow until the 3rd decade of life, and a decline in growth occurs thereafter. • Mean size reported • 3813.85 mm^3 (Children: 0-10yrs) • 7095.20 mm^3 (Adult: 19-44yrs)	60%
Hill, 2011	Columbia, Missouri (Human Cadaveric Temporal Bone)	28	-	-	0–25 years	To systematically quantify the normal development of pneumatized spaces. (Ontogenetic study)	A cross-sectional sampling of 28 human temporal bones using 3D reconstruction Quant3D Software and method of ROI and VOI Age grouping: 5 categories (infant, young child, middle child, adolescent, & adult)	• Temporal bone is not well-pneumatized in infants as it is limited to the mastoid antrum • Surface area and volumes of pneumatized spaces double before age 4 • There is a twofold to threefold increase in air cells' size between age nine and adulthood.	60%

[b] Retrieved from the review and reference study on the growth rate and size of the mastoid air cell system and mastoid bone (Cinamon, 2009).

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All included studies were retrospective studies [6, 45–51], except for Diamant [41] which was a prospective study. Age groupings varied among studies; 33.3% utilized 1 year age grouping [45, 50, 51], 33.3% utilized 5 years age grouping [41, 46, 47], 11.1% utilized 10 year age grouping [49], 11.1% utilized inconsistent age grouping [6], while 11.1% age grouping was not defined [48]. Most (55.6%) of the studies included sex in their study [41, 46–49]. In reporting the size of mastoid air cells across age and age groupings, the majority (66.7%) utilized area [41, 45–47, 50, 51], 22.2% used volume [48, 49], while 11.1% used both area and volume [6].

Methodological quality of the eligible study

The nine included studies were deemed of very good quality as they answered the first two screening questions and fulfilled at least three quantitative criteria of MMAT. On the quantitative criteria, 7 met three criteria- 60% while two met four criteria- 80% (Table 2).

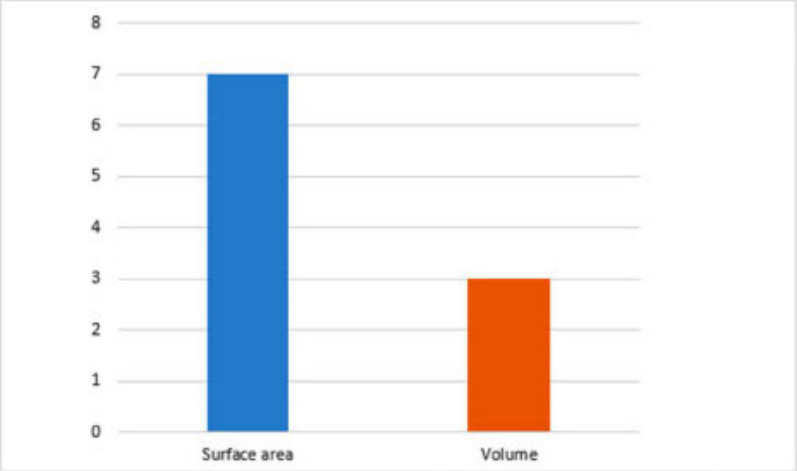

Fig 2. Bar chart showing the frequency of measurement methods of the size of mastoid air cells with age in the literature from 1940 till present. The X-axis displays measurements of air cells, and the Y-axis illustrates the number of articles.

https://doi.org/10.1371/journal.pone.0269360.g002

Mastoid air cell growth rate reported in studies of 1 year consecutive age grouping in area

Three of the included studies that utilized 1-year age grouping were conducted among Swedish, Finnish, and Japanese children [46, 50, 51]. A linear pattern of air cell growth was observed from age 1–6 years, and the mastoid air cells system continues to enlarge throughout the years, 1 to 15 years, except for the study among Japanese children, which was limited to age 6 (Fig 3).

Mastoid air cell growth rate reported in studies of 5 years consecutive age grouping in area

Three of the included studies utilized 5-year age grouping [41, 46, 47], but only the study of Diamant [41] and Chatterjee *et al.* [47] among Swedish children and Bangele people of Indian

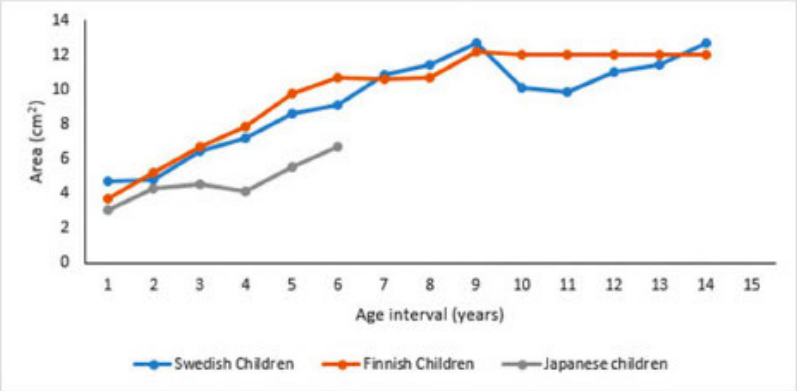

Fig 3. Line graph showing growth rate and size of mastoid air cell systems of studies that utilized 1 year age grouping. X-axis displays age in years, and Y-.axis illustrates the size of the mastoid air cells.

https://doi.org/10.1371/journal.pone.0269360.g003

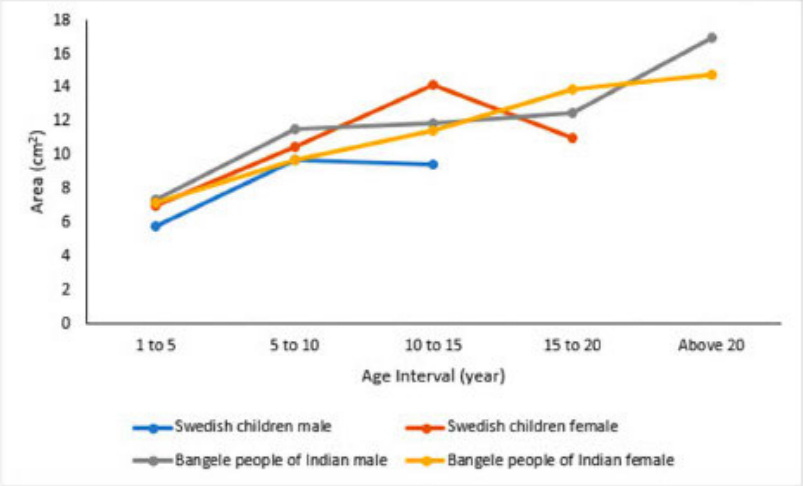

Fig 4. Line graph showing growth rate and size of mastoid air cell systems of studies that utilized 5 year age grouping. X-axis displays the age range in years, and Y-axis illustrates the size of the mastoid air cells.

https://doi.org/10.1371/journal.pone.0269360.g004

gave information from age one. Fig 4 showed rapid growth patterns of mastoid air cell systems for both studies among males and females. Among Swedish children, the area of mastoid air cells increases with age by about 4 cm^2 in every 5 years but terminates at puberty, 10 years for males and 15 years for females. Mastoid air cells in females was larger and increased significantly. However, among Bangele people of Indian, mastoid air cells increase by about 2 cm^2 every 5 years, and it continues even after 20 years of age for both sexes, both at a slower rate with males having larger pneumatization than females.

Mastoid air cell growth rate reported in studies of 10 years consecutive age grouping in volume

Only one study in the included studies utilized 10-year age grouping utilized volumetric measurements of mastoid air cells among the Korean population [49]. Fig 4 showed that mastoid aeration grows and increases at a faster rate from birth to the early 2^{nd} decade of life. Between the late 2^{nd} and 3^{rd} decades of life, the air cells continue to grow slowly. It slowly declines after the 3rd decade of life, then rapidly after the 7^{th} decade of life. Among females, the volume of air cells increases rapidly but experiences an earlier slow growth rate (Fig 5).

Discussion

Temporal bone pneumatization is a process that begins during prenatal development (mastoid antrum) but prominent during postnatal growth as air cells enlarge with age and become readily visible, with completion of pneumatization to be around age 10 [6, 15, 27]. Following a thorough literature search, this review is the first scoping review on the size of mastoid air cells with respect to age. Since the first study conducted on the growth of the mastoid air cell system with age conducted by Diamant [41], very few studies have reported the size of mastoid air cells with respect to age involving different age groupings and measurement methods.

Although, a study by Cinamon [8] supported the opinion of Virapongse *et al.* [27] on the development of pneumatization to be three stages from birth till adult size (infantile stage-

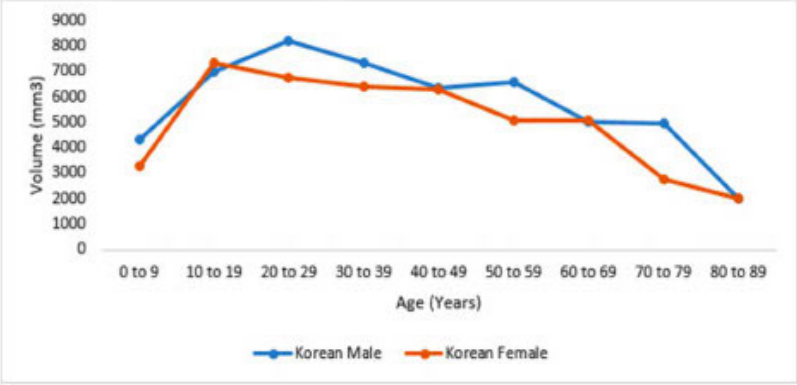

Fig 5. Line graph showing growth rate and size of mastoid air cell systems of study that utilized 10 year age grouping. X-axis displays age range in years, and Y-axis illustrates the volume of the mastoid air cells.

https://doi.org/10.1371/journal.pone.0269360.g005

birth to 2 years; transitional stage- 2 to 5 years; and adult stage- 6 years above), the present review has revealed some differences in the size of mastoid air cells with age. The ontogenetic study by Hill [6] using human cadaveric temporal bone reported air cells to be limited to the mastoid antrum, but area and volumes double before age 4. A twofold to threefold increase in the size of air cells was observed between age 9 and adulthood.

In studies that utilized planimetric measurements (area), a linear pattern of air cell growth was observed among some populations with different ethnic origins from age 1 to 6. However, the growth rate and size of air cells with age still differ. This was observed among Scandinavian and Japanese children, where air cells add about 1–1.2 cm^2 per year between ages 1–6. However, the size of air cells was reported to increase until puberty among the Scandinavian children reaching adult size ~ 12 cm^2, with an increase of about 4 cm^2 every 5 years from age 1–15. There was no report on the size of mastoid air cells after age 6 for Japanese children, and the maximum air cell size reached was 6.68 cm^2. Among South Asian children (North Indian population and Bangalee people of India), the size of mastoid air cells increases about 2 cm^2 every 5 years terminating at puberty, reaching an adult size of about 9.66 cm^2 among the North Indian population. However, there was a continuous increase after puberty reported among the Bangalee people of India, even after age 20 with adult size ~ 16 cm^2. Isono *et al.* [48] and Lee *et al.* [49] used volumetric measurements on CT images in the East Asian region (Japanese and Korean populations). They reported that the volume of mastoid air cells increased with age. Though both studies were age-related, Isono *et al.* [48] did not specify their age grouping. However, it was observed that the volume of mastoid air cells among the Japanese population increased rapidly until puberty.

Nevertheless, the study of Lee *et al.* [49] specified their age grouping (10-year consecutive age group) and observed among the Korean people that mastoid air cells continue to grow until 30 years with a rapid increase observed among females until puberty with a maximum volume of 7320.6 mm^3. However, the increase in males steadies till age 29 with a maximum volume of 8211.7 mm^3. Nonetheless, the highest growth rate reported in this population might be due to the method used.

In addition, from age-related studies that considered sex, the size of mastoid air cells was larger in females until puberty with rapid growth. This could be a reflection of females' early initiation of general physical growth [8]. However, from the studies that considered ages above

puberty, it was reported that the mastoid air cells in males became larger after puberty with a corresponding increase in size and growth rate.

Based on the fact that this review considered studies that measured area and volume air cells, information retrieved suggests that the size of air cells follows a linear growth pattern from age 1 to 6. This is followed by a rapid increase in size from age 6 until puberty and a slow, steady growth from puberty until early adulthood. This, however, contradicts the review and reference study of Cinamon [8], who suggested a slower increment in the size of air cells up to adult size at puberty, but did not elaborate on the growth rate from puberty to early adulthood. Information retrieved from this study also suggests variations in the size of mastoid air cells with age regarding sex and ethnicity.

Furthermore, in ENT and its related surgeries, the interest in the size of mastoid air cells and its importance arose from the association between temporal bone aeration and otitis media either as a cause or a consequence. It may also be considered when planning chronic ear and middle ear surgeries [8]. This is because the mastoid air cell system has been noted as an air reservoir for the middle ear and the volume of air cells governs the capacity of this reservoir [49]. A small mastoid air cell has also been linked to chronic middle ear disease [15]. In human development and growth, the size of mastoid air cells has been well documented to increase with age [2, 4]. Both areas and volumes can measure the size of mastoid air cells. However, volumetric measurements likely give the foremost comprehensive insight to appreciate the estimate of mastoid air cells because it measures three-dimensional space while area gives only surface (2D) information [8]. The present review notes that most of the available information on the mastoid air cell system size with age was based on the surface area through planimetric measurements. However, volumetric estimation of mastoid air cells with age was limited to three studies [6, 48, 49]. Although the study of Lee *et al.* [49] reported the mean volume of air cells in children (0–10 years) to be 3813.85 mm^3 and adults (19–44 years) to be 7095.20 mm^3, there is a dearth of information on the volume of air cells in the suggested three stages of development of temporal bone pneumatization owing to the large age grouping employed in their study. Besides, Isono *et al.* [48] and Hill [6] utilized inconsistent age grouping and could not provide pediatric air cell volume information. This means that these studies lack information on the volume of air cells in the infant, transitional, and adult stages. What then is the volume of air cells of healthy temporal bone pneumatization in these developmental stages? Is there any variation in the volume of these air cells with age? Hence, information on the volume of mastoid air cells developmentally remains limited.

Conclusion

The findings from this review indicate that the size of mastoid air cells increases beyond puberty, even up to 20 years of age among populations of separate ethnic groups. The use of volumetric analysis reported air cells to increase up to around 30 years of age. This review also revealed that the knowledge on the volume of mastoid air cells with respect to age is still lacking despite the comprehensive insights volumetric analysis gives in estimating air cell sizes and their clinical importance. Furthermore, the present study also highlights that no age-related studies on the size of mastoid air cells and temporal bone pneumatization have been conducted in sub-Saharan Africa and low-income countries considering the global prevalence of otitis media and its high incidence rate among children in sub-Saharan Africa. Finally, this review has shown that there is little in the form of research publications on the size of mastoid air cells with age and development of temporal bone pneumatization, as a total of 9 unique age-related articles were found describing this. Further age-related studies are encouraged on the growth and development of the mastoid air cell system and temporal bone pneumatization

utilizing volumetric measurement to give a comprehensive insight and a more consolidated description of the size of air cells across age groups in different populations. Three-dimensional reconstructive volumetric analysis is also encouraged to reveal possible morphological (shape) variations of the mastoid air cell system with age.

Supporting information

S1 Checklist. PRISMA checklist.
(DOCX)

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References

1. Osama AMK. Anatomical characteristics of temporal bone on computerized tomography. IOSR-JDMS. 2018; 17(5): 88–96.
2. Standring S, Gray H. Gray's anatomy: The anatomical basis of clinical practice. 40th ed. Edinburgh: Churchill Livingstone; 2008.
3. Drake RL, Vogl WA, Mitchell AWM, Gray H. Gray's anatomy for students. 4th ed. Philadelphia: Elsevier; 2020.
4. Isaacson B. Anatomy and surgical approach of the ear and temporal bone. Head Neck Pathol. 2018; 12 (3): 321–327. https://doi.org/10.1007/s12105-018-0926-2 PMID: 30069845
5. Mudgal P, Hacking C. Temporal bone. Reference article, Radiopaedia.org. 2014 Mar 20 [revised 2021 Jul 01; accessed 2021 Dec 28]. Available from: https://doi.org/10.53347/rID-28310.
6. Hill CA. Ontogenetic change in temporal bone pneumatization in humans. Anat Rec. 2011; 294(7): 1103–1115. https://doi.org/10.1002/ar.21404 PMID: 21618436
7. Koc A, Ekinci G, Bilgili AM, Akpinar IN, Yakut H, Han T. Evaluation of the mastoid air cell system by high resolution computed tomography: Three-dimensional multiplanar volume rendering technique. J Laryngol Otol. 2003; 117: 595–598. https://doi.org/10.1258/002221503768199906 PMID: 12956911
8. Cinamon U. The growth rate and size of the mastoid air cell system and mastoid bone: A review and reference. Eur Arch Oto-Rhino-L. 2009; 266(6): 781–786. https://doi.org/10.1007/s00405-009-0941-8 PMID: 19283403

9. Lee D-H, Kim M-J, Lee S, Choi H. Anatomical factors influencing pneumatization of the petrous apex. Clin Exp Otorhinolaryngol. 2015; 8(4): 339–344. https://doi.org/10.3342/ceo.2015.8.4.339 PMID: 26622951

10. Secchi MMD, Moraes JFS, Castro FB. Fractures of the temporal bone in patients with traumatic brain injury. Int Arch Otorhinolaryngol. 2012; 6(1): 62–66.

11. Kang TK, Ha R, Oh JH, Sunwoo W. The potential protective effects of temporal bone pneumatization: A shock absorber in temporal bone fracture. PLoS One. 2019; 14(5): e0217682. https://doi.org/10.1371/journal.pone.0217682 PMID: 31150482

12. Dewan MC, Rattani A, Gupta S, Baticulon RE, Hung Y-C, Punchak M, et al. Estimating the global incidence of traumatic brain injury. J Neurosurg. 2019; 130: 1080–1097.

13. Mokolane NS, Minne C, Dehnavi A. Prevalence and pattern of basal skull fracture in head injury patients in an academic hospital. S Afr J Rad. 2019; 23(1): a1677. https://doi.org/10.4102/sajr.v23i1.1677.

14. Todd NW, Pitts RB, Braun IF, Heindel H. Mastoid size determined with lateral radiographs and computerized tomography. Acta Otolaryngol. 1987; 103(5–6): 226–231. https://doi.org/10.3109/00016488709107788 PMID: 21449646

15. Han SJ, Song MH, Kim J, Lee WS, Lee H-K. Classification of temporal bone pneumatization based on sigmoid sinus using computed tomography. Clin Radiol. 2007; 62: 1110–1118. https://doi.org/10.1016/j.crad.2007.04.019 PMID: 17920872

16. Morris PS, Leach AJ. Acute and chronic otitis media. Pediatr Clin N Am. 2009; 56(6): 1383–1399. https://doi.org/10.1016/j.pcl.2009.09.007 PMID: 19962027

17. Vos T, Barber RM, Bell B, Bertozzi-Villa A, Biryukov S, Bolliger I. Global, regional, and national incidence, prevalence, and years lived with disability for 301 acute and chronic disease and injuries in 188 countries, 1990–2013: a systemic analysis for the global burden of disease study. Lancet. 2015; 386 (9995): 743–800. https://doi.org/10.1016/S0140-6736(15)60692-4 PMID: 26063472

18. DeAntonio R, Yarzabal J-P, Cruz JP, Schmidt JE, Kleijnen J. Epidemiology of otitis media in children from developing countries: A systematic review. Int J Pediatr. Otorhinolaryngol. 2016; 85: 65–74. https://doi.org/10.1016/j.ijporl.2016.03.032 PMID: 27240499

19. Tesfa T, Mitiku H, Sisay M, Weldegebreal F, Ataro Z, Motbaynor B, et al. Otitis media in sub-Saharan Africa: a systemic review and meta-analysis. BMC Infect Dis. 2020; 220: 225.

20. World Health Organization. World Report on Hearing; 2021. ISBN 978-92-4-002048-1.

21. Biagio L, Swanepoel DW, Laurent C, Lundberg T. Paediatric otitis media at a primary healthcare clinic in South Africa. S Afr Med J. 2014; 104(6): 431–435. https://doi.org/10.7196/samj.7534 PMID: 25214254

22. Phanguphangu MC. Otoscopic examinations reveal high prevalence of outer and middle ear pathologies in pediatrics in Limpopo, South Africa. Int J Audiol. 2016; 56(4): 215–218. https://doi.org/10.1080/14992027.2016.1244868 PMID: 27783901

23. Ojala L. Contributing to the physiology and pathology of mastoid air cell formation. Acta Otolaryngol. 1950; 86(Suppl): 1–134.

24. Ojala L. Pneumatization of the bone and environmental factors: Experimental studies in chick humerus. Acta Otolaryngol. 1957; 1(Suppl): 33:1–28. PMID: 13469326

25. Singh V, Chaitanya DC, Chauchan BKS, Kumar IDV. A Comparative study of pneumatization of temporal bone. J Anat Soc India. 2017; 66: 78–81.

26. Tremble GE. Pneumatization of the temporal bone. Arch Otolaryngol. 1934; 19: 172–182.

27. Virapongse C, Sarwar M, Bhimani S, Sasak C, Shapiro R. Computed tomographic anatomy of the temporal bone: Normal pattern and morphology. AJR Am J Neuroradiol. 1985; 145: 473–481.

28. Shambaugh GE, Glassock ME. Surgery of the ear, 3rd ed. Philadelphia: Saunders; 1980. p. 24–25.

29. Beaumont GD. The effects of exclusion of air from pneumatized bones. J Laryngol Otol. 1966; 80: 236–249. https://doi.org/10.1017/s0022215100065208 PMID: 5907834

30. Sethi A, Singh I, Agarwal AK, Sareen D. Pneumatization of mastoid air cells: Role of acquired factors. Int J Morphol. 2006; 24(1): 35–38.

31. Knipe H, Hacking C. Mastoid air cells. Reference article, Radiopaedia.org. 2014 Mar 23 [revised 2021 Nov 19; accessed 2021 Dec 26]. Available from: https://doi.org/10.53347/rID-28366.

32. Cheatle AH. The infantile types of mastoid with ninety-six specimens. J Laryngol. 1907; 22: 256.

33. Schillinger R. Pneumatization of the mastoid. Radiology. 1939; 33: 54–69.

34. Allam AF. Pneumatization of the temporal bone. Ann Otol Rhinol Laryngol. 1969; 78: 49–64. https://doi.org/10.1177/000348946907800105 PMID: 5763190

35. Schmalfuss IM. Petrous Apex. In: Chong V, editors. Skull Base Imaging. Missouri: Elsevier; 2018. p. 233–245.

36. Orhan K, Delilbasi C, Orhan AI. Radiographic evaluation of pneumatized articular eminence in a group of Turkish children. Dentomaxillofac Radiol. 2006; 35: 365–370. https://doi.org/10.1259/dmfr/77401728 PMID: 16940485

37. Wright A, Davis A, Bredberg G, Ulehlová L, Spencer H, Bock G, et al. Hair cell distributions in the normal human cochlea. A report of a European working group. Acta Otolaryngol. 1987; 436: 15–24. https://doi.org/10.3109/00016488709124972 PMID: 3478958

38. Turgut S, Tos M. Correlation between temporal bone pneumatization, location of lateral sinus, and length of the mastoid process. J Laryngol Otol. 1992; 106: 485e9.

39. Palva T, Palva A. Size of the human mastoid air cell system. Acta Otolaryngol. 1966; 62: 237–251. https://doi.org/10.3109/00016486609119570 PMID: 5970742

40. Aoki K, Esaki S, Honda Y, Tos M. Effect of middle ear infection on pneumatization and growth of the mastoid process. An experimental study in pigs. Acta Otolaryngol. 1990; 110(5–6): 399–409. https://doi.org/10.3109/00016489009107461 PMID: 2284915

41. Diamant M. Otitis and pneumatization of the mastoid bone. Acta Otolaryngol. 1940;41.

42. Arksey H, O'Malley l. Scoping studies: towards a methodological framework. Int J Soc Res Methodol. 2005; 8: 19–32.

43. Levac D, Colquhoun H, O'Brien KK. Scoping studies: Advancing the methodology. Implement Sci. 2010; 5(1): 69. https://doi.org/10.1186/1748-5908-5-69 PMID: 20854677

44. Hong QN, Pluye P, Fabregeus S, Bartlett G, Boardman F, Cargo M, et al. Mixed-method appraisal tool (MMAT)-Version 2018: User Guide. McGill; 2018.

45. Kawamura S, Okabe K, Mogi S, Terao A. The normal development of the mastoid pneumatic cells. J Otorhinolaryng Soc Jap. 1963; 66: 909–912. https://doi.org/10.3950/jibiinkoka.66.909 PMID: 14075498

46. Arora MML, Sain U, Sodhi JS. Mastoid pneumatization in children—a roentgenographic planimetric study. Indian J Otolaryngol Head Neck Surg. 1973; 25:87–90.

47. Chatterjee D, Ghosh TB, Ghosh BB. Size variation of mastoid air cell system in Indian people at different age groups: a radio-graphic planimetric study. J Laryngol Otol. 1990; 104: 603–605. https://doi.org/10.1017/s0022215100113349 PMID: 2230550

48. Isono M, Ito A, Nakayama K, Miyashita H, Saito K, Murata K. Computerized assessment of developmental changes in the mastoid air cell system. Int Congr Ser. 2003; 1254: 487–491.

49. Lee D-H, Jun B-C, Kim D-G, Jung M-K, Yeo S-W. Volume variation of mastoid pneumatization in different age groups: a study by three-dimensional reconstruction based on computed tomography images. Surg Radiol Anat. 2005; 27: 37–42. https://doi.org/10.1007/s00276-004-0274-7 PMID: 15349696

50. Rubensohn G. Mastoid pneumatization in children at various ages. Acta Otolaryngol. 1965; 60: 11–14. https://doi.org/10.3109/00016486509126983 PMID: 14337947

51. Qvarnberg Y. Acute otitis media. A prospective clinical study of myringotomy and antimicrobial treatment. Acta Otolaryngol. 1981; 375: 1–157. PMID: 6274132

BRIDGING TEXT

From Chapter Two to Chapter Three

As reported in chapter two, only nine studies were able to report mastoid air cells with age. It reported that the size of TBP increased with age, having a linear growth pattern until early adulthood. Also, it suggested variations in the size of mastoid air cells with age regarding sex and population group. Most of the available information on the mastoid air cell system size with age was based on the surface area through planimetric measurements with limitations as a result of too large and inconsistent age groupings leaving a significant gap in the understanding of pediatric air cell volume and air cell volume in the suggested three stages of development of TBP. It is in this respect that Chapter three was designed to investigate the size of TBP with age, and to describe the normal distribution of air cell volumes in different stages of human growth postnatally.

The manuscript in chapter three, titled ***"Three-dimensional volumetric analyses of temporal bone pneumatization from early childhood to early adulthood in a South African population,"*** was submitted to Folia Morphologica on 19th October 2022 and published on 2nd March 2023. (Manuscript and references were written according to journal format).

CHAPTER THREE

Manuscript Two

Three-dimensional volumetric analyses of temporal bone pneumatization from early childhood to early adulthood in a Selected South African population

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ABSTRACT

Background: A debate exists on whether the size of temporal bone pneumatization is a cause or consequence of otitis media (a global disease burden). However, a normal middle-ear mucosa is a prerequisite for normal temporal bone pneumatization. This study investigated the size of

temporal bone pneumatization with age and the normal distribution of air cell volume in different stages of human growth postnatally.

Materials and methods: A three-dimensional computer-based volumetric-rendering technique was performed bilaterally on 248 head/brain and internal acoustic meatus CT images of slice thickness ≤ 0.6 mm consisting of 133 males and 115 females with age range 0-35 years.

Results: The average volume of infant (0-2 years) pneumatization was 1920 $mm^{3,}$ with an expected rapid increase to about 4510 mm^3 in childhood (6-9 years). The result also showed a significant increase ($p < 0.001$) in the volume of air cells up to the young adult stage I (19-25 years), followed by a significant decline in young adult stage II (26-35 years). However, the females were observed to experience an earlier increase than males. Also, population differences were observed as the Black South African population group showed a higher increase in volume with age than the White and Indian South African population groups, though the volumes of the latter increased up to young adult stage II.

Conclusions: This study concludes that the pneumatization of a healthy temporal bone is expected to continue a linear increase up until at least adult stage I. Termination of temporal bone pneumatization in an individual before this stage could signify pathologic involvement of the middle ear during childhood.

Keywords: pneumatization, temporal bone, air cells, three-dimensional

INTRODUCTION

Since the interest of science in the temporal bone and ear dating back to 'Hippocrates' (460 B.C.), studies regarding the development of temporal bone pneumatization or the size of air cells with age remain minimal [1, 15, 45]. Embryologically, the temporal bone pneumatization or air cell system begins between the 22nd and 24th week of intrauterine life, as the mastoid antrum (the only visible cell) begins to develop during this period [15, 45]. During late foetal life or at birth, the mastoid antrum (the large central air cell) is fully developed, either pneumatized or filled with embryonic connective tissue [8, 15]. After birth, temporal bone air cells become readily visible as hollowed-out spaces lined by flattened, non-ciliated squamous epithelium [27, 38, 40]. As postnatal development and growth continue, these air cells exhibit variability in size and extent, communicating with the middle ear via the mastoid antrum and the aditus ad antrum

and extending variably to the petrous apex and around the inner ear [24, 39, 45]. However, a gradual reduction in air cells is expected throughout life as the individual continues growing older [48].

Although the prevalence of minimal pneumatization of temporal bones in connection with chronic inflammatory middle-ear disease is well known, controversy about the relationship between temporal bone pneumatization and chronic middle-ear disease still exists [12, 25, 42]. A common infection to the middle ear is otitis media (OM) which still exists as one of the global burdens of diseases and a predisposing factor to hearing loss with increasing prevalence in sub-Saharan Africa with South Africa inclusive [11, 31, 41, 46]. More so, studies in South Africa revealed an 8.2% prevalence rate of OM among children [9, 13, 32]. Recent studies have shown an increased incidence rate of OM among younger and older children, with 31.4% and 16.7% prevalence, respectively [6, 34]. It was also recorded as the major significant risk factor for the high prevalence of hearing loss (up to 19.88%) [20, 28].

Much as genetically determined hypo-cellularity predisposes to acute and chronic otitis, the concrete fact remains that a normal middle-ear mucosa is a prerequisite for normal pneumatization, which may be hampered throughout childhood by inflammation, infection, and poor tubal function [12, 25, 42]. Another substantiated fact is that the onset of middle-ear infection such as OM has been linked to the development of the temporal bone pneumatization and air cell system, which in turn tends to affect the size of the air cells with age [3, 25]. Evidence has demonstrated that a temporal bone pneumatization with larger air cells tends to improve functional results after surgery (e.g., *mastoidectomy*) than one with smaller air cells [25, 30]. Among major theories, the hereditary theory explains the factors determining an individual pneumatization. However, the normal size of air cells and growth rate within a population should not be disregarded since there is an established link between OM and the size of pneumatization. On this account, there is a paucity of information on the normal size of the air cells and growth rate concerning a particular population, especially in sub-Saharan Africa and South Africa.

Several reports have utilized different techniques to measure the size of the temporal bone or mastoid pneumatization quantitatively. These techniques include the water-weight, acoustic and pressurized transducer [2, 30]. Following the development of radiological tools, more accurate and easier methods have been developed and mostly employed in measuring the size of temporal bone pneumatization in area or volume.

Various studies have been identified to utilize different radiological tools in evaluating the size of temporal bone pneumatization with age [4, 7, 12, 15, 18, 21, 27, 35, 37]. These studies, however, have revealed changes in the size of air cells with age and discrepancies in

growth rates. These reported discrepancies may be due to different methods or techniques used and the differences in age, sex, and population groups of the study populations, with the highest growth rate reported to be around the third decade of life among the Korean population [27] and age-related changes (beginning from infants; 0-2 years) in the bony organization of pneumatized spaces in various regions of the temporal bone reported in Missouri, Columbia [15].

Although both areas (2D sizes) and volumes (3D sizes) were used to measure the size of air cells in these studies, volumetric analysis, which likely gives the foremost comprehensive insight to appreciate the air cells estimate, was limited to three studies [15, 18, 27]. In addition, the slice thickness of computed tomography (CT) images used in those studies ranges between 1 mm to 2.5 mm. Precision in quantifying air cells requires very thin slices of about 0.6 mm and below, which brings about the limitations of these studies.

The present study focuses on the CT images of slice thickness ≤ 0.6 mm for precision in volumetric quantification of air cells utilizing a 3D computer-based volume rendering technique arriving at a more accurate volume as possible to achieve a normal distribution of air cells with age as well as the growth rate in other to ascertain the development of temporal bone pneumatization from early childhood to adulthood. In addition, this study also considered sex, laterality, and population groupings.

MATERIALS AND METHODS

Study design and population

Following ethical approval obtained from the University of KwaZulu-Natal Biomedical Research Ethics Committee (Protocol Ref. No.: BREC/00002263/2020) and ethical clearance obtained from the National Health Research Committee of the Kwazulu-Natal Department of Health (NHRD Ref.: KZ_202102_026), 248 head and neck/brain and internal acoustic meatus (IAM) CT images of South African patients (133 males & 115 females) from the radiology departments of public hospitals in Durban and Pietermaritzburg, Kwazulu-Natal, South Africa were retrospectively retrieved, reviewed and analyzed bilaterally (giving a total of 496) from January 2011 to August 2021. These CT scans were selected because they meet the inclusion criteria, which are as follows; a) scans of patients between the age range 0 – 35 years, b) High-resolution multidetector CT images acquired with ≤ 0.6 mm collimation, c) images without observable signs of abnormal pathological processes in the temporal bone or compatible with chronic otitis and/or mastoiditis on CT, d) images of patients with no history of middle ear

infection such as otitis media and any other pathology (by reviewing patients' medical history), and e) absence of bony destruction, fluid, or mass in any of the temporal bone air spaces. The age range of 0 to 35 years was further conveniently subdivided into seven levels: 0-2 (infant); 3-5 (young child); 6-9 (middle child); 10-14 (early adolescent); 15-18 (middle adolescent); 19-25 (young adult stage I); 26-35 (young adult stage II). Age categorization was similar to that reported by Hill [15]: according to age-related changes in the bony organization of pneumatized spaces in various regions of the temporal bone. The distribution of patients in the age categorization used for this study is presented in Table I.

The South African population groups included in this study were as follows; Black South African (202; 81.4%), Indian South African (28; 11.3%), and Whites South African (18; 7.3%) [Table I]. (Note: Generally, of the South African population, Black South Africans make up about 79.8%, White South Africans make up about 8.7%, while Asian/Indians make up about 2.5%) [22, 26].

Imaging protocol

The head and neck, and IAM CT images were taken using a Multi-Detector row Computed Tomography (MDCT) Scanner (GE Revolution Evo 64 slice, 128 configuration, Milwaukee, Wisconsin, USA). The axial view was reconstructed parallel to the orbito-meatal line using a slice thickness of 0.625 mm, detector coverage of 20mm, and a PITCH of 0.5. The scan was performed using 140kV and modulated mAs ranging between 280 – 400 mA with 30% dose reduction and ASIR-V application in a bony algorithm with a window width of >3000 hU and a window centre of 500 hU.

Calculation of 3D volume of air cells of the temporal bone

Continuous non-overlapping temporal bone CT scans with acquisition parameters of ≤ 0.6 mm slice thickness, 140 kV, and modulated mAs ranging between 280 – 400 mA were used for this study. The DICOM images stored in the PACS of these hospitals were transferred to a Workstation running IntelliSpace Portal (ISP) Version 11.1 (Philips Image and Information Management software, Nederland).

With a surface rendering algorithm of lowest limit window level of -1,024 hU and uppermost limit window level of -318 hU, the clip and 3D segmentation process were used to achieve 3D reconstruction and the volume of air cells of each temporal bone. The axial image was double-clicked in other to be enlarged. Next, 3D models were created using a smart segmentation process. The IntelliSpace Portal (ISP) Version 11.1 then provided a calculator that

automatically calculates the volume of each 3D reconstructed temporal bone pneumatization from the mastoid process to the petrous apex, including the middle ear [Figure 1].

Inter-observer reliability testing

The accuracy and repeatability of the volume calculation were determined by using 50 randomly selected temporal bone CT scans independently by two authors, and a third observer (Specialist Radiologist) verified the volumetric calculation for inter-observer reliability.

Statistical Analysis

The statistical data analysis was conducted in R Statistical computing software of the R Core Team, 2020, version 3.6.3, and presented in the form of descriptive and inferential statistics. The continuous variables were non-normal and were presented in median (interquartile ranges). The median differences were assessed using Wilcoxon for two groups. The median differences across at least three categorical variable levels (in the case of population group) were assessed with the aid of Kruskal Wallis. In the case of significant median difference, post-hoc tests were conducted using the Dunn test. All the inferential statistical analysis tests were conducted at 5% significance levels.

RESULTS

Data from 496 HRCT temporal bones (right and left side) of 248 patients' scans were presented as the median and interquartile range (IQR). The intraclass correlation was 89% for volumetric calculation for inter-observer reliability testing.

Average volume (mm^3) of temporal bone pneumatization according to laterality, sex, and population group

The average volume of temporal bone pneumatization in this study population was 8300 mm^3 (interquartile range of 4100 – 12200 mm^3). The result presented in Table II showed no significant difference in the average volume of temporal bone pneumatization as regards laterality ($p = 0.719$), sex ($p = 0.363$), and population group ($p = 0.416$) using Ranksum and Kruskal-Wallis tests.

The volume of temporal bone pneumatization with age

From early childhood to adulthood, the average volumes of temporal bone pneumatization of infants (0-2 years), children (3-9 years), adolescents (10-18 years), and adults (19-35 years) were 1920 mm^3, 6005 mm^3, 11750 mm^3, and 11550 mm^3, respectively. In general, the Kruskal Wallis test showed a significant difference ($p < 0.001$) in the volume of temporal bone pneumatization between age groups [Table III], with a linear and rapid increase at an average of 2400 mm^3 between age groups up to 19-25 years followed by a decrease [Figure 2]. However, the volume of temporal bone pneumatization was higher on the right side, as shown in figure 2.

The volume of temporal bone pneumatization with age concerning sex

The Kruskal-Wallis test showed a significant difference ($p < 0.001$) in the volume of temporal bone pneumatization with age groups in males and females. In the distribution of the volume of air cells with age, a decrease in pneumatization was also observed after the age group 19-25 years, but the females showed a more rapid increase in pneumatization of the temporal bone earlier (6-9 years) than males [Table IV]. However, pneumatization in males was observed to follow a rapid linear growth between the age groups 10-14 years and 19-25 years [Figure 3].

The volume of temporal bone pneumatization with age concerning population groups

The Kruskal-Wallis test showed a significant difference ($p < 0.001$) in the volume of temporal bone pneumatization with age groups among the Black South African population. Still, it showed no significant difference in the volume of temporal bone pneumatization with age groups among the Indians and Whites with $p = 0.053$ and $p = 0.058$, respectively [Table V]. In the distribution of the volume of air cells with age, a rapid linear increase in the volume of air cells was observed among South African Blacks from 0-2 years up to 19-25 years, afterward a decline. However, a slow increase in air cell volume was observed in the Indian and White population from 3-5 years, continuing up to 26-35 years [Figure 4].

DISCUSSION

The interest in the size of temporal bone pneumatization and its importance arose from the association between mastoid air cells and otitis media either as a cause or a consequence. Concerning human development and growth, Virapongse et al. [45] described changes in the size of temporal bone pneumatization to occur in three stages: "*the infantile stage- occurring from birth to two years of age (air cells begin to appear and are readily visible by two years);*

transitional stage- from two to five years (squamomastoid/mastoid undergoes gradual enlargement with the migration of air cells toward the periphery); and adult stage- age 6 and above (attainment of this stage result in cessation of pneumatization).” Cinamon [10] also supported this description and further identified that air cells continue to increase in size until puberty, while Aladeyelu et al. [1] identified a continuous increase in the size of air cells beyond puberty.

Two theories on pneumatization have been hypothesized: the first is that the size of air cells in temporal bone pneumatization is genetically determined [12]; while the second is that the size of air cells in temporal bone pneumatization is determined by the degree of pathologic involvement of the middle ear during childhood [14, 33, 44]. The second hypothesis validated this study as the degree of pathologic involvement during life may influence the size of mastoid pneumatization with age. Although considering the first theory, there may be a few limitations resulting from interindividual variation. However, to overcome these limitations, a longitudinal study needs to be employed, which would be a dilemma and seem impossible in practice as it would involve tracking all subjects daily for scanning and measurement and could take an entire career of these subjects to measure the size of their air cells. Hence, the second hypothesis appears to be widly used and generally accepted [4, 7, 15, 18, 21, 27, 35, 37, 43].

This study utilized a 3D computer-based volumetric-rendering technique on head/brain and inner ear CT images of slice thicknesses of ≤ 0.6 mm. The average volumes of infants, children, adolescents, and adults’ temporal bone pneumatization obtained in this study were quite higher than the previous reports [15, 17, 18 19, 23, 25, 27, 29]. This discrepancy may be due to technical characteristics (e.g., 0.6 mm slice thickness which gives more detailed volumetric information) or population differences. It may also be due to the cranial size and shape of the study population. Hence, the average air cell volumetric size of temporal bone pneumatization in a South African population is higher than in other age-related studies reported in Japanese, Korean, and Colombian populations [15, 18, 27]. The temporal bone pneumatization with average volumes of 1920 mm^3 in pediatrics and 4510 mm^3 in young children indicates that pneumatization of the temporal bone is expected to follow a rapid growth during childhood development. This finding agrees with previous studies, which reported that air cells are readily visible after birth and immediately begin to increase in size and extent [24, 40].

In this study, various developmental stages were subdivided into the infant, young child, middle child, early adolescents, middle adolescents, young adult stage I, and young adult stage II to reflect human postnatal growth stages and understand the possible age when pneumatization ceases. An evident increase in the volume of temporal bone pneumatization relative with age

until young adult stage I and reduction in the volume of air cells as well as cessation in pneumatization in young adult stage II observed in this study concurs with the previous study that linked aging-related changes to reduction in air cells [48]. In contrast, this finding contradicts the previous reports about pneumatization terminating at puberty though these reports utilized planimetric measurements and were only to give information on the area of air cells, not volume [4, 12, 35].

Notably, a significant increase in pneumatization volumes in different age groups in relation to sex was observed in this study. But the females showed a much earlier rapid increase in the volume of temporal bone pneumatization before the onset of puberty (6-9 years) which is similar to the report of Diamant [12] that utilized surface area and Hill [15] that utilized both 2D and 3D methods. This may, however, be linked to early puberty in females [10]. However, the males were observed to have a larger pneumatization at late puberty up to the young adult stage I, which is similar to the previous study by Chatterjee et al. [7] that utilized 2D planimetric measurements of temporal bone pneumatization. This implies that the development of temporal bone pneumatization tends to be more rapid in adolescent females, with the females first attaining adult size before adolescent males.

Furthermore, differences were also observed among population groups within the study population. The present study considered three groups: Black South Africans (indigenous African origin or Native group), White South Africans (European descent), and Indians (Asian descent). Although the pediatric volume was about the same size with a rapid increase in volume during childhood development, the volume of temporal bone pneumatization was observed to increase significantly with age showing a rapid linear growth up to the young adult stage I among the Black South Africans. The significant increase in the volume of pneumatization observed from the young child to young adult stage I conforms with the increase in the volume of paranasal air sinus in the same stages of postnatal growth in a South African population as reported by Rennie et al. [36]. Kim et al. [23] also identified a correlation between pneumatization mastoid air cells and paranasal air sinus.

However, among the South African White and Indians, the volume of temporal bone pneumatization follows a rapid increase from infant up to the young child (3-5 years), followed by a slow increase up to the young adult stage I; thereafter, a plateau with no significant difference. This could be attributed to the small skull sizes, especially among Indians, because the skull size influences the pneumatization of the temporal bone [5, 7, 16]. In addition, the early study of Arora et al. (1973) also identified this attribute while working with the population in the Northern part of the Indian subcontinent and found the size of the temporal bone air cell system

to have a value much less than that of the Swedish population in the study of Diamant [12] and assumed that it could be due to the smaller sized cranial bones of Indians. Although, there were no significant differences in the volume of temporal bone pneumatization within age groups among Indians and White. However, the continuous increase in the pneumatization among these two population groups up to young adult stage II conforms with the previous study among the Korean population of Asian descent [27].

Although the two hypothesized theories of pneumatization (genetic and environmental) have described the relationship between temporal bone pneumatization and middle-ear diseases to be "a chicken and egg" tale [14, 44], a small pneumatization of the temporal bone could possibly permit normal ventilation of the ear. However, a small mastoid system predisposes to acute and chronic otitis media. Consequently, the degree of pathologic involvement of the middle ear during childhood, such as acute and chronic otitis media, is well known to be a determinant factor in temporal bone pneumatization. The present study has been able to analyze healthy temporal bones in order to know the expected size of normal temporal bone pneumatization at every stage of human growth, ascertaining its growth rate and completion stage in adult life. This study also utilized a method with high accuracy and hope that it will contribute to establishing general references of what is expected to be the size of temporal bone volume and size as regards to age and development, which could help give an understanding of the history of the middle-ear of any patient, most especially during childhood.

CONCLUSIONS

This study investigated the size of temporal bone pneumatization from early childhood to adulthood utilizing a 3D computer-based volumetric rendering technique of normal CT images of slice thickness of ≤ 0.6 mm. A rapid increase in the size of pneumatization was observed during childhood development, with females showing a more rapid increase. In addition, the volume of air cells was observed to increase at an average of 2400 mm^3 at every stage of human postnatal growth, with a higher volume of the right temporal bone up to the young adult stage I before experiencing a decline. Population group differences were also observed in the distribution of air cells as the volume of temporal bone pneumatization of other population groups aside from Black South Africans increased up to adult stage II. The study concludes that the pneumatization of a healthy temporal bone is expected to continue linear increase up until at least adult stage I (19-25 years). This study hopes that its findings will contribute significantly to achieving a unanimous age landmark expected for the temporal bone pneumatization to be

complete among otolaryngologists. Furthermore, it could also be useful in anatomical and forensic sciences for predicting age by evaluating the volume of temporal bone air cells of skulls.

Ethical approval

The design was approved by the Institutional Review Board/Ethics Committee (Biomedical Research Ethics Committee of the University of KwaZulu-Natal with Ref. No.: BREC/00002263/2020) and the National Health Research Committee of the Kwazulu-Natal Department of Health (NHRD Ref.: KZ_202102_026).

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Conflict of interest: None declared

REFERENCES

1. Aladeyelu OS, Olaniyi KS, Olojede SO, Mbatha W-BE, Sibiya AL, Rennie CO. Temporal bone pneumatization: A scoping review on the growth and size of mastoid air cell system with age. PLoS One. 2022; 17(6):e0269360. https://doi.org/10.1371/journal.pone.0269360
2. Andreasson L, Mortensson W. Comparison between the area and the volume of the air-filled ear space. Acta Radio. 1975; 16:347–352.
3. Aoki K, Esaki S, Honda Y, Tos M. Effect of middle ear infection on pneumatization and growth of the mastoid process. An experimental study in pigs. Acta Otolaryngol. 1990; 110(5-6):399–409.
4. Arora MML, Sain U, Sodhi JS. Mastoid pneumatization in children—a roentgenographic planimetric study. Indian J Otolaryngol Head Neck Surg. 1973; 25:87–90.
5. Balzeau A, Girmaud-Herve D, Semah F. Characteristics and variation of the temporal bone pneumatization in Asian Homo errectus. EurASEAA, Bougon papers. 2006; 21–27.
6. Biagio L, Swanepoel DW, Laurent C, Lundberg T. Paediatric otitis media at a primary healthcare clinic in South Africa. S Afr Med J. 2014; 104(6):431–435.
7. Chatterjee D, Ghosh TB, Ghosh BB. Size variation of mastoid air cell system in Indian people at different age groups: a radio-graphic planimetric study. J Laryngol Otol. 1990; 104:603–605.
8. Cheatle AH. The infantile types of mastoid with ninety-six specimens. J Laryngol. 1907; 22:56.
9. Cilliers NJ, van der Merwe A, Hurter M, Nel. The manifestation of middle ear pathology in an elderly group. S Afr J Commun Disord. 1988; 35(1):37–44.

10. Cinamon U. The growth rate and size of the mastoid air cell system and mastoid bone: A review and reference. Eur Arch Oto-Rhino-L. 2009; 266(6):781–786.
11. DeAntonio R, Yarzabal J-P, Cruz JP, Schmidt JE, Kleijnen J. Epidemiology of otitis media in children from developing countries: A systematic review. Int J Pediatr Otorhinolaryngol. 2016;85: 65–74.
12. Diamant M. Otitis and pneumatization of the mastoid bone. Acta Otolaryngol. 1940; 41.
13. Halama AR, Voogt GR, Musgrave GM. Prevalence of otitis media in children in a black rural community in Venda (South Africa). Int J Pediatr Otorhinolaryngol. 1986; 11(1):73–77.
14. Han SJ, Song MH, Kim J, Lee WS, Lee H-K. Classification of temporal bone pneumatization based on sigmoid sinus using computed tomography. Clin Radiol. 2007; 62:1110–1118.
15. Hill CA. Ontogenetic change in temporal bone pneumatization in humans. Anat Rec. 2011; 294(7):1103–1115.
16. Inal M, Muluk NB, Dag E, Arikan OK, Kara SA. The pitfalls and important distances in temporal bones HRCT of the subjects with high jugular bulb- Preliminary Review. Adv Clin Exp Med. 2015; 24(2):315–325.
17. Isono M, Murata K, Azuma H, Ishikawa M, Ito A. Computerized assessment of the mastoid air cell system. Auris Nasus Larynx. 1999; 26:139–145.
18. Isono M, Ito A, Nakayama K, Miyashita H, Saito K, Murata K. Computerized assessment of developmental changes in the mastoid air cell system. Int Congr Ser. 2003; 1254:487–491.
19. Jadhav AB, Fellows D, Hand AR, Tadinada A, Lurie AG. Classification and volumetric analysis of temporal bone pneumatization using cone-beam computed tomography. Oral Surg Oral Med Oral Pathol Oral Radiol. 2014; 117(3):376–84.
20. Joubert K, Botha D. Contributing factors to high prevalence of hearing impairment in the Elias Motsoaledi Local Municipal area, South Africa: A rural perspective. S Afr J Commun Disord. 2019; 66(1):1–7.
21. Kawamura S, Okabe K, Mogi S, Terao A. The normal development of the mastoid pneumatic cells. J Otorhinolaryng Soc Jap. 1963; 66:909–912.
22. Khalfani AK, Zuberi T. Racial classification and the modern census in South Africa, 1911–1996. Race Soc. 2001; 4:161–176.
23. Kim J, Song SW, Cho J-H, Chang K-H, Jun BC. Comparative study of the pneumatization of the mastoid air cells and paranasal sinuses using three-dimensional reconstruction of computed tomography scans. Surg Radiol Anat. 2010; 32:593–599.
24. Knipe H, Hacking C. Mastoid air cells. Reference article, Radiopaedia.org. 2014 Mar 23 [revised 2021 Nov 19; accessed 2021 Dec 26]. Available from: https://doi.org/10.53347/rID-28366.
25. Koc A, Ekinci G, Bilgili AM, Akpinar IN, Yakut H, Han T. Evaluation of the mastoid air cell system by high resolution computed tomography: Three-dimensional multiplanar volume rendering technique. J Laryngol Otol. 2003; 117:595–598.
26. L'Abbé EN, Van RC, Nawrocki SP, Becker PJ. An evaluation of non-metric cranial traits used to estimate ancestry in a South African sample. Forensic Sc Int. 2011; 209(1-3):195.e1-7.
27. Lee D-H, Jun B-C, Kim D-G, Jung M-K, Yeo S-W. Volume variation of mastoid pneumatization in different age groups: a study by three-dimensional reconstruction based on computed tomography images. Surg Radiol Anat. 2005; 27:37–42.
28. Louw C, Wet SD, Eikelboom, RH, Hugo J. Prevalence of hearing loss at primary health care clinics in South Africa. Afri Health Sci. 2018; 18(2):313–320.
29. Luntz M, Malatskey, S, Tan M, Bar-Meir E, Ruimi D. Volume of mastoid pneumatization: three-dimensional reconstruction with ultrahigh-resolution computed tomography. Ann. Otol. Rhinol. Laryngol. 2001; 110:486–490.

30. Molvaer OI, Vallersnes FM, Kringlebotn M. The size of the middle ear and the mastoid air cell system measured by an acoustic method. Acta Otolaryngol. 1978; 85:24–32.
31. Morris PS, Leach AJ. Acute and chronic otitis media. Pediatr Clin N Am. 2009; 56(6):1383–1399.
32. Nel M, Odendall W, Hurter M, Meyer S, van der Merwe A. The occurrence and nature of hearing problems and middle ear pathologies with a group of black African urban children. S Afr J Commun Disord. 1988; 35(1):25–30.
33. Palva T, Palva A. Size of the human mastoid air cell system. Acta Otolaryngol. 1966; 62:237–251.
34. Phanguphangu MC. Otoscopic examinations reveal high prevalence of outer and middle ear pathologies in pediatrics in Limpopo, South Africa. Int J Audiol. 2016; 56(4):215–218.
35. Qvarnberg Y. Acute otitis media. A prospective clinical study of myringotomy and antimicrobial treatment. Acta Otolaryngol 1981; 375:1–157.
36. Rennie CO, Haffajee MR, Satyapal KS. Development of the paranasal air sinuses in a South African Population utilising three dimensional (3D) reconstructed models. Eur J Anat. 2017; 21(3): 197–209.
37. Rubensohn G. Mastoid pneumatization in children at various ages. Acta Otolaryngol. 1965; 60:11–14.
38. Schillinger R. Pneumatization of the mastoid. Radiology. 1939; 33:54–69.
39. Schmalfuss IM. Petrous Apex. In: Chong V, editors. Skull Base Imaging. Missouri: Elsevier; 2018. p. 233–245.
40. Sethi A, Singh I, Agarwal AK, Sareen D. Pneumatization of mastoid air cells: Role of acquired factors. Int J Morphol. 2006; 24(1):35–38.
41. Tesfa T, Mitiku H, Sisay M, Weldegebreal F, Ataro Z, Motbaynor B, et al. Otitis media in sub-Saharan Africa: a systemic review and meta-analysis. BMC Infect Dis**.** 2020; 220:225.
42. Todd NW, Pitts RB, Braun IF, Heindel H. Mastoid size determined with lateral radiographs and computerized tomography. Acta Otolaryngol. 1987; 103(5-6):226–231.
43. Tos M, Stangerup SE. The causes of asymmetry of the mastoid air cell system. Acta Otolaryngol. 1985; 99:564–570.
44. Turgut S, Tos M. Correlation between temporal bone pneumatization, location of lateral sinus, and length of the mastoid process. J Laryngol Otol. 1992; 106:485e9.
45. Virapongse C, Sarwar M, Bhimani S, Sasak C, Shapiro R. Computed tomographic anatomy of the temporal bone: Normal pattern and morphology. AJR Am J Neuroradiol. 1985; 145:473–481.
46. Vos T, Barber RM, Bell B, Bertozzi-Villa A, Biryukov S, Bolliger I. Global, regional, and national incidence, prevalence, and years lived with disability for 301 acute and chronic disease and injuries in 188 countries, 1990–2013: a systemic analysis for the global burden of disease study. Lancet. 2015; 386(9995):743–800.
47. World Health Organization. Deafness and hearing loss: Prevalence. World Health Organization, Health topics 2022 [Accessed 2022 June 06]. Available from: https://www.who.int/health-topics/hearing-loss#tab=tab_2.
48. Wright A, Davis A, Bredberg G, Ulehlová L, Spencer H, Bock G, et al. Hair cell distributions in the normal human cochlea. A report of a European working group. Acta Otolaryngol. 1987; 436:15–24.

Table I. Distribution of patients according to age groupings, sex and population groups

Age groupings [years]	Overall (n = 248)			Black South African (n = 202)			Indian South African (n = 28)			White South African (n = 18)		
	Male	Female	Total	Male	Female	Total	Male	Female	Total	Male	Female	Total
0–2	12	10	22	10	8	18	1	1	2	1	1	2
3–5	11	13	24	8	12	20	2	0	2	1	1	2
6–9	22	15	37	18	12	30	1	3	4	2	1	3
10–14	39	14	53	34	12	46	3	1	4	2	1	3
15–18	10	16	26	9	13	22	1	1	2	0	2	2
19–25	14	22	36	11	19	30	1	2	3	2	1	3
26–35	25	25	50	16	20	36	7	4	11	2	1	3

Table II. Average volume (mm^3) of temporal bone pneumatization according to laterality, sex, and population group

Laterality			Sex			Population group			
Left Median (IQR)	Right Median (IQR)	L vs. R	Male Median (IQR)	Female Median (IQR)	M vs. F	SA Black Median (IQR)	Indian Median (IQR)	White Median (IQR)	B vs. I vs. W
7830 mm^3 (3860–12200)	8500 mm^3 (4210–12200)	P = 0.719	8510 mm^3 (4340–12100)	8900 mm^3 (4550–12700)	P = 0.363	7580 mm^3 (4010–12200)	9400 mm^3 (4400–10800)	9900 mm^3 (3060–10900)	P = 0.416

Table III. Median volumes (mm^3) and interquartile range of temporal bone pneumatization according to age groups of human stages of development (Overall and Laterality)

Laterality	Age groups [years]							P-value
	0–2 (n = 22)	3–5 (n = 24)	6–9 (n = 37)	10–14 (n = 53)	15–18 (n = 26)	19–25 (n = 36)	26–35 (n = 50)	
Left [mm^3] Median (IQR)	1680 (1510–2910)	4880 (4990–9190)	6750 (4990–9190)	10300 (7000–11800)	13000 (9360–18600)	14100 (8230–14500)	9840 (3810–14500)	< **0.001***
Right [mm^3]	1950	4330	7600	10700	12800	15300	8800	<

Median (IQR)	(1450–2400)	(3910–5450)	(5300–8790)	(7090–12400)	(8120–15000)	(11100–18900)	(4750–12400)	**0.001***
Both sides [mm^3] (average) Median (IQR)	1920 (1450–2450)	4510 (4010–5450)	7500 (5080–8840)	10500 (6950–12100)	13000 (9420–18900)	14000 (7970–15000)	9100 (4240–113900)	< **0.001***

Table IV. Median volume (mm^3) and interquartile range of temporal bone pneumatization of males and females according to age groups of human stages of development

Male								
Age range [years]	0–2 (n = 12)	3–5 (n = 11)	6–9 (n = 22)	10–14 (n = 39)	15–18 (n = 10)	19–25 (n = 14)	26–35 (n = 25)	P-value
Volume [mm^3] Median (IQR)	1940 (1410–2480)	4320 (3550–4880)	5570 (3920–8300)	10600 (6930–12000)	13600 (10800–14100)	16700 (8830–20800)	9700 (5800–16100)	< **0.001***
Female								
Age range [years]	0–2 (n = 10)	3–5 (n = 13)	(6–9 (n = 15)	10–14 (n = 14)	15–18 (n = 16)	19–25 (n = 22)	26–35 (n = 25)	P-value
Volume [mm^3] Median (IQR)	1920 (1510–2450)	5230 (4170–5800)	8100 (6650–9880)	11500 (7300–12500)	13000 (10900–17100)	15000 (7900–15100)	9100 (3880–12300)	< **0.001***

Black South African								
Age range [years]	0–2 (n = 18)	3–5 (n = 20)	6–9 (n = 30)	10–14 (n = 46)	15–18 (n = 22)	19–25 (n = 30)	26–35 (n = 36)	P-value
Volume [mm^3] Median (IQR)	1920 (1450–2450)	4470 (4010–5450)	7500 (5140–8790)	10500 (7010–15000)	14000 (7970–15000)	17100 (9200–19300)	9100 (4130–13700)	< **0.001***
Indian South African								
Age range [years]	0–2 (n = 2)	3–5 (n = 2)	6–9 (n = 4)	10–14 (n = 4)	15–18 (n = 2)	19–25 (n = 3)	26–35 (n = 11)	P-value
Volume [mm^3] Median (IQR)	1920 (1510–2450)	4210 (3100–4400)	5510 (5510–5510)	7270 (5860–9360)	8600 (7100–10200)	9900 (7680–10400)	10500 (8900–11800)	0.053
White South African								
Age range [years]	0–2 (n = 2)	3–5 (n = 2)	6–9 (n = 3)	10–14 (n = 3)	15–18 (n = 2)	19–25 (n = 3)	26–35 (n = 3)	P-value
Volume [mm^3] Median (IQR)	1950 (1510–2480)	4300 (3500–4850)	5700 (4250–5900)	7900 (5910–9600)	9200 (7200–10900)	11000 (7550–11500)	11500 (7840–11500)	0.053

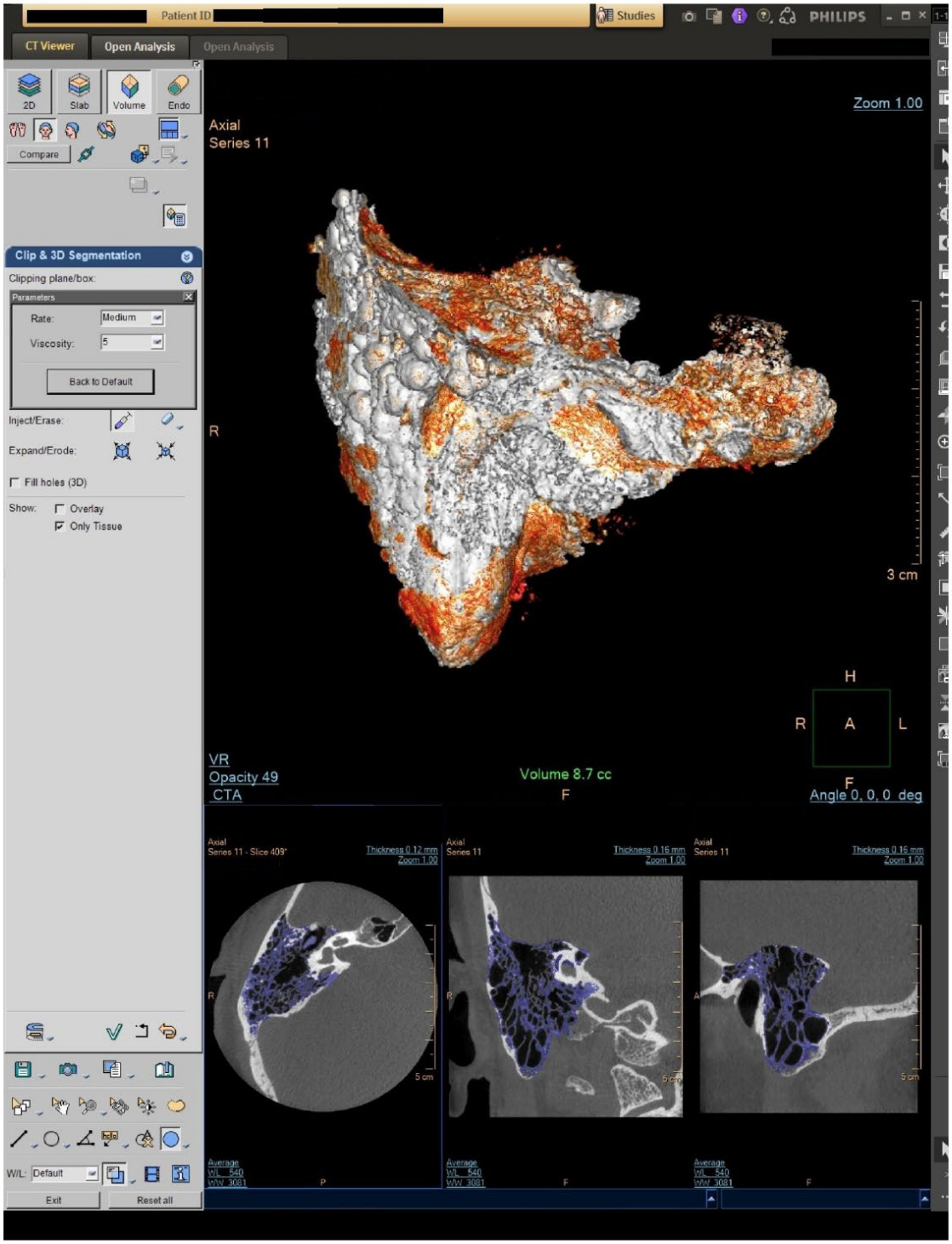
Table V. Population group distribution median volume (mm^3) and interquartile range of temporal bone pneumatization according to age groups of human stages of growth

Figure 1. Three-dimensional using computer-based volume rendering reconstruction technique. Pneumatization of the right temporal bone composing the middle ear, petrous, and mastoid air cells with a volume of 8.7 cc (cubic centimeter) (Conversion to cubic millimeters = 8700 mm^3)

Figure 2. Distribution of volumes of temporal bone pneumatization of left and right sides according to human stages of development.

Figure 3. Distribution of volumes of temporal bone pneumatization of males and females according to human stages of development**.**

Figure 4. Distribution of volumes of temporal bone pneumatization of SA Blacks, SA Indians, and SA whites according to human stages of growth (SA= South African).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H
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Opacity 49
CTA
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Angle 0, 0, 0 deg
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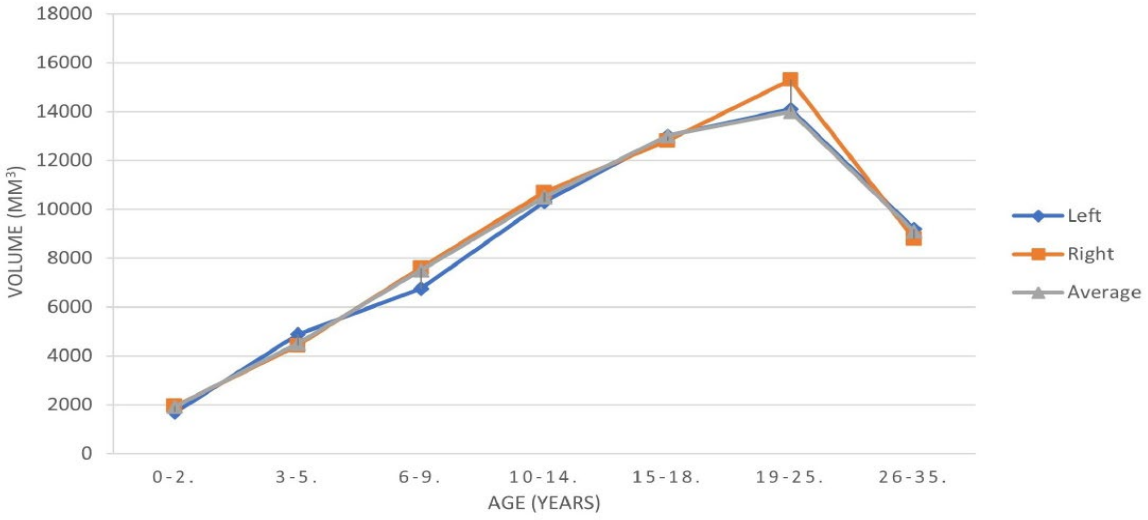
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VOLUME (MM³)
0-2.
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AGE (YEARS)
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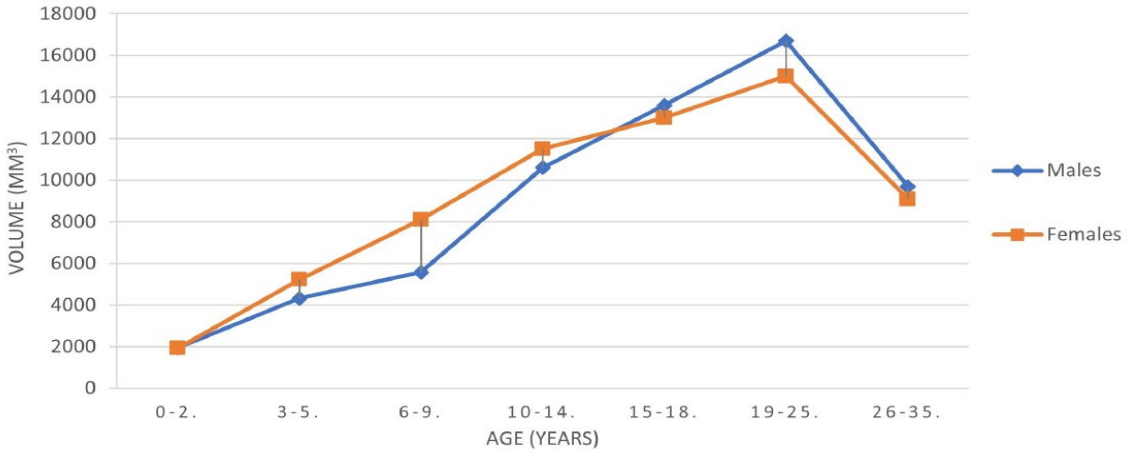
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VOLUME (MM³)
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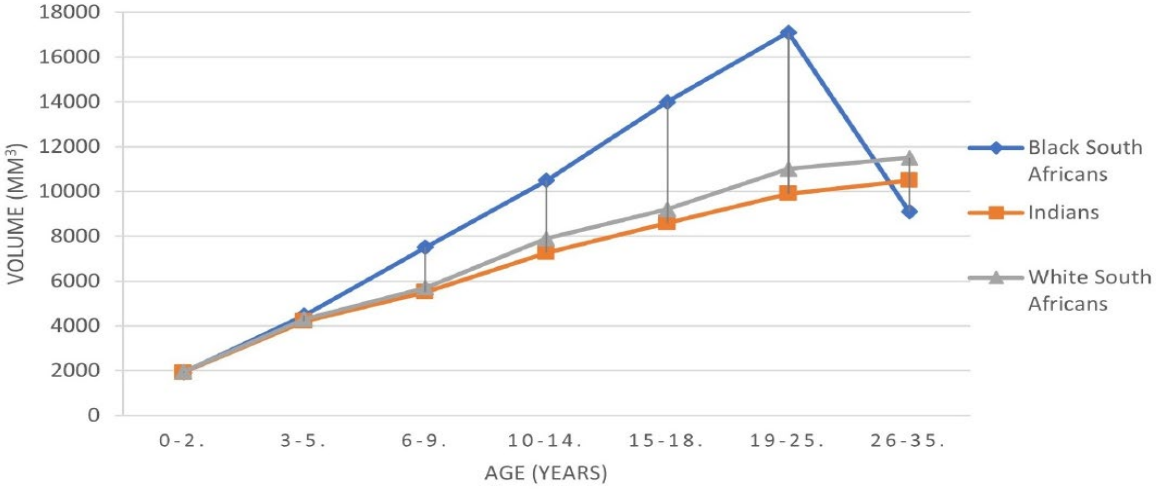
15-18.
19-25.
26-35.
AGE (YEARS)
Males
Females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VOLUME (MM³)
0-2.
3-5.
6-9.
10-14.
15-18.
19-25.
26-35.
AGE (YEARS)
Black South Africans
Indians
White South Africans

BRIDGING TEXT

From Chapter Three to Chapter Four

In chapter three, the volumes of air cells in healthy temporal bones were observed to increase significantly with age up to adult stage I (19-25 years), followed by a significant decline in young adult stage II (26-35 years). The females were observed to experience an earlier increase than males. Also, differences in population groups were observed as the Black Africans had a higher volume with age than the White and Indian South African population groups. However, the rate at which a temporal bone is pneumatized have been hypothesized to contribute (as a result of a change in surface area) to the anatomical variations of temporal bone-related vasculature. This vasculature is very important in temporal bone or ear-related surgeries either as landmarks or pitfalls to be avoided during related surgeries. This hypothesis requires further research to substantiate this claim. In chapter four, the pattern or degree of TBP in relation to the morphology of some related vasculatures in the petromastoid part of the temporal bone and their morphometric relationship with the ear regions was investigated.

The manuscript in chapter four, titled ***"Influence of pneumatization on morphology of some temporal bone-related vasculatures and their morphometric relationship with ear regions: a computed tomography study,"*** was submitted to Scientific Reports on 14th September 2022 and published on 3rd February 2023. (Manuscript and references were written according to journal format).

CHAPTER FOUR

Manuscript Three

Influence of pneumatization on morphology of temporal bone-related vasculatures and their morphometric relationship with ear regions: A Radiological study

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Influence of pneumatization on morphology of temporal bone-related vasculatures and their morphometric relationship with ear regions: a computed tomography study

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Anatomical variations in the location and position of temporal bone-related vasculature are routinely encountered in clinical practice, contributing to clinical syndromes and complexities in ear-related and neurological surgeries. Pneumatization of the temporal bone (TB) is one of several factors that have been hypothesized to influence the variabilities and variations of these vessels. This study aimed to investigate the association between the degree of pneumatization and the morphologies of some TB-related vessels, as well as their morphometrical relationship with ear regions. Observational retrospective chart review of 496 TBs computed tomographic scans were examined. Different degrees of pneumatization were observed, with hyper-pneumatization being the most common and hypo-pneumatization being the least. Various anatomical variants of the sigmoid sinus (SS), jugular bulb (JB), and internal carotid artery (ICA) were observed. Distances of SS and JB to ear regions were observed to have significant differences ($p < 0.05$) in laterality. These distances increased relative to increased air cells, showing a significant association ($p < 0.05$). A significant association ($p < 0.001$) was also observed between the degree of pneumatization and variants of JB and ICA. High JB, JB dehiscence, and ICA dehiscence were significantly associated with increased pneumatization, while flat JB was significantly associated with decreasing pneumatization. However, no significant association ($p = 0.070$, $p = 0.645$) was observed between the degree of pneumatization and morphologies of SS. This study concludes that the degree of pneumatization influences only the jugular bulb variants and ICA dehiscence, as well as the distances of SS and JB to ear regions.

Abbreviations

EAC	External acoustic canal
IAC	Internal acoustic canal
ICA	Internal carotid artery
JB	Jugular bulb
LSCC	Lateral semicircular canal
ME	Middle ear
TM	Tympanic membrane

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TB Temporal bone
SS Sigmoid sinus

The anatomy of the temporal bone (a pair of bones located on the lateral aspect of the human skull) involves a complicated relationship between critical structures[1,2]. Its anatomical complexity poses a challenge in interpreting anatomical findings and diagnosing various pathological conditions affecting this skull region[3].

The temporal bone (TB), though relatively small, contains the middle and inner ear structures, along with several cranial nerves and major vessels, all within a relatively small space[2].

The location, as well as the size and shape of these vasculatures, such as sigmoid sinus (SS) and jugular bulb (JB) (a connection between the SS and the internal jugular vein), is highly variable, including a significant difference in laterality[2,4–6]. The pneumatization of the TB has been reported to be responsible for these variabilities[7,8]. This was also indicated in the study of Singh et al.[9], highlighting how pneumatization of the TB influences the morphology of the SS.

Anatomical variations of these vasculatures and their anomalies, such as protrusive SS, dehiscence SS, high or high riding JB, and JB dehiscence, are not rare in the TB[10,11]. For instance, high JB has been seen to occur in 6–20% of the population[11]. Other reports found variations in the incidence of high JB, with some citing as low as 3.5% and others reporting high incidences up to 65%[11–14].

These variations of the SS and JB are frequently encountered in clinical practice, affecting the middle and inner ear functions and causing tinnitus, vertigo, and/or hearing loss[15]. The variations also impact the complexity of neurotological surgeries and are a vital pitfall encountered in TB and ear-related surgeries[2,11,16]. For example, injuries to these vessels due to surgical trauma have been mostly observed after mastoidectomy procedures[11]. Their significance, even in relatively minor otological surgery, was highlighted in a case of a myringotomy in a 10-year old boy with acute otitis media[16]. The myringotomy of a dark-blue tympanic membrane led to massive bleeding and subsequent death of the child following thrombosis of an iatrogenically injured dominant SS[16].

Acute otitis media requiring, minor otological surgeries and TB-related fractures resulting in surgical intervention are not rare in South Africa, sub-Saharan Africa, and other regions of the world[17–22]. Most TB and ear-related surgeries, depending on the approach, require a good knowledge of the degree of TB pneumatization and the relationship between SS, JB, the external acoustic canal (EAC), the middle ear (ME), and the internal acoustic canal (IAC) in order to avoid intraoperative complication[2]. For instance, the SS is one of the most familiar landmarks used during trans-mastoid and posterolateral skull base approaches[23,24]. It can also be used as a reference structure when evaluating the degree of mastoid pneumatization[25].

Since the studies of Ichijo et al.[23] and Dai et al.[26] that hypothesized possible influences of mastoid pneumatization on the position of SS, observable and measurable data concerning the influence of TB pneumatization on the morphology of TB-related vessels and their morphometric relationship with ear-related structures/regions remain scarce. Hence, this study sets out to investigate any possible influence TB pneumatization may have on the morphology and morphometry of its related vasculature by measuring the shortest distances between selected vasculature (such as SS and JB) and EAC, ME, and IAC, evaluating their vascular variants, and analyzing for any possible association with the degree of pneumatization of the TB.

Methods

Study population. The present study was an observation and retrospective review of 496 TBs computed tomography (CT) images of 248 head and neck/brain CTs of patients retrieved from the Picture Archiving and Communication Systems (PACS) of public hospitals in Durban and Pietermaritzburg, Kwazulu-Natal, South Africa. The three population groups identified in the study were South African Blacks, South African Indians, and South African Whites.

Inclusion criteria. These include high-resolution multi-detector CT images acquired with 0.6 mm collimation, images without observable signs of abnormal pathological processes in the TB, and absence.

Scanning protocol. The CT images were acquired using Multi-Detector row Computed Tomography (MDCT) Scanners (Lightspeed CT, GE Healthcare Medical System, Milwaukee, Wisconsin, USA and SOMATOM Definition Flash CT Scanner, Siemens Healthineers, Forcheim, Germany, both of 64 and 128 slice configuration respectively). The scans were performed in a craniocaudal topographical direction using 140 kV, modulated mAs ranging between 280 and 400 mA (beam collimation 64×0.625; rotation 0.5 s) 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 axial view was reconstructed parallel to the orbito-meatal line using slice thickness of 0.625 mm, detector coverage of 20 mm, and a PITCH of 0.5. Voxel size of images is isotropic.

Morphological and morphometrical analyses. Using digital imaging and communication in medicine (DICOM), TB CT images retrieved from the PACS of public hospitals selected for this study were transferred to a Workstation, and all morphological and morphometrical analyses were carried out using IntelliSpace Portal (ISP) Version 11.1 (Philips Image and Information Management software, Nederland). Prior to the morphologic and morphometric analyses of images selected for this study, a pilot study was initially conducted on 20 TB CT images in other to ascertain specific landmarks for analysis of vascular variants, degree of pneumatization, and distant measurements. Also, 50 randomly selected temporal CT images (both left and right) were analyzed by a first, second, and third observer (a Clinical Anatomist, a Radiographer, and a Specialist Radiologist- Head and Neck, respectively) for inter-observer reliability testing. This was done to achieve the accuracy and repeatability of measurements.

Morphometric analysis of SS and JB from the ear region (EAC, ME & IAC). The shortest distances between the selected TB-related vessels (SS and JB) and ear regions (EAC, ME & IAC) were achieved as described in Fig. 1. The points of measurement were standardized based on surgical relevance. Axial images at the level or about the level of the lateral semi-circular canal were used (visible landmarks of ear regions are best identified around this level). SS to EAC- from the apex of SS to the posterior wall of EAC; SS to ME- from the anterior wall of SS to the tympanic membrane (TM); SS to IAC- from the anterior edge of SS to the posterior of IAC; JB to EAC- from the apex of the bulb to tympanic border; JB to ME- from the apex of the bulb to the sigmoid plate; JB to IAC from the dome of the bulb to inner ear.

Morphological analysis of vascular variants. The variants of the jugular bulb analyzed in the study are as follows: high jugular bulb (when the bulb's dome rises close to the tympanic membrane's annulus), jugular bulb dehiscence (when HJB extends into the middle-ear cavity due to dehiscent sigmoid plate), and flat jugular bulb (no bulb or absence of the dome) (Fig. 2a–c, respectively). The internal carotid artery was analyzed for ICA dehiscence into the middle ear (Fig. 2d). Finally, for the sigmoid sinus, the following morphologies were analyzed based on shape: Half-moon type (SS-Diameter = ½SS-Width), Protrusive type (SS-Diameter > ½SS-Width), and Saucer type (SS-Diameter < ½SS-Width). SS-Diameter and SS-Width were achieved as described in Fig. 3.

Degree of pneumatization. Following the proposed classification system by Han et al.[25], the degree of TB pneumatization was analyzed by evaluating the air cells around the sigmoid sinus on an axial CT image. This involved the application of three parallel lines in the anterolateral direction angled at 45° on the axial CT section, where the malleoincudal complex appears as an ice-cream-cone shape. These lines were applied at positions in which each crossed the most anterior point of the sigmoid sinus at the junction with the petrous bone, the most lateral aspect along the transverse plane of the sigmoid groove, and the most common posterior point of the sigmoid sinus, respectively (Fig. 3). Hence, the degree of pneumatization was classified into four groups: Hypo-pneumatization- pneumatization that extends to the line drawn at the most anterior aspect of the SS (Fig. 4a); Moderate pneumatization- pneumatization that extends to the space between arbitrary lines drawn at the most anterior point and most lateral aspect of the sigmoid sinus (Fig. 4b); Good pneumatization- Pneumatization that extends to the space between the lines drawn at the most lateral region and the most posterior point of the SS (Fig. 4c) and; Hyper-pneumatization- pneumatization that extends postero-laterally beyond the line drawn at the posterior point of the sigmoid sinus (with possible extension into the petrous- extensive pneumatization) (Fig. 4d).

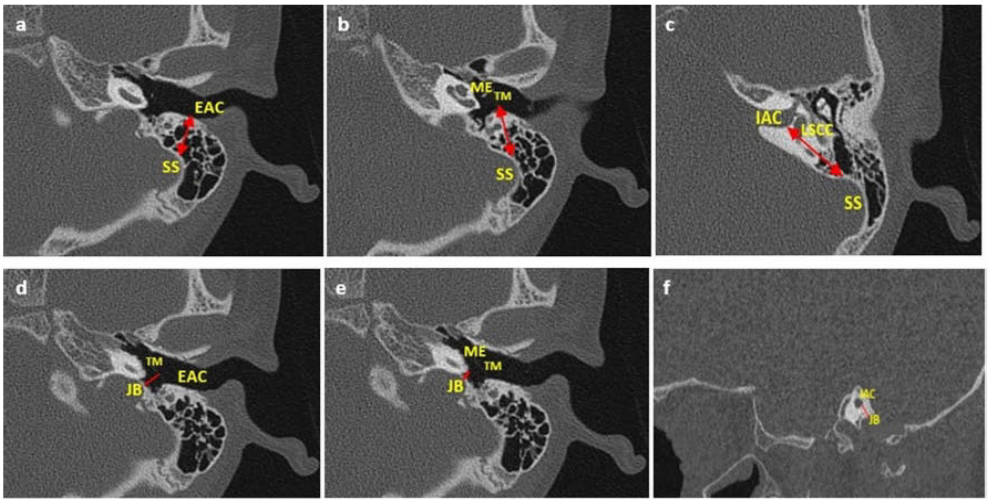

Figure 1. Diagrammatic representation of all measurements. *SS* sigmoid sinus, *JB* jugular bulb, *EAC* internal acoustic canal, *ME* middle-ear, *IAC* internal acoustic canal, *TM* tympanic membrane, *LSCC* lateral semicircular canal. (**a**) SS – EAC (on the axial plane, a double-tipped red arrow from the apex of SS to the posterior wall of EAC); (**b**) SS – ME (on the axial plane, a double-tipped red arrow from the anterior edge of SS to the tympanic membrane); (**c**) SS – IAC (on the axial plane, a double-tipped red arrow from the anterior edge of SS to the posterior wall of IAC); (**d**) JB – EAC; (on the axial plane, a red line from JB to the tympanic border); (**e**) JB – ME (on the axial plane, a red line from JB to the sigmoid plate); (**f**) JB – IAC (on the sagittal plane a red line from the dome of JB to the inner ear).

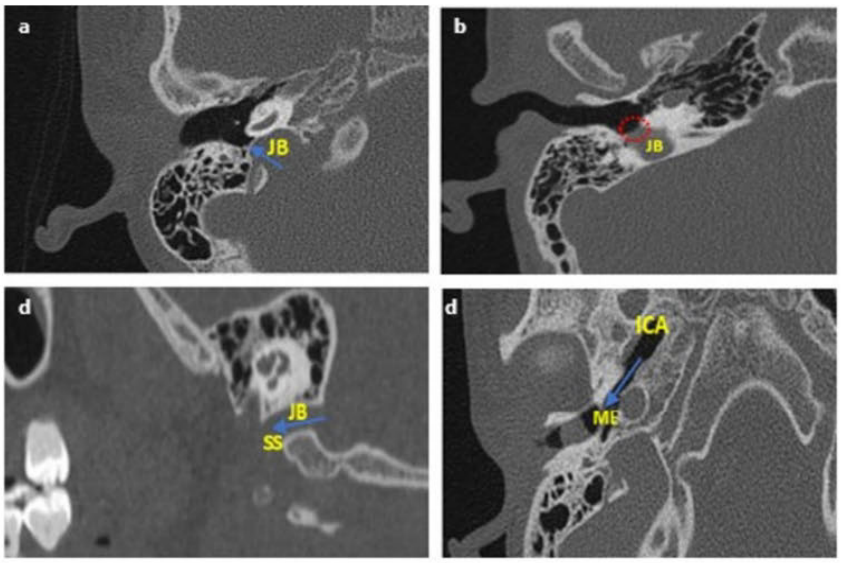

Figure 2. Diagrammatic representation of all vascular variants on the axial and sagittal plane. *JB* jugular bulb, *ICA* internal carotid artery, *ME* middle-ear, *SS* sigmoid sinus. (**a**) HJB- blue arrow showing the bulb rising to the sigmoid plate; (**b**) JBD- red dotted circle showing absence of sigmoid plate due to descent of JB into the middle ear; (**c**) FJB- absence of the dome (rising bulb), blue arrow showing SS continue into the internal jugular vein; and (**d**) ICA-Deh: blue arrow showing focal dehiscence of the carotid canal into the middle ear.

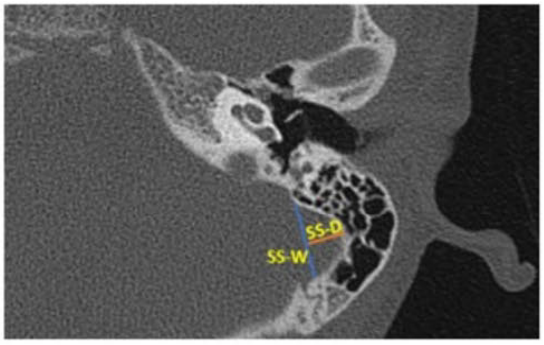

Figure 3. Diagram showing the measurements of sigmoid sinus width and sigmoid sinus diameter. *SS* sigmoid sinus, *W* width, *D* diameter. SS-W (blue line) and SS-D (orange line).

Statistical analysis. The statistical data analysis was conducted in the R Statistical computing software of the R Core Team, 2020, version 3.6.3. The results were presented in the form of descriptive and inferential statistics. The numeric measurements were non-normal and summarized in median and interquartile ranges. The categorical variables were presented in numbers and percentages. The median differences between two groups were assessed using the Wilcoxon test. The median differences across at least three levels of a categorical variable were assessed with the aid of Kruskal Wallis. In the case of significant median difference, post-hoc tests were conducted using Dunn test. Chi-Square tests were applied to determine the association between categorical variables, and when the distribution of the cross-tabulations contained an expected value of less than five, a Fisher's exact test was applied. All the inferential statistical analysis tests were conducted at 5% significance levels.

Ethical approval. The study was approved by the Biomedical Research Ethics Committee of the University of KwaZulu-Natal (Protocol Ref. No.: BREC/00002263/2020) and the National Health Research Committee of the KwaZulu-Natal Department of Health (NHRD Ref.: KZ_202102_026). All methods were carried out in

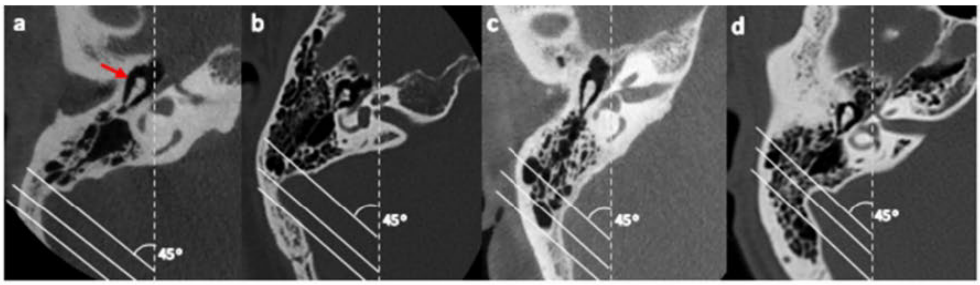

Figure 4. Degrees of pneumatization by evaluating air cells around the sigmoid sinus. Axial section where the malleoincudal complex (red arrow) appeared as an ice-cream-cone shape. Three parallel lines were drawn angled at 45° to the anteroposterior axis (dotted line). (**a**) Hypo-pneumatization: pneumatization remains anteromedial to the anterior line (passing the most anterior point). (**b**) Moderate pneumatization: pneumatization between the anterior and middle lines (passing the most lateral point). (**c**) Good-pneumatization: pneumatization between the middle and posterior lines (passing the most posterior point). (**d**) Hyper-pneumatization: pneumatization extends posterolaterally beyond the posterior line.

accordance with the University of KwaZulu-Natal standard-approved guidelines and regulations, as well as all experimental protocols in accordance with the declaration of Helsinki.

Results

All continuous and categorical data were presented as the median and interquartile range (IQR) and percentage (%). A total of 248 patients with 496 HRCT TB scans (right and left sides) were included in this study. The median age of the patients was 13.0 years (interquartile range, 8.0–23.0). Of the patients, 115 (46.4.5%) were females, and 133 (53.6%) were males (Fig. 5).

For inter-observer reliability testing for all linear measurements, the intraclass correlation coefficient was 92% for SS-EAC length, 91% for SS-ME length, 92% for SS-IAC length, 90% for JB-EAC length, 85% for JB-ME length, 87% for JB-IAC length, 92% for SS-diameter, and 93% for SS-Width.

Overall degree of pneumatization of the temporal bone. The degree of pneumatization was achieved by evaluating air cells around the sigmoid sinus, according to Han et al.[26]. The degree of pneumatization was classified into four groups; hypo-, moderate-, good- and hyper- pneumatization. The most common degree of pneumatization is hyper-pneumatization (140, 37.9%), where pneumatization extends beyond the arbitrary line drawn at the most posterior point of the SS. However, females were more likely to have hyper-pneumatization (73, 41.2%), while males were more likely to have hypo-pneumatization (31, 16.1%). Also, hypo-pneumatization was observed to have a higher incidence on the left, while moderate and good pneumatization had higher incidences on the right. In most patients, the degree of pneumatization was observed to be the same on both sides of the TB, with a significant association at $p<0.05$. The results are detailed in Table 1.

Variations in the morphometric relationship between SS and JB and the ear regions (EAC, ME & IAC.). The average distances of SS to EAC, ME, and IAC and JB to EAC, ME, and IAC were observed to be greater on the left. According to laterality, the Wilcoxon rank test showed a significant difference in average distances of SS-EAC, SS-ME, SS-IAC, JB-ME, and JB-IAC ($p<0.01$) except for JB-EAC, which showed no significant difference ($p=0.55$) (Table 2). For sex, there was no significant difference observed in distances of SS-ME (Right, $p=0.718$; Left, $p=0.679$), SS-ME (Right, $p=0.608$; Left, $p=0.776$), SS-IAC (Right, $p=0.618$; Left, $p=0.086$), JB-EAC (Right, $p=0.389$; Left, $p=0.859$), JB-ME (Right, $p=0.914$; Left, $p=0.749$), and JB-IAC on

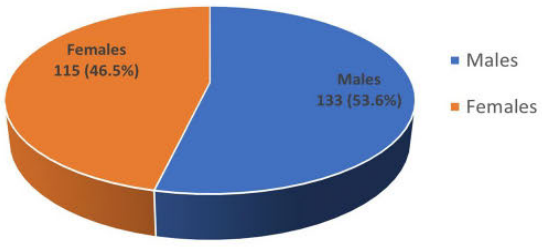

Figure 5. Pie chart of sex distribution of patients.

Degree of pneumatization	Female			Male			Overall		
	Left *f* (%)	Right *f* (%)	Total *f* (%)	Left *f* (%)	Right *f* (%)	Total *f* (%)	Left *f* (%)	Right *f* (%)	Total *f* (%)
Hypo	14 (15.7)	11 (12.5)	25 (14.1)	14 (14.3)	17 (18.1)	31 (16.1)	28 (15.0)	28 (15.4)	56 (15.2)
Moderate	17 (19.1)	19 (21.6)	36 (20.3)	24 (24.5)	25 (26.6)	49 (25.5)	41 (21.9)	44 (24.2)	85 (23.0)
Good	19 (21.3)	24 (27.3)	43 (24.3)	24 (24.5)	21 (22.3)	45 (23.4)	43 (23.0)	45 (24.7)	88 (23.8)
Hyper	39 (43.8)	34 (38.6)	73 (41.2)	36 (36.7)	31 (33.0)	67 (34.9)	75 (40.1)	65 (35.7)	140 (37.9)

Table 1. Overall degree of temporal bone pneumatization, including sex and laterality. *f* frequency; *%* percentage.

	SS-EAC median (IQR) *mm*	SS-ME median (IQR) *mm*	SS-IAC median (IQR) *mm*	JB-EAC median (IQR) *mm*	JB-ME median (IQR) *mm*	JB-IAC median (IQR) *mm*
Right (a)	15.5 (13.8–17.7)**	12.6 10.8–14.9)***	19.0 (16.4–21.8)***	13.0 (10.2–16.0)	7.10 (3.82–10.5)***	7.11 (5.57–9.08)*
Left (b)	15.9 (13.7–18.0)**	13.2 (11.4–14.4)***	20.1 (18.0–21.9)***	13.1 (9.95–15.9)	7.70 (4.00–10.2)***	7.49 (6.03–8.85)*
a vs. b (sig. diff) *p-value*	0.006	0.0027	0.002	0.55	0.0045	0.041

Table 2. Average distances of the sigmoid sinus and jugular bulb from selected ear region (external acoustic canal, middle-ear & internal acoustic canal) according to side differences. *mm* millimeters, *IQR* Interquartile range, *SS* sigmoid sinus, *JB* jugular bulb, *EAC* internal acoustic canal, *ME* middle-ear, *IAC* internal acoustic canal. Wilcoxon rank test showing *Significant different with $p < 0.05$; **Significant different with $p < 0.01$; ***Significant different with $p < 0.005$.

the left ($p = 0.292$). However, a significant difference ($p < 0.05$) was observed in the average distance of JB-IAC on the right, with the females having a distance of 7.56 (6.11–10.1) mm and the males having a distance of 6.78 (4.97–8.17) mm (Table 3). There was no significant difference observed with age for all measurements.

Association between the degree of pneumatization and morphometry of SS and JB to ear regions. As presented in Table 4, it was observed that the distances between SS and selected ear regions and between JB and the selected ear regions increase in the different degrees of pneumatization of the TB on both sides, with significant differences at $p < 0.05$. Hyper-pneumatization was observed to be associated with increased distances for all measurements. Overall, a significant association was observed between TB pneumatization and distances of SS and JB to selected ear regions at $p < 0.05$ and $p < 0.01$.

Variations in morphology of vasculature. The incidence of anatomical variations and morphologies of the sigmoid sinus, jugular bulb, and internal carotid artery in the selected study population is summarized in Table 5. All vascular variants included in this study were seen to be present regardless of the age of the patients or their population groups in the study population.

	Right			Left		
	Female (1) (N = 115)	Male (2) (N = 133)	(1) vs (2)	Female (3) (N = 115)	Male (4) (N = 133)	(3) vs (4)
SS–EAC median (IQR) *mm*	16.0 (13.9–17.6)	16.0 (13.8–17.9)	p = 0.718	16.00 (13.6–17.9)	15.7 (14.0–18.1)	p = 0.679
SS–ME median (IQR) *mm*	12.9 (10.6–14.7)	13.0 (10.8–15.0)	p = 0.609	12.9 (11.4–14.4)	12.5 (11.4–14.5)	p = 0.776
SS–IAC median (IQR) *mm*	19.7 (16.4–21.7)	19.1 (16.0–22.2)	p = 0.618	20.10 (19.2–22.2)	20.10 (17.1–21.5)	p = 0.086
JB–EAC median (IQR) *mm*	13.1 (10.5–16.0	12.0 (9.90–16.1)	p = 0.389	13.3 (10.2–15.1)	12.7 (9.91–16.0)	p = 0.859
JB–ME median (IQR) *mm*	7.10 (3.83–9.78)	7.10 (3.83–10.7)	p = 0.915	7.10 (4.30–10.2)	7.01 (3.94–10.5)	p = 0.746
JB–IAC median (IQR) *mm*	7.56 (6.11–10.1)*	6.78 (4.97–8.17)*	p = 0.043	8.14 (6.18–8.85)	7.21 (5.75–8.77)	p = 0.292

Table 3. Morphometric analysis (distance) of the sigmoid sinus and jugular bulb from ear region (external acoustic canal, middle-ear & internal acoustic canal) according to sex. *mm* millimeters, *IQR* Interquartile range, *SS* sigmoid sinus, *JB* jugular bulb, *EAC* internal acoustic canal, *ME* middle-ear, *IAC* internal acoustic canal. *Significant different with $p < 0.05$.

	Right pneumatization					Left pneumatization				
	Hypo (N = 28)	Moderate (N = 44)	Good (N = 45)	Hyper (N = 65)	p-value	Hypo (N = 28)	Moderate (N = 41)	Good (N = 43)	Hyper (N = 75)	p-value
SS–EAC median (IQR) *mm*	14.6 (11.6–16.7)[a]	15.0 (13.1–16.9)	16.0 (13.8–17.8)	16.4 (14.1–17.6)[a]	0.015*	13.4 (12.8–16.9)[acd]	15.7 (13.9–17.8)[c]	16.0 (14.1–19.2)[d]	16.5 (14.7–18.2)[a]	0.007**
SS–ME median (IQR) *mm*	12.3 (9.85–13.4)	12.6 (10.4–15.1)	12.9 (10.2–14.9)	13.5 (11.8–15.0)	0.017*	11.5 (10.1–13.5)[a]	12.8 (11.2–13.9)	12.8 (11.7–14.4)	13.6 (11.5–14.9)[a]	0.021*
SS–IAC median (IQR) *mm*	18.0 (15.9–21.0)	19.3 (16.4–22.3)	19.5 (16.2–21.4)	19.5 (16.5–22.1)	0.019**	19.8 (16.8–21.1)[ad]	19.8 (17.2–20.1)[be]	20.2 (19.2–22.1)[de]	20.3 (19.2–22.8)[ab]	0.003**
JB–EAC median (IQR) *mm*	10.9 (7.97–15.2)[a]	13.1 (10.2–15.4)	13.7 (10.5–16.3)	14.0 (10.2–15.4)[a]	0.011*	10.0 (8.34–14.0)[a]	12.9 (11.0–15.2)	13.9 (9.72–16.7)	14.0 (11.4–16.4)[a]	0.002**
JB–ME median (IQR) *mm*	5.07 (2.63–7.15)[a]	7.18 (4.11–11.6)	7.62 (4.53–10.5)	8.40 (6.68–10.3)[a]	0.008**	4.85 (2.85–7.70)[a]	6.61 (4.42–12.5)	7.85 (4.05–9.15)	8.69 (5.15–10.5)[a]	0.012*
JB–IAC median (IQR) *mm*	6.50 (5.02–7.68)	6.98 (6.01–8.01)[b]	7.11 (5.65–10.4)	7.68 (6.13–10.4)[b]	0.011*	6.70 (5.70–8.68)[a]	7.31 (5.51–8.85)	7.32 (5.78–8.68)	8.14 (6.55–8.85)[a]	0.046*

Table 4. Association between pneumatization of temporal bone and distances of the sigmoid sinus and jugular bulb to selected ear regions (external acoustic canal, middle-ear & internal acoustic canal). *mm* millimeters, *IQR* Interquartile range, *SS* sigmoid sinus, *JB* jugular bulb, *EAC* internal acoustic canal, *ME* middle-ear, *IAC* internal acoustic canal. *Significant association* at *p < 0.05, **p < 0.01 with *significant difference*, a, b, c, d, e, (Kruskal–Wallis test followed by Wilcoxon Signed Rank test). [a]hypo vs. hyper. [b]good vs. hypo. [c]hypo vs. moderate. [d]hypo vs. good. [e]moderate vs. good.

	Female				Male				Overall			
Vascular Variations	Left *f* (%)	Right *f* (%)	p-value	Total *f* (%)	Left *f* (%)	Right *f* (%)	p-value	Total *f* (%)	Left *f* (%)	Right *f* (%)	p-value	Total *f* (%)
SS			0.650				0.148				0.119	
Half-moon	5 (5.6)	3 (3.4)		8 (4.5)	3 (3.1)	4 (4.6)		7 (3.8)	8 (4.3)	7 (4.0)		15 (4.2)
Protrusive	34 (38.2)	38 (43.7)		72 (40.9)	23 (23.7)	31 (35.6)		54 (29.3)	57 (30.6)	69 (39.7)		126 (35.0)
Saucer	50 (56.2)	46 (52.9)		96 (54.5)	71 (73.2)	52 (59.8)		123 (66.8)	121 (65.1)	98 (56.3)		219 (60.8)
JB			0.289				0.518				0.189	
Flat JB	5 (5.7)	5 (5.8)		10 (5.7)	7 (7.3)	8 (8.9)		15 (8.1)	12 (6.5)	13 (7.3)		25 (6.9)
High JB	30 (34.5)	32 (36.4)		62 (35.4)	23 (24.0)	30 (33.2)		52 (28.0)	55 (29.9)	60 (33.8)		115 (31.85)
JB dehiscence	0 (0.0)	4 (4.6)		4 (2.3)	1 (1.0)	2 (2.2)		3 (1.6)	1 (0.5)	6 (3.4)		7 (1.9)
ICA			0.041*				0.040*				0.030*	
Dehiscence	2 (2.3)	4 (4.5)		6 (3.4)	1 (1.0)	6 (6.6)		7 (3.7)	3 (1.6)	10 (5.6)		13 (3.5)

Table 5. Incidence of anatomical variations of the sigmoid sinus, jugular bulb, and internal carotid artery. X^2, significant different at *p < 0.05. *f* frequency, % percentage, *SS* sigmoid sinus, *JB* jugular bulb, *ICA* internal carotid artery.

Sigmoid sinus (SS). Overall, the saucer-shaped and protrusive types of SS were more common, with the former having a higher incidence. Saucer-shaped SS was observed to have an incidence of 219 (60.9%) with a non-significant (X^2, p = 0.199) dominance on the left TB (121, 65.1%). Protrusive SS was observed to have an incidence of 126 (35.0%) with a non-significant (X^2, p = 0.199) dominance on the right TB (69, 39.7%). The half-moon type of SS was observed to have the lowest incidence (4.2%). For sex, the saucer-shaped SS was observed to be higher in males with an incidence of 123 (66.8%) and non-significant dominancy on the left for both sexes (male left- 71 (73.2%), Fisher's, p = 0.148; female left- 50 (56.2%), Fisher's, p = 0.659). While, the protrusive SS was observed to be higher in females with an incidence of 72 (40.9%) and dominancy on the right for both sexes (female right- 38 (43.7%), Fisher's, p = 0.659; male right- 31 (35.6%), Fisher's, p = 0.148).

Jugular bulb. Jugular bulb variants observed in the study were FJB- 25 (6.9%) (Fig. 2a), HJB- 115 (31.8%) (Fig. 2b), and JB Dehiscence- 7 (1.9%) (Fig. 2c) in which the right TB (right ear) tends to have a higher incidence of 13 (7.3%), 60 (33.8%) and 6 (3.4%), respectively. Non-significant side dominancy was also observed in relation to sex (female- Fisher's, p = 0.289; male- Fisher's, p = 0.518), with the female having more incidence of HJB (62 (35.4%)) and JB Dehiscence (4 (2.3%)), while the male showed more incidence of FJB (15 (8.1%)).

Internal carotid artery. ICA dehiscence incidence was observed to be 13 (3.5%), with males having an incidence of 7 (3.7%) and females having an incidence of 6 (3.4%). The incidence was also more dominant in the right ear (right TB) in the overall incidence and with sex at p < 0.05.

Association between degrees of pneumatization and vascular variants. For both right and left, vascular variants in the shape of SS analyzed in this study were observed to occur in the different degrees of pneumatization, with the most occurrence of half-moon-shaped SS in patients with hypo-pneumatized TB. In contrast, protrusive and saucer-shaped SS occurs more in hyper-pneumatized patients. However, there was no significant association between the incidences of these variable shapes of SS and the degree of TB pneumatization (Rt- $p = 0.070$; Lt- $p = 0.645$).

For the analyzed JB variants in the study, HJB was observed in the different degrees of pneumatization but with a high incidence in patients having hyper-pneumatized TB on both sides (Rt- 63.3%; Lt- 51.4%) with a significant association at $p < 0.001$. JB dehiscence was also observed to have a significant association ($p < 0.001$) with hyper-pneumatization on both sides, mostly occurring in patients with HJB. However, more incidence of FJB was observed in patients with hypo-pneumatized TB with a significant association at $p < 0.001$.

Lastly, the incidence of ICA dehiscence was observed only in patients with hyper-pneumatized TB on both sides, showing a significant association of $p < 0.01$. The results are detailed in Table6.

Discussion

The degree of TB pneumatization has been implicated as one of the factors influencing the relative morphology and location of its related blood vessels in relation to the ear regions[2,11]. However, observable and measurable data relating this to different degrees of pneumatization of TB remains scarce. Moreso, previous studies have highlighted that there is still a paucity of data to ascertain the association between different degrees of pneumatization of the TB anatomical variations of its related vessels and their relationship with ear regions Dai et al.[26] and Singh et al.[9].

In this study, the classification of Han et al.[25] was utilized by evaluating air cells around the sigmoid sinus and classifying the degrees of TB pneumatization into hypo-, moderate-, good-, and hyper-pneumatization. All degrees of pneumatization existed in the present study population regardless of age or population group. Overall, hyper-pneumatization had the highest incidence (37.9%), and hypo-pneumatization had the lowest incidence (15.2%), which is the same as reported by Tan et al.[27] in the Singapore population. Bronoosh et al.[28] also identified hyper-pneumatization as the most common pattern occurring in 30.9% of their study subjects in an Iranian population.

Generally, the position and location of TB-related vasculature to ear regions vary greatly among individuals and between right and left ears which corresponds to the findings from the present study[26,29–35]. No significant difference was observed with age or among population groups. However, the present study identified the distances between SS and JB and the selected ear regions, i.e., EAC, ME, and IAC, to vary significantly between right and left, with the left significantly higher than the right for all distances ($p < 0.05$, $p < 0.01$, $p < 0.005$).

All distances measured were highest in patients with hyper-pneumatized TB. Significant associations ($p < 0.05$, $p < 0.01$) existed between the different degrees of pneumatization and all distances measured. This was because distances between SS and JB and the selected ear regions increase as pneumatization extends across each of the three parallel lines anterolaterally applied at angle 45°, which was utilized to classify the degree of pneumatization in this study. According to Lima et al.[36], mastoid surface areas and volume follow a linear correlation. This implies that an increased pneumatization denotes an increased surface area, which increases the distances observed between these vessels and ear regions as pneumatization increases.

The present study also analyzed the incidence of some variants of vessels such as SS, JB, and ICA relative to TB structures, which have implications for the development of pathologic abnormalities, such as encroachment on the structures of the middle ear or eroding into the inner ear[37]. These, of course, are encountered in routine clinical practice and may pose dangers in ear-related and mastoid surgeries in which surgeons need to avoid such pitfalls[9,11,16,38]. The SS and its variant shapes were observed in the different degrees of pneumatization for right and left. Although in the reviewed literature, the half-moon-shaped SS had been ascribed to a healthy mastoid

	Right temporal bone pneumatization					Left Temporal bone pneumatization				
	Hypo (N = 28)	Moderate (N = 44)	Good (N = 45)	Hyper (N = 65)	p-value	Hypo (N = 28)	Moderate (N = 44)	Good (N = 45)	Hyper (N = 65)	p-value
SS					0.070 (NSA)					0.645 (NSA)
Half-moon	4 (14.8%)	2 (4.5%)	1 (2.3%)	0 (0.0%)		3 (11.1%)	2 (4.9%)	1 (2.3%)	2 (2.7%)	
Protrusive	7 (25.9%)	19 (43.2%)	16 (37.2%)	27 (45.0%)		9 (33.3%)	13 (31.7%)	13 (30.2%)	21 (28.4%)	
Saucer	16 (59.3%)	23 (52.3%)	26 (60.5%)	33 (55.0%)		15 (55.6%)	26 (63.4%)	29 (67.4%)	51 (68.9%)	
JB					<0.001**					<0.001**
Flat JB	5 (18.5%)	4 (6.8%)	3 (6.7%)	1 (2.2%)		5 (10.7%)	4 (9.8%)	3 (0.0%)	0 (6.9%)	
High JB	2 (7.4%)	9 (20.0%)	10 (22.7%)	38 (63.3%)		6 (21.4%)	5 (12.2%)	7 (16.3%)	37 (51.4%)	
JB dehiscence	0 (0.0%)	0 (0.0%)	2 (4.5%)	4 (6.7%)		0 (0.0%)	0 (0.0%)	0 (0.0%)	1 (1.4%)	
ICA dehiscence					0.002*					0.009*
Yes	0 (0.0%)	0 (0.0%)	0 (0.0%)	10 (16.8%)		0 (0.0%)	0 (0.0%)	0 (0.0%)	3 (4.0%)	

Table 6. Association between pneumatization of the temporal bone and some selected vascular variants of the sigmoid sinus, jugular bulb, and internal carotid artery. Fisher's test showing significant association at *$p < 0.01$, **$p < 0.001$. *NSA* no significant association, *SS* sigmoid sinus, *JB* jugular bulb, *ICA* internal carotid artery.

and was seen as the most common type of SS[39], the present study identified the SS as more saucer-shaped in the study population with no significant association with the degree of pneumatization. In contrast, half-moon-shaped SS was found more in patients with hypo-pneumatized TB; however, there was no significant association.

For JB and its anatomical variants, HJB was found to be the most common variant of JB. This high incidence conforms with the studies of Aslan et al.[4] and Kawano et al.[38], who reported high incidences of HJB to be 23% and 16%, respectively, and supports the claims of Friedmann et al.[8] and Park et al.[40] that HJB is the most common JB variant not rare in a population. This, however, is significantly associated ($p < 0.001$) with increasing pneumatization. This implies that, as pneumatization extends the three parallel lines, most significantly where pneumatization extends beyond the arbitrary line drawn at the most posterior point of SS (hyper-pneumatization), increase in the incidence of HJB was observed. Although JB abnormalities are rarely encountered during ear surgeries, a high jugular bulb remains a recognized problem that can lead to brisk venous haemorrhage if the bulb is inadvertently opened[41]. Hence, ENT surgeons should watch out for the possibility of a high-riding jugular bulb in patients with hyper-pneumatized TB.

Like HJB, this study also observed a significant association between hyper-pneumatization and JB dehiscence. The similarity in the significant association observed for HJB and JB dehiscence follows their anatomical relationship. According to Gaillard[42], HJB becomes a dehiscent JB when the sigmoid plate between high-riding JB and the middle ear is missing, allowing the JB to bulge into the middle ear cavity. This means that an individual with hyper-pneumatized TB is at risk of having a dehiscent JB in the absence of the sigmoid plate, which is one of the common causes of pulsatile tinnitus[43].

In addition, a lower incidence of flat JB was observed in this study. This contradicts the report of Vachata et al.[16], who documented a higher incidence of FJB. A significant association between decreasing pneumatization and incidence of FJB was observed, especially when pneumatization is limited to the first anteromedial line, i.e., hypo-pneumatization or nothing near this line. In this case, the mastoid contains more marrow than air cells (diploic) or contains mainly dense bone[44,45], which could inhibit the formation of the bulb.

Furthermore, ICA dehiscence as a vascular variant was considered in this study. The dehiscence of ICA was observed to occur with an incidence of 3.5% from the analyzed scans, which was only seen in the TB to be significantly associated with hyper-pneumatized TBs with extensive pneumatization. An extensive pneumatization is when pneumatization spreads to the petrous apex (and even beyond), where the ICA is seen to exit the carotid canal into the foramen lacerum to enter the skull[1,46]. The transition of the bony petrous into air cells in an extensive pneumatized could result in dehiscence of the ICA due to the loss of bony elements.

Importantly, in ENT and its related surgeries, most of these vascular variants can result in ear disturbances and dysfunction, as well as diagnostic and surgical difficulties[47]. Although middle ear disease such as chronic otitis media is one common cause of hearing loss, high jugular bulb (HJB), for instance, when associated with diverticulum or dehiscence high-riding JB, has been reported to result in sensorineural hearing loss, conducting hearing loss, and Meniere-like syndrome (a disorder of inner ear that can lead to dizzy spell and hearing loss common to the left ear) due to compression of the inner ear[47–52]. The high incidence of HJB and JB dehiscence reported in this study due to increased pneumatization (hyper-pneumatization- 37.9%) could also contribute to hearing loss in children, teenagers, and adults.

Conclusion

This study investigated the association between the degree of pneumatization and TB-related vasculature in terms of their morphologies and morphometric relationship with ear regions/structures. Hyper-pneumatization was more common in the study population and significantly associated with HJB, JB dehiscence, and ICA dehiscence, while hypo-pneumatization was least common and significantly associated with FJB. No significant association between the degree of pneumatization and SS variants. Furthermore, distances of SS and JB to ear regions increase as the degree of pneumatization increases. Hence, this study concludes that TB pneumatization is a factor that influences the relative morphological variants of JB and ICA only and the distances of SS and JB to different ear regions. Awareness of these will contribute significantly to predicting and avoiding relative morphological variants and the location of these vessels, which are recognized pitfalls that could become distressful or cause complications during ear-related surgeries.

Data availability

Data are available upon reasonable request and with permission from the KwaZulu-Natal Department of Health, South Africa.

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References

1. Standring, S. & Gray, H. *Gray's anatomy: The anatomical basis of clinical practice* 40th edn. (Churchill Livingstone, 2008).
2. Osch, K. V. *et al.* Morphological analysis of sigmoid sinus anatomy: Clinical application to neurotological surgery. *J. Otolaryngol.-Head N.* **48**, 2 (2019).
3. Osama, A. M. K. Anatomical characteristics of temporal bone on computerized tomography. *IOSR-JDMS* **17**(5), 88–96 (2018).
4. Aslan, A. Anatomical considerations of high jugular bulb in lateral skull base surgery. *J. Laryngol. Otol.* **3**, 333–336 (1997).
5. Sarmiento, P. B. & Eslait, F. G. Surgical classification of variations in the anatomy of the sigmoid sinus. *Otolaryngol.-Head Neck Surg.* **131**, 192–199 (2004).
6. Kitamura, M. A. P., Costa, L. F. & Silva, D. O. Cranial venous sinus dominance: What to expect? Analysis of 100 cerebral angiographies. *Arq. Neurosiquiatr.* **75**(5), 296–300 (2017).
7. Sirikci, A. *et al.* Assessment of mastoid air cells size versus sigmoid sinus variables with tomography-assisted digital image processing program and morphometry. *Surg. Radiol. Anat.* **26**, 145–148 (2004).

8. Friedmann, D. R. Development of the jugular bulb: A radiologic study. *Otol. Neurotol.* **32**(8), 1389–1395 (2011).
9. Singh, A., Kumar, I. D. V., Sikka, K., Verma, H. & Thakar, A. Study of sigmoid sinus variations in the temporal bone by micro dissection and its classification—A cadaveric study. *Int. Arch. Otorhinolaryngol.* **23**, e311–e316 (2019).
10. Hourani, R., Carey, J. & Yousem, D. M. Dehiscence of the jugular bulb and vestibular aqueduct. Findings on 200 consecutive temporal bone computed tomography scans. *J. Comput. Assist. Tomogr.* **29**, 657–662 (2005).
11. Inal, M., Muluk, N. B., Dag, E., Arikan, O. K. & Kara, S. A. The pitfalls and important distances in temporal bones HRCT of the subjects with high jugular bulb- Preliminary Review. *Adv. Clin. Exp. Med.* **24**(2), 315–325 (2015).
12. Saleh, E. A. *et al.* Management of the jugular bulb in the translabyrinthine approach. *Otolaryngol. Head Neck Surg.* **110**, 397–399 (1994).
13. Koesling, S., Kunkel, P. & Schul, T. Vascular anomalies, sutures and small canals of the temporal bone on axial CT. *Eur. J. Radiol.* **54**, 335–343 (2005).
14. Roche, P. H. *et al.* High jugular bulb in the translabyrinthine approach to the cerebellopontine angle: Anatomical considerations and surgical management. *Acta Neurochir.* **148**, 415–420 (2006).
15. Friedmann, D. R., Thuy, L. B., Pramanik, B. K. & Lalwani, A. K. Clinical spectrum of patients with erosion of the inner ear by jugular bulb abnormalities. *Laryngoscope* **120**, 365–372 (2010).
16. Vachata, P., Petrovicky, P. & Sames, M. An anatomical and radiological study of the high jugular bulb on high-resolution CT scans and alcohol-fixed skulls of adults. *J. Clin. Neurosci.* **17**, 473–478 (2010).
17. Morris, P. S. & Leach, A. J. Acute and chronic otitis media. *Pediatr. Clin. N. Am.* **56**(6), 1383–1399 (2009).
18. Vos, T. *et al.* Global, regional, and national incidence, prevalence, and years lived with disability for 301 acute and chronic disease and injuries in 188 countries, 1990–2013: A systemic analysis for the global burden of disease study. *Lancet* **386**(9995), 743–800 (2015).
19. DeAntonio, R., Yarzabal, J.-P., Cruz, J. P., Schmidt, J. E. & Kleijnen, J. Epidemiology of otitis media in children from developing countries: A systematic review. *Int. J. Pediatr. Otorhinolaryngol.* **85**, 65–74 (2016).
20. Dewan, M. C. *et al.* Estimating the global incidence of traumatic brain injury. *J. Neurosurg.* **130**, 1080–1097 (2019).
21. Psychology Today. *What is Trauma?* www.psychologtoday.com/za/basics/trauma%3famp (2020).
22. Tesfa, T. *et al.* Otitis media in sub-Saharan Africa: A systemic review and meta-analysis. *BMC Infect. Dis.* **220**, 225 (2020).
23. Ichijo, H., Hosokawa, M. & Shinkawa, H. The relationship between mastoid pneumatization and the position of the sigmoid sinus. *Eur. Arch. Otorhinolaryngol.* **253**, 421–424 (1996).
24. Comert, E., Kilic, C. & Comert, A. Jugular bulb anatomy for lateral skull base approach. *J. Craniofac. Surg.* **29**(7), 1969–1972 (2018).
25. Dai, P.-D. *et al.* Morphological and positional relationships between the sigmoid sinus and the jugular bulb. *Surg. Radiol. Anat.* **29**, 643–651 (2007).
26. Han, S. J., Song, M. H., Kim, J., Lee, W. S. & Lee, H.-K. Classification of temporal bone pneumatization based on sigmoid sinus using computed tomography. *Clin. Radiol.* **62**, 1110–1118 (2007).
27. Tan, D. A., Ng, J. H., Lim, S. A., Low, D.Y.-M. & Yuen, H. W. Classification of temporal bone pneumatization of high-resolution computed tomography: Prevalence, patterns and implication. *Otolaryngol. Head Neck Surg.* **1**, 1–7 (2018).
28. Bronoosh, P., Shakibafard, A., Mokhtare, M. R. & Rad, T. M. Temporal bone pneumatisation: A computed tomography study of pneumatized articular tubercle. *Clin. Radiol.* **69**, 151–156 (2014).
29. Atilla, S., Akpek, S., Uslu, S., Ilgit, E. T. & Isik, S. Computed tomographic evaluation of surgically significant vascular variations related with the temporal bone. *Eur. J. Radiol.* **20**, 52–56 (1995).
30. Tomura, N. *et al.* Normal variation of the temporal bone on High-Resolution CT: Their incidence and clinical significance. *Clin. Radiol.* **50**, 144–148 (1995).
31. Gangopadhyay, K., McArthur, P. D. & Larsson, S. G. Unusual anterior course of the sigmoid sinus: Report of a case and review of the literature. *J. Laryngol. Otol.* **110**, 984–986 (1996).
32. Zaytoun, G. & Hamdan, A.-L. The sigmoid venous sinus in temporal bone surgery: Anatomic variations with case presentations. *Otorhinolaryngol. Nova.* **10**, 291–295 (2000).
33. Dai, P. *et al.* Positional relationship between the facial nerve and other structures of the temporal bone. *J. Laryngol. Otol.* **118**, 106–111 (2004).
34. Bożek, P., Kluczewska, E., Misiołek, M., Ścierski, W. & Lisowska, G. The prevalence of persistent petrosquamosal sinus and other temporal bone anatomical variations on high-resolution temporal bone computed tomography. *Med. Sci. Monit.* **22**, 4177–4185 (2016).
35. Onyango, S., Mugwe, P. & Thinwa, J. Vascular anatomical variants of the temporal bone as depicted on high resolution temporal bone CT scans done in Nairobi, Kenya. East and Central Africa. *J. Otolaryngol. Head Neck Surg.* **5**, 19–23 (2021).
36. Lima, M. A. R., Farage, L., Cury, M. C. L. & Junior, F. B. Mastoid surface area-to-volume ratios in adult Brazilian individuals. *Braz. J. Otorhinolarynol.* **79**(4), 446–453 (2013).
37. Schatz, A. & Sade, J. Correlation between mastoid pneumatization and position of the lateral sinus. *Ann. Otol. Rhinol. Laryngol.* **99**, 142–145 (1990).
38. Kawano, H., Tono, T., Schachern, P. A., Paparella, M. M. & Komune, S. Petrous high jugular bulb: A histological study. *Am. J. Otolaryngol.* **21**, 161–168 (2000).
39. Ichijo, H., Hosokawa, M. & Shinkawa, H. Differences in size and shape between the right and left sigmoid sinuses. *Eur. Arch. Otorhinolaryngol.* **250**, 297–299 (1993).
40. Park, J. J., Shen, A., Keil, S., Kuhl, C. & Westhofen, M. Jugular bulb abnormalities in patients with Meniere's disease using high-resolution computed tomography. *Eur. Arch. Otorhinolaryngol.* **272**(8), 1879–1884 (2015).
41. Fox, R., Nash, R. & Tatler, T. Encountering a high jugular bulb during ear surgery. *Ann. R. Coll. Surg. Engl.* **99**(1), 36–37 (2017).
42. Gaillard, F. & Bickle, I. *Dehiscent jugular bulb.* Reference article, Radiopaedia.org. (Assessed on 28 Mar 2022) (2019).
43. Erdogan, H., Arslan, S., Arslan, F. Z., Durmaz, M. S. & Cengiz, A. Dehiscent high jugular bulb. *Clin. Med. Img. Lib.* **3**, 065 (2017).
44. Virapongse, C., Sarwar, M., Bhimani, S., Sasak, C. & Shapiro, R. Computed tomographic anatomy of the temporal bone: Normal pattern and morphology. *AJR Am. J. Neuroradiol.* **145**, 473–481 (1985).
45. Hill, C. A. Ontogenetic change in temporal bone pneumatization in humans. *Anat. Rec.* **294**(7), 1103–1115 (2011).
46. Schmalfuss, I. M. Petrous apex. In *Skull Base Imaging* (ed. Chong, V.) 233–245 (Elsevier, 2018).
47. Low, W. K., Fenton, J. E., Fagan, P. A. & Gibson, W. P. R. The influence of race on the position of jugular bulb. *J. Laryngol. Otol.* **109**, 610–613 (1995).
48. Jahsdoerfer, R. A., Cail, W. S. & Cantrell, R. W. Endolymphatic duct obstruction from a jugular bulb diverticulum. *Ann. Otol. Rhinol.* **90**, 619–623 (1981).
49. Hannell, G. & Fagan, P. A. (1987) The clinical significance of jugular bulb anomalies. *J. Otolaryngol. Soc. Aust.* **6**(1), 46–49 (1987).
50. Hitier, M. *et al.* New treatment of vertigo caused by jugular bulb abnormalities. *Surg. Innov.* **21**(4), 365–371 (2014).
51. Koo, Y. H., Lee, J. Y., Lee, J. D. & Hong, H. S. Dehiscent high-riding jugular bulb presenting as conductive hearing loss: A case report. *Medicine (Baltimore)* **97**(26), e11067 (2018).
52. John Hopkins Medicine. *Meniere disease: What is Meniere disease?* Retrieved from hopkinsmedicine.org/health/conditions-and-disease/menieres-disease (2022).

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Author contributions
All authors contributed in one way or the other as follows: O.S.A., W.-B.E.M., A.L.S. and C.O.R. conceptualized the project; O.S.A., S.O.O., S.K.L. and W.-B.E.M. collected and analyzed data; O.S.A., S.O.O., S.K.L., W.-B.E.M., A.L.S. and C.O.R.: wrote and edited manuscript. W.-B.E.M., A.L.S. and C.O.R.: supervised the project.

Competing interests
The authors declare no competing interests.

Additional information
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BRIDGING TEXT

From Chapter Four to Chapter Five

Chapter four reported the incidences of anatomical variations of temporal bone-related vasculature and was able to prove the claim that the rate or degree of pneumatization is one factor that influences the morphology of some temporal bone-related vasculatures and their morphometric relationship with ear regions. This was because the different degrees of temporal bone pneumatization were found to be significantly associated with the position of SS and JB to ear regions and the incidences of JB variants and ICA dehiscence. However, the classification of temporal bone degree of pneumatization is still yet to reach a consensus among otologists. With the methods utilized in this study, this current chapter tends to review and propose a simple and concise classification of the degree of TBP using reference structures and landmarks.

This manuscript in chapter five explored the degree of variation in assessment of the temporal bone degree of pneumatization at two levels of CT in order to establish methods through which the degree of pneumatization can quickly and easily be classified.

The manuscript in chapter five, titled ***"An inter-observer assessment of mastoid pneumatization and degree classification using sigmoid sinus: Comparing two levels of temporal bone computed tomograms,"*** was submitted to Surgical and Radiologic Anatomy on 7th October 2022 and published on 6th April 2023. (Manuscript and references were written according to journal format).

CHAPTER FIVE

Manuscript Four

An inter-observer assessment of mastoid pneumatization and degree classification using sigmoid sinus: Comparing two levels of temporal bone computed tomograms

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ORIGINAL ARTICLE

An inter-observer assessment of mastoid pneumatization and degree classification using sigmoid sinus: comparing two levels of temporal bone computed tomograms

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Abstract

Background The degree of mastoid pneumatization of the temporal bone (TB) has been implicated in the pathogenesis of TB diseases and surgical implications, and planning of a few otologic surgeries. However, there is lack of consensus in the classification of the degree of pneumatization. This study aimed to suggest a simple, quick, and less-burden classification system for assessing and rating the degree of pneumatization by comparing two levels of TB computed tomographs (CTs) using the SS as a reference in an inter-observer assessment among otologists.

Methods This was a randomized pilot survey among otologists. A questionnaire consisting of different axial CTs of TB taken at two levels: the level of malleoincudal junction (MIJ) and the level of lateral semicircular canal (LSCC), with different pneumatization patterns, was used to assess participants' impressions of the degree of pneumatization. The terms "hypo-," "moderate," "good," and "hyper-" pneumatization were listed as options to rate their impressions on the degree of mastoid pneumatization of the TB images using the SS as a reference structure. Likert scale was used to assess their level of agreement or disagreement with using SS as a reference in evaluating mastoid pneumatization.

Results Participants who correctly rated images taken at the level of LSCC according to their respective degree of pneumatization were significantly higher ($p < 0.05$) regardless of their year of experience compared to those that correctly rated corresponding images taken at the level of MIJ. A 76% positivity in their level of agreement with the use of sigmoid sinus in evaluating mastoid pneumatization was observed on the Likert-scale chart.

Conclusion Findings from this study suggest that evaluating air cells around the SS at the level of LSCC on CTs could be easier in assessing and classifying the degree of mastoid pneumatization.

Keywords Pneumatization · Temporal bone · Classification · Sigmoid sinus

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Introduction

The clinical significance of temporal bone (TB) and its mastoid pneumatization (presence or development of air-filled cavities or air cells) has been highlighted by a number of studies from early 1900 to this present millennium [1–6]. These include playing important roles in surgical intervention in this region of the skull [7, 8], serving as a prognostic factor in chronic and middle ear surgeries [7–9], and providing a protective function to the middle and inner ear in trauma cases [10, 11].

Mastoid pneumatization is clinically relevant in a variety of scenarios. The degree of pneumatization of the mastoid is considered an indirect sign of Eustachian tube function and gas exchange through the mucosa during the first years of life. Early middle ear infections, otitis-prone conditions, and recurrent OME do not allow wide pneumatization of the temporal bone within the first 4 to 6 years of skull growth during childhood. Most acquired cholesteatomas, therefore, present with some degree of sclerosis within the mastoid [12].

Increased pneumatization of the temporal bone is associated with an improved prognosis in otitis media with effusion (OME) [13], as well as higher tympanoplasty graft success rates [14]. It is also relevant to surgical planning for bone conduction implants, active middle ear implants, and even cochlear implantation when assessing the space required for implant placement or predicting access to the middle ear via trans-mastoid, retro-facial approaches [15]. Formerly, a sclerotic mastoid most often required an open (canal wall down) technique, whereas a sufficiently wide and ventilated mastoid led to a combined approach [12]. This is relevant too when considering implantable hearing devices that require an approach through the mastoid, such as the Bone Bridge from Medel, which requires a certain volume of air cells for placement within the mastoid, active middle ear implants that require coupling to ossicles in the epitympanum or cochlear implants that require access through a posterior tympanotomy.

In addition, poorly pneumatized or 'contracted' temporal bones may be associated with a low-lying tegmen mastoid, a relatively anteriorly placed sigmoid sinus, or prominent jugular bulb [16, 17], for example, making the surgical approach increasingly precarious [15].

However, the degree and the extent to which the mastoid and entire TB are pneumatized vary among individuals in the same or different population settings [6, 7, 11, 18–21]. According to hereditary theory, the size and the degree of mastoid pneumatization are genetically determined [4]. At the same time, the environmental theory states that how a mastoid is pneumatized solely depends on the degree of pathologic involvement of the middle ear during childhood [20, 22, 23]. Based on these theories, different individuals are expected to exhibit different degrees of mastoid pneumatization in their TBs. Hence, recognizing and classifying different pneumatization patterns are highly important in otology for teaching, diagnosis, and surgical planning.

Very few studies have been identified to classify the degree of pneumatization in TB into Grades, Groups, and Types utilizing computed tomography (CT) scans of the TB [7, 11, 20, 21, 24, 25]. The advent of CT (high resolution) scanning in the 1980s and its uses stirred up diagnostic imaging of the TB and ear structures [26]. This is because CT scanning offers the greatest structural definition of any recently available imaging modality [27, 28]. For instance, TB CT aids in surgical planning and is likely to be useful in evaluating CSF leak risk after surgical base surgery [29].

Of these very few studies, only Han et al. [20] utilized reference structure and specific (anatomical) landmarks to which the degree of mastoid pneumatization was classified. However, the method of Han et al. [20] could be time-consuming and a burden for otologists in a few otologic surgeries, such as primary mastoidectomies, as it involves applying three arbitrary parallel lines angled at 45° in the anterolateral direction, with each line crossing the most anterior point of the sigmoid sinus at the junction with the petrous bone, the most lateral aspect along the transverse plane of the sigmoid groove, and the most posterior point of the sigmoid sinus, respectively.

Furthermore, there was no specific landmark to which the vertical plane for which the three parallel lines are drawn to be angled at 45°, resulting in inaccuracy, especially in axial CT not presented in a straight plane. Therefore, the present study was undertaken to suggest a simple, quick, and less-burden classification system for assessing and rating the degree of pneumatization by comparing two levels of TB computed tomograms using the SS as a reference in an inter-observer assessment among otologists.

Methods

Study population

This was a randomized pilot survey among twenty-five (25) cohort otologists comprising registrars and specialists in the Kwazulu-Natal (KZN) province of South Africa. According to the South African Society of Otorhinolaryngology-Head and Neck Surgery (SA Society of ORL-HNS), the sample size used for this pilot survey represents 50% of active and registered Otorhinolaryngologists in KZN, South Africa, excluding emeritus and retirees (Table 1).

Table 1 Total number of active and registered otorhinolaryngologists in Kwazulu-Natal, South Africa (Source: Administrative Office, SA Society of ORL-HNS, 2022)

	Kwazulu-Natal	South Africa
Specialists/surgeons	34	226
Registrars	16	70
Total	50	296

Ethical approval

This was obtained from the Biomedical Research Ethics Committee of the University of KwaZulu-Natal (Protocol Ref. No.: BREC/00002263/2020) and the National Health Research Committee of the Kwazulu-Natal Department of Health (NHRD Ref.: KZ_202102_026).

The instrument for data collection

A questionnaire that consists of three sections was designed to retrieve data from participants. This questionnaire was constructed after consultation with the Biostatistician of the College of Health Sciences, the University of KwaZulu-Natal, and afterward subjected to face and content validity.

Questionnaire description

Section "Introduction" consisted of demographic items to retrieve participants' biodata. Section "Methods" consisted of different axial CT images of TB taken at two levels: the level of malleoincudal junction (MIJ) and the level of the lateral semicircular canal (LSCC), showing different pneumatization patterns. These images were randomly placed on 8 separate pages of the questionnaire, with 4 images per page ($4 \times 8 = 32$ images). The terms "Hypo-, Moderate, Good, and Hyper-pneumatization" were listed as options for participants to rate their impressions on the degree of mastoid pneumatization of the TB images using the SS as a reference structure. The SS was selected as a reference structure according to Shatz and Sadé [30] and Han et al. [20], while the use of qualitative description of the degree of pneumatization was employed in other to strengthen the value of data obtained by standardizing the options into the 4 categories (Hypo, Moderate, Good, and Hyper) for further comparative analysis according to previous studies by Bronoosh et al. [18], Han et al. [20] and as well as recent studies of Aladeyelu et al. [31], Kang et al. [32], and Tan et al. [6]. Section "Results" consisted of a Likert scale to assess the level to which participants agree or disagree with the use of sigmoid sinus as a reference structure in evaluating mastoid pneumatization.

Image source

All TB CT images used in the questionnaire were sourced retrospectively from the picture archiving and communication systems (PACS) of public hospitals selected for this study in the Kwazulu-Natal province of South Africa. All sourced images were taken using a Multi-Detector row Computed Tomography (MDCT) Scanner (GE Revolution Evo 64 slice, 128 configuration, Milwaukee, Wisconsin, USA).

Image selections and preparations

Two radiographers were employed in the selection and preparation of images. Images were taken from patients with no ear disease or surgical history. Only scans of patients aged 20 years and above were considered (in other to ensure the completion of pneumatization). Demographically, patients were between the age range 20 and 35 years, of which 18 were males, and 14 were females, belonging to the following South African population groups; Black South African (25; 77%), Indian South African (5; 16%), and White South African (2; 7%).

Computed tomographs at the MIJ level using SS as a reference

Here, images were prepared using the classification system proposed by Han et al. [10]. At the axial section in which the malleoincudal complex appears like an ice-cream cone shape, three parallel lines were applied in the anterolateral direction angled at 45°, with each crossing the most anterior point of the sigmoid sinus at the junction with the petrous bone, the most lateral aspect along the transverse plane of the sigmoid groove, and the most common posterior point of the sigmoid sinus, respectively (Fig. 1). With the application of these lines, the degree of mastoid pneumatization was classified into four groups: Hypo-pneumatization—pneumatization that extends to the line drawn at the most anterior aspect of the SS (Fig. 1a); Moderate pneumatization—pneumatization that extends to the space between arbitrary lines drawn at the most anterior point and most lateral aspect of the sigmoid sinus (Fig. 1b); Good pneumatization—pneumatization that extends to the space between the lines drawn at the most lateral region and the most posterior point of the SS (Fig. 1c) and; Hyper-pneumatization—pneumatization that extends postero-laterally beyond the line drawn at the posterior point of the sigmoid sinus (Fig. 1d). After that, the arbitrary lines were removed before images were placed in the questionnaire (Fig. 2).

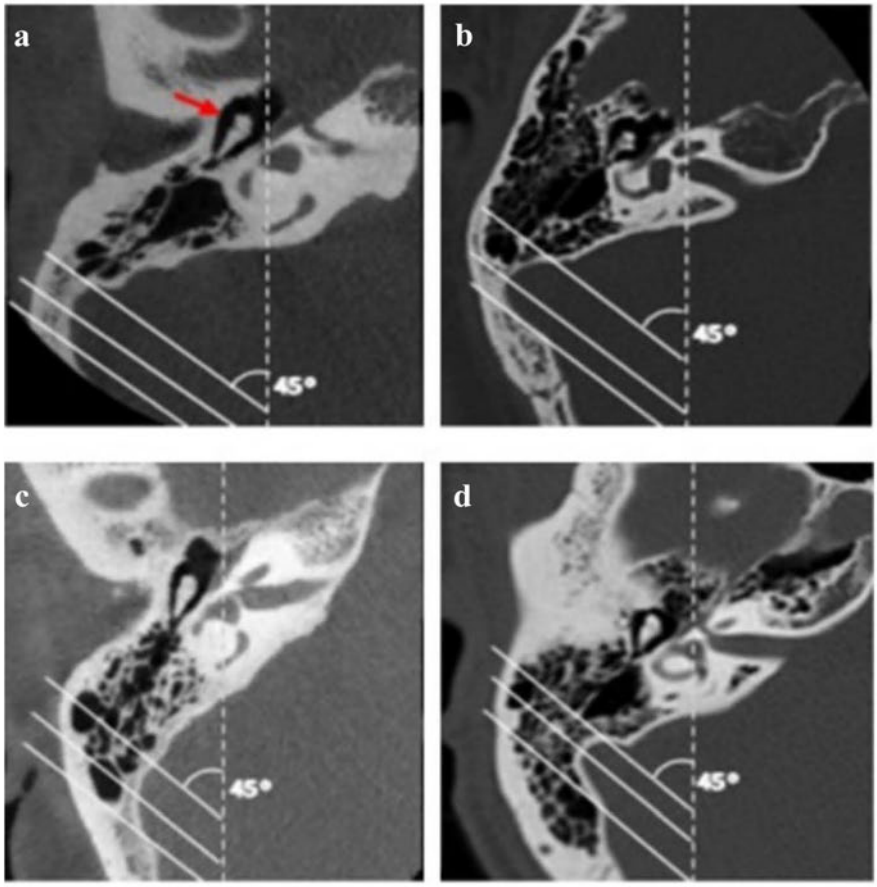

Fig. 1 Degrees of pneumatization using SS a reference structure according to Han et al. [10]. On the axial section where the malleoincudal complex (red arrow) appeared as an ice-cream-cone shape. Three parallel lines drawn angled at 45° to the anteroposterior axis (dotted line). **a** hypo-pneumatization, **b** moderate pneumatization, **c** good pneumatization, **d** hyper-pneumatization (Color figure online)

Computed tomographs at the LSCC level using SS as a reference

Here, images were prepared using this study's present suggested classification system. On the axial CT image at the level of the lateral semicircular canal (LSCC) level, the lateral convex or semicircular-shaped line/border of the sigmoid sinus was divided into three equal segments by two imaginary dots (gray dots); superior-lateral 1/3 (black arrow), lateral 1/3 (blue arrow), and inferolateral 1/3 (green arrow) (Fig. 3). The degree of mastoid pneumatization was classified as follows: hypo-pneumatization—when no air cells are found around any of the three segments of the lateral convex border of the sigmoid sinus (Fig. 3a); Moderate pneumatization—when air cells are found only in relation to the superior–lateral 1/3 segment and limited to this segment (Fig. 3b); Good pneumatization—when air cells are found in relation to both the superior–lateral 1/3 and the lateral 1/3 segments (Fig. 3c); Hyper-pneumatization—when air cells are found in relation to all three segments and even extend further after the inferolateral 1/3 (Fig. 3d). In addition, this classification system was verified by comparing each degree of mastoid pneumatization of the present suggested classification system with their corresponding degree of mastoid pneumatization in the classification system proposed by Han et al. [10] before using it to select CT images that were put in the questionnaire (Fig. 4).

Statistical analysis

The statistical analysis was conducted using R Statistical computing software of the R Core Team, 2020, version 3.6.3. Participants who correctly rated the degree of pneumatization of images taken at any of the two levels were expressed in counts and percentages. The mean and the mode were calculated for the Likert scale. Because of the small sample size, Fisher's exact test was used to compare the percentage of participants who correctly rated images taken at the level of the LSCC to the percentage of participants who correctly rated images taken at the level of the

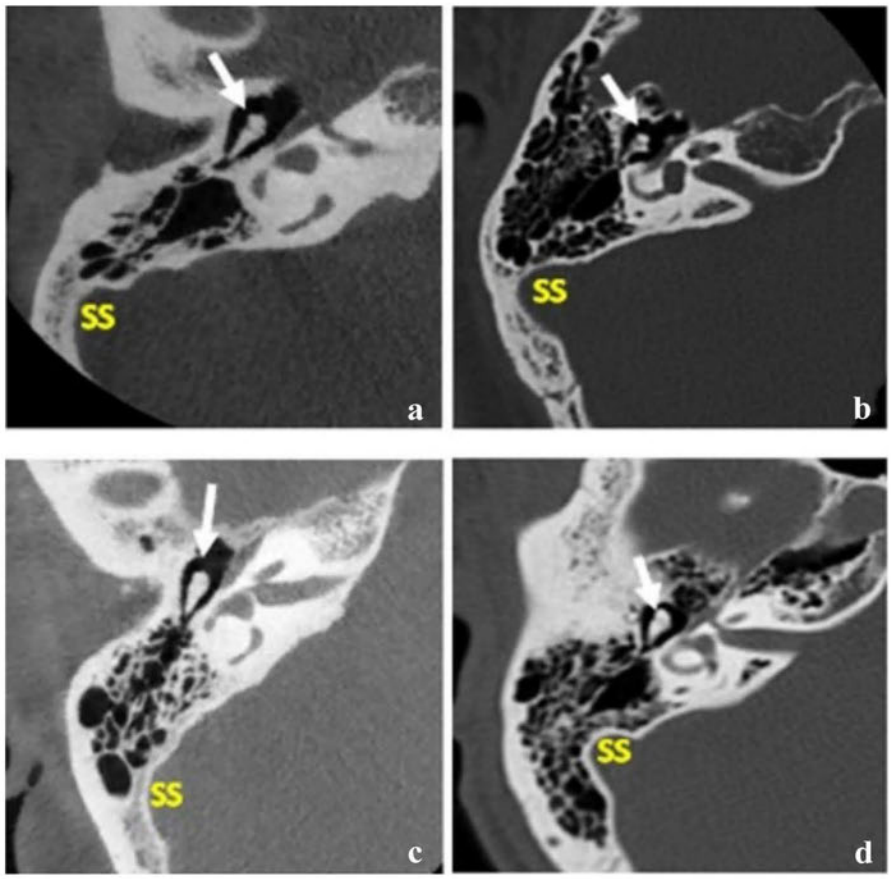

Fig. 2 A representation of axial CT images taken at the level of the MIJ (white arrow) used in the questionnaire showing different degrees of pneumatization after removing the arbitrary lines. **a** hypo-pneumatization; **b** moderate pneumatization; **c** good pneumatization; **d** hyper-pneumatization. *SS* sigmoid sinus (Color figure online)

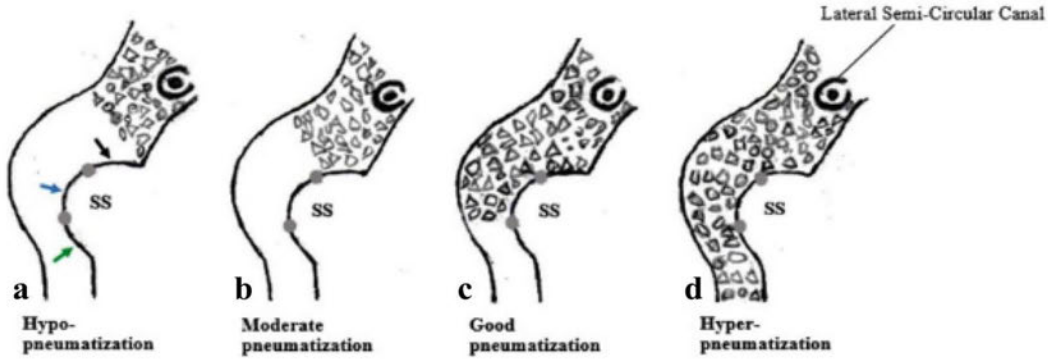

Fig. 3 Diagram showing the proposed classification system. SS—sigmoid sinus. Gray dots—2 imaginary dots. Black arrow—superior–lateral 1/3 segment. Blue arrow—middle–lateral 1/3 segment. Green arrow—inferolateral side 1/3 segment (Color figure online)

MIJ. Statistical significance was set at $p < 0.05$. Furthermore, a Likert Chart was plotted in a Python programming environment using Google Colab.

Results

A total of twenty-five questionnaires were distributed, and a 100% return rate was achieved. Among the otologists

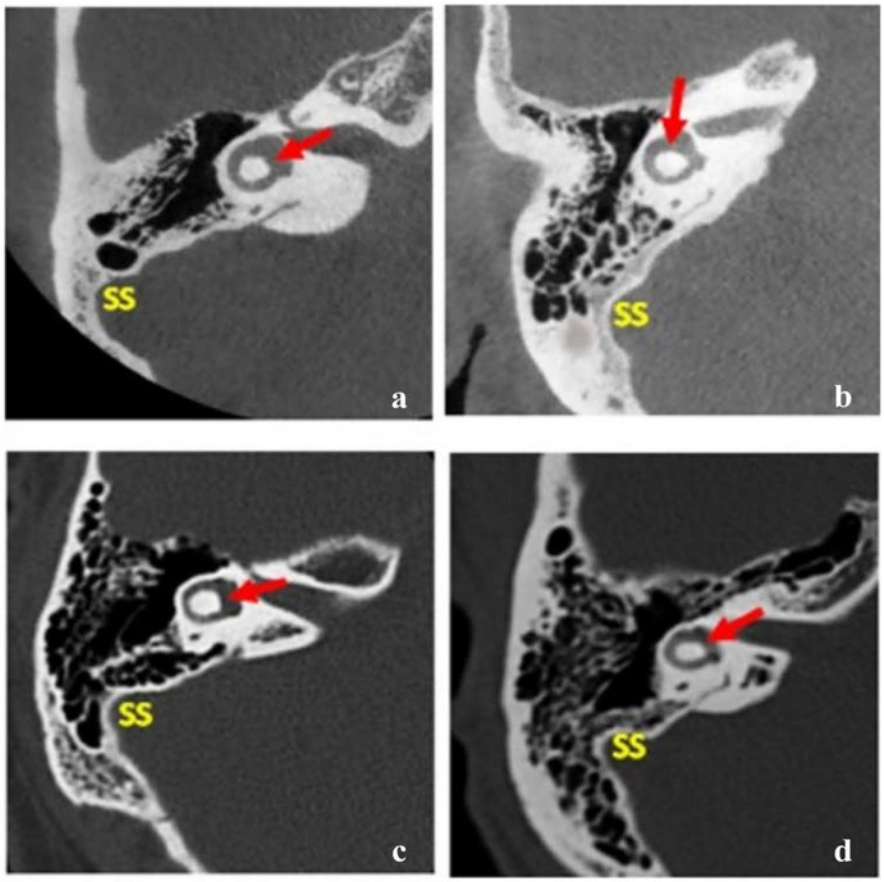

Fig. 4 A representation of axial CT images taken at the level of the LSCC (red arrow) used in the questionnaire showing different degrees of pneumatization after dividing the lateral convex or semicircular-shaped line/border of the sigmoid sinus into three equal segments using two imaginary dots. **a** hypo-pneumatization; **b** moderate pneumatization; **c** good pneumatization; d) hyper-pneumatization. *SS* sigmoid sinus (Color figure online)

who participated in the study, 64% were specialists, while 32% were registrars. In their year of experience as otologists, 36% have had 1–5 years of experience, 28% have had 6–10 years of experience, and 36% have had more than 11 years of experience. In their relative otology burden or TB-related surgeries monthly, 20% of the respondents encounter < 20% in a month, 56% encounter between 21 and 50% in a month, and 24% encounter > 51% in a month.

The result presented in Table 2 showed the percentage of participants that correctly rated the degree of pneumatization of axial images taken at the level of MIJ and LSCC. The total number of participants who correctly rated all images taken at the level of LSCC according to their respective degree of pneumatization was above 50%. For moderate, good, and hyper-pneumatized images, participants who correctly rated at the level of LSCC were more than participants who correctly rated these images at the level of MIJ, with

Table 2 Comparison between overall participants who correctly rated images at LSCC level and MIJ level

	Axial CTs sections taken at the level of LSCC No. of participants (%)	Axial CTs sections taken at the level of MIJ No. of participants (%)	*p* value
Hypo-pneumatized images	14 (56)	19 (76)	0.056
Moderately pneumatized images	13 (52)	3 (12)	0.014*
Good pneumatized images	18 (72)	5 (20)	0.003*
Hyper-pneumatized images	16 (64)	6 (24)	0.012*

*$p < 0.05$ shows significant differences in the total number of participants who correctly rated images taken at the level of LSCC when compared to images taken at the level of MIJ at different degrees of pneumatization

significant differences of $p < 0.05$. Participants who correctly rated hypo-pneumatized images taken at the level of MIJ were higher. Still, there was no significant difference ($p = 0.056$) when compared to the number of participants who correctly rated hypo-pneumatized images taken at the level of LSCC.

As per professional status, all participants in the two professional statuses contributed to the total percentage of participants who correctly rated all axial CT images taken at the level of LSCC, but specialists contributed more. The same was observed in the years of experience of participants, with the participants with the highest work experienced participants (> 11 years) contributing more (Table 3). As for axial CT images taken at the MIJ level, not all participants, as per professional status and years of experience, contributed to the overall percentage of participants who correctly rated images taken at this level (Table 4). Furthermore, comparing participants with the same year of experience in the rating of images at the LSCC level and MIJ level showed that in the different groups of year experience, more participants were able to rate correctly images taken at the level of LSCC (Table 5).

The level to which participants agree or disagree with using SS as a reference structure in the evaluation of mastoid pneumatization is presented in Fig. 5. The Likert scale was rated from 1 to 5: 1- strongly disagree, 2- disagree, 3- neutral, 4- agree, and 5- strongly agree. Statistically, participants' mean and mode responses were 3.6 and 4, respectively. The Likert-scale 4 (agree) was observed to have the highest frequency, with 48%. Generally, the Likert chart showed 76% positivity and 24% negativity.

Discussion

The degree of mastoid pneumatization of the TB is of various clinical significance, including implications on the pathogenesis of TB diseases and surgical implications and planning of a few otologic surgeries, such as primary mastoidectomies [8, 17, 29, 32]. It also can give the life history of an individual TB exposure to diseases and Eustachian tube function. This is because, on the one hand, a small mastoid pneumatization is a prerequisite of middle-ear disease. On the other hand, the extent of pneumatization mostly

Table 3 Percentage of participants who correctly rated images of axial sections taken at LSCC level based on professional demographics

Images	Percentage of participants (%)	Percentage as per professional status		Percentage as per years of experience		
		Specialist (%)	Registrar (%)	1–5 (%)	6–10 (%)	> 11 (%)
Hypo-pneumatized	56.0	36	20	12	20	24
Moderately pneumatized	52.0	40	12	12	12	28
Good pneumatized	72.0	52	14	20	20	32
Hyper-pneumatized	64.0	52	18	12	20	32

Table 4 Percentage of participants who correctly rated images of axial sections taken at MIJ level based on professional demographics

Images	Percentage of participants (%)	Percentage as per professional status		Percentage as per years of experience		
		Specialist (%)	Registrar (%)	1–5 (%)	6–10 (%)	> 11 (%)
Hypo-pneumatized	76.0	48	28	28	20	28
Moderately pneumatized	12.0	12	0	0	0	12
Good pneumatized	20.0	20	0	4	12	4
Hyper-pneumatized	24.0	20	0	4	4	16

Table 5 Comparison between participants who correctly rated images at LSCC level and MIJ level in relation to their year of experience

Images	Percentage as per year of experience between LSCC level and MIJ level					
	1–5 years		6–10 years		> 11 years	
	LSCC (%)	MIJ (%)	LSCC (%)	MIJ (%)	LSCC (%)	MIJ (%)
Hypo-pneumatized	12	28	20	20	24	28
Moderately pneumatized	12	0	12	0	28	12
Good pneumatized	20	4	20	12	32	4
Hyper-pneumatized	12	4	20	4	32	16

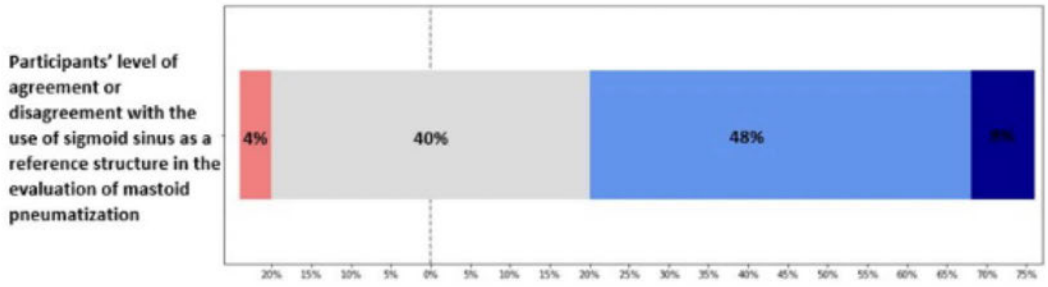

Fig. 5 Showing the level to which participants agree or disagree with the use of sigmoid sinus as a reference structure in evaluating mastoid pneumatization

depends on the degree of pathological involvement of the middle ear during childhood [20, 23]. Despite these, there is still a lack of consensus about the classification of TB pneumatization among otologists.

The present study utilized axial CT images of temporal bone taken at the level of MIJ and LSCC to conduct an interobserver assessment of the pneumatization of the temporal bone images among otologists utilizing the classification terms provided to rate the degree of mastoid pneumatization of the temporal bone using SS as a reference. The use of SS as a reference conforms to the study of Han et al. [20] and Shatz and Sadé [30].

More otologists were able to correctly rate axial CT images of TB taken at the level of LSCC according to the respective degree of mastoid pneumatization (with participants with the highest work experience and professional status contributing more), which was significantly higher when compared to the number of otologists who correctly rated corresponding axial CT images of TB taken at the level of the MIJ. It is worth noting that participants were blinded to the fact that axial CT images included in the survey were limited to 2 levels. In addition, the study also found that otologists with the lowest year of experience and professional status could correctly rate the degree of mastoid pneumatization of all axial CT images taken at the level of LSCC. This, however, reflects the simplicity and preciseness of this study's suggested new classification system, as less experienced doctors could also utilize this system in classifying the degree of mastoid pneumatization of the TB. It also reflects a high correlation between mastoid pneumatization and sigmoid sinus at this level, as reported by Shatz and Sadé [30]. This, however, could be easily utilized when reviewing CT images of TB prior to surgery as well-pneumatized TBs are possibly skeletonizing or exposing critical structures, such as facial nerve and labyrinth.

The Likert chart observed a high positivity in participants' level of agreement with the use of SS in evaluating mastoid pneumatization. This, however, agrees with Han et al. [20] on utilizing the SS as a reference structure since the evaluation of air cells around the sigmoid sinus could interpret the entire pneumatization of the TB. In addition, the extent of mastoid air cells was also reported by Yamakami et al. [29] and Hindi et al. [33] to correlate significantly to the pneumatization of the petrous apex and other parts of the TB.

Hence, estimating the degree of mastoid pneumatization using SS at the level of the LSSC as a reference point during surgical planning can be easily utilized by otologists in analyzing critical areas or structures that might be affected by varying degrees of pneumatization, such as the proximity of the facial nerve as well as the articular eminence of the temporo-mandibular joint (TMJ) to the canal in procedures, such as canaloplasty or subtotal petrosectomy [34, 35], as well as approaches to the sinus tympani and its relationship to the facial nerve and posterior semicircular canal (PSCC) [36].

Conclusion

This study conducted an interobserver assessment of mastoid pneumatization and classification of its degree of pneumatization using sigmoid sinus by comparing axial CT images taken at the level of MIJ and the level of LSCC among otologists. The result from this survey revealed that evaluating air cells around the SS on TB axial computed tomograms taken at the level of the LSCC was more precise among the participants regardless of their professional status and year of experience. This study hopes that the suggested new classification system (Fig. 3) could be generalized among otologists as it could be easier and less burdensome, assisting otologists in reviewing mastoid pneumatization before surgery in other to analyze critical structures that might be at risk.

Suggestions for future study

It is noteworthy that, following a thorough literature search, this is a novel approach reproducible in developing a classification system for the degree of mastoid pneumatization. Hence, the authors would like to allude to future studies such as: (i) Testing the repeatability of this suggested classification system in a new group of clinicians (including radiologists and surgeons) who are taught the classification beforehand and correlate with clinical disease entities such as cholesteatoma or otitis media effusion or chronic otitis media. (ii) Conducting a survey among clinicians to characterize the degree of pneumatization at different levels of CT images, including the MIJ and LSCC levels.

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Author contributions OSA, COR, W-BEM, and ALS conceptualized and designed the project; OSA and SKL developed the questionnaire; COR, W-BEM, and ALS reviewed and validated the questionnaire; OSA, SKL, and W-BEM collected data; OSA, SKL, and KS analyzed data; OSA, COR, KS, SKL, W-BEM, and ALS wrote and edited the manuscript.

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Data availability Available on request.

Declarations

Conflict of interest The authors declare that they have no competing interests.

Ethical approval The design was approved by the Institutional Review Board/Ethics Committee (Biomedical Research Ethics Committee of the University of KwaZulu-Natal with Ref. No.: BREC/00002263/2020) and the National Health Research Committee of the KwaZulu-Natal Department of Health (NHRD Ref.: KZ_202102_026).

Consent to participate This was obtained from each participant using a consent form.

References

1. Aladeyelu OS, Olaniyi KS, Olojede SO, Mbatha W-BE, Sibiya AL, Rennie CO (2022) Temporal bone pneumatization: a scoping review on the growth and size of mastoid air cell system with age. PLoS ONE 17(6):e0269360
2. Allam AF (1969) Pneumatization of the temporal bone. Ann Otol Rhinol Laryngol 78:49–64
3. Aoki K, Esaki S, Honda Y, Tos M (1990) Effect of middle ear infection on pneumatization and growth of the mastoid process. An experimental study in pigs. Act Otolaryngol 110(5–6):399–409
4. Diamant M (1940) Otitis and pneumatization of the mastoid bone. Acta Otolaryngol (Stockh) Suppl 41:1–149
5. Sethi A, Singh I, Agarwal AK, Sareen D (2006) Pneumatization of mastoid air cells: role of acquired factors. Int J Morphol 24(1):35–38
6. Tan DA, Ng JH, Lim SA, Low DY-M, Yuen HW (2018) Classification of temporal bone pneumatization of high-resolution computed tomography: prevalence, patterns, and implication. Otolaryngol Head Neck Surg 1:1–7
7. Koc A, Ekinci G, Bilgili AM, Akpinar IN, Yakut H, Han T (2003) Evaluation of the mastoid air cell system by high resolution computed tomography: three-dimensional multiplanar volume rendering technique. J Laryngol Otol 117:595–598
8. Lee D-H, Kim M-J, Lee S, Choi H (2015) Anatomical factors influencing pneumatization of the petrous apex. Clin Exp Otorhinolaryngol 8(4):339–344
9. Cinamon U (2009) The growth rate and size of the mastoid air cell system and mastoid bone: a review and reference. Eur Arch Oto-Rhino-L 266(6):781–786
10. Ilea A, Butnaru A, Sfrângeu SA et al (2014) Role of mastoid pneumatization in temporal bone fractures. Am J Neuroradiol 35(7):1398–1404
11. Jadhav AB, Fellows D, Hand AR, Tadinada A, Lurie AG (2014) Classification and volumetric analysis of temporal bone pneumatization using cone-beam computed tomography. Oral Surg Oral Med Oral Pathol Oral Radiol 117(3):376–384
12. Linder TE, Shah S, Martha AS, Röösli C, Emmett SD (2019) Introducing the "ChOLE" classification and its comparison to the EAONO/JOS consensus classification for cholesteatoma staging. Otol Neurotol 40(1):63–72
13. Sadé J, Fuchs C (1997) Secretory otitis media in adults: II. The role of mastoid pneumatization as a prognostic factor. Ann Otol Rhinol Laryngol 106(1):37–40
14. Baklaci D, Bilgin E, Çelik EK, Kılıç A, Erdem D, Eliçora SS (2022) Effects of mastoid and middle-ear volume on graft success and hearing outcomes in pediatric tympanoplasty. J Laryngol Otol 136(5):404–409
15. Galal A, Caruso A, Lauda L, Eldin OG, Baki F, Sanna M (2021) Effect of sigmoid sinus position on the difficulty and approaches to cochlear implantation surgery. J Int Adv Otol 17(1):23–29
16. Friedmann DR, Eubig J, McGill M, Babb JS, Pramanik BK, Lalwani AK (2011) Development of the jugular bulb: a radiologic study. Otol Neurotol 32(8):1389–1395

17. Singh V, Chaitanya DC, Chauchan BKS, Kumar IDV (2017) A comparative study of pneumatization of temporal bone. J Anat Soc India 66:78–81
18. Bronoosh P, Shakibafard A, Mokhtare MR, Rad TM (2014) Temporal bone pneumatization: a computed tomography study of pneumatized articular tubercle. Clin Radiol 69:151–156
19. Demirel O, Kaya E, Ucok CO (2014) Evaluation of mastoid pneumatization using cone-beam computed tomography. Oral Radiol 30:92–97
20. Han SJ, Song MH, Kim J, Lee WS, Lee H-K (2007) Classification of temporal bone pneumatization based on sigmoid sinus using computed tomography. Clin Radiol 62:1110–1118
21. Virapongse C, Sarwar M, Bhimani S, Sasak C, Shapiro R (1985) Computed tomographic anatomy of the temporal bone: normal pattern and morphology. AJR Am J Neuroradiol 145:473–481
22. Palva T, Palva A (1966) Size of the human mastoid air cell system. Acta Otolaryngol 62:237–251
23. Turgut S, Tos M (1992) Correlation between temporal bone pneumatization, location of lateral sinus, and length of the mastoid process. J Laryngol Otol 106:485e9
24. Al-Faleh W, Ibrahim ME (2005) A tomographic study of air cell pneumatization of the temporal components of the TMJ in patients with temporomandibular joint disorders. Egypt Dent J 51:1835–1842
25. Marchioni D, Soloperto D, Colleselli E, Tatti M, Patel N, Jufas N (2016) Round window chamber and fustis: endoscopic anatomy and surgical implications. Surg Radiol Anat 38:1013–1019
26. Redleaf M (2022) CT scan of the temporal bone. Available from: emedicine.medscape.com/article/875593-overview. Accessed 13 June 2022
27. Fujii N, Inui Y, Katada K (2010) Temporal bone: correlation of multiplanar reconstruction sections and three-dimensional computed tomography images. Jpn J Radiol 28(9):637–648
28. Schwab SA, Eberle S, Adamietz B et al (2012) Comparison of 128-section single-shot technique with conventional spiral multisection CT for imaging of the temporal bone. AJNR Am J Neuroradiol 33(4):E55–E60
29. Yamakami I, Uchino Y, Kobayashi E, Yamaura A (2003) Computed tomography evaluation of air cells in the petrous bone: relationship with postoperative cerebrospinal fluid rhinorrhea. Neurol Med Chir 24:334–339
30. Shatz A, Sadé J (1990) Correlation between mastoid pneumatization and position of the lateral sinus. Ann Otol Rhinol Laryngol 99(2):142–145
31. Aladeyelu OS, Olojede SO, Lawal SK, Mbatha WBE, Sibiya AL, Rennie CO (2023) Influence of pneumatization on morphology of temporal bone-related vasculatures and their morphometric relationship with ear regions: a computed tomography study. Sci Rep 13(1):1996
32. Kang TK, Ha R, Oh JH, Sunwoo W (2019) The potential protective effects of temporal bone pneumatization: a shock absorber in temporal bone fracture. PLoS ONE 14(5):e0217682
33. Hindi K, Alazzawi S, Raman R, Prepageran N, Rahmat K (2014) Pneumatization of mastoid air cells, temporal bone, ethmoid and sphenoid sinuses: any correlation? Indian J Otolaryngol Head Neck Surg 66:429–436
34. Heim N, Götz W, Reich RH, Faron A (2018) The prevalence of pneumatized articular eminence in the temporal bone. Do we need a high resolution computed tomography-based novel risk classification for eminectomy? J Craniomaxillofac Surg 46(12):1996–2002
35. Merati M, Kazemi MA, Dabiri S, Kouhi A (2021) Radiologic evaluation of the mastoid segment of the facial nerve tract in the intact temporal bone. Surg Radiol Anat 43:145–151
36. Wojciechowski T, Bartoszewicz R, Szopiński K (2023) Sinus tympani revisited for planning retrofacial approach—radiologic study in pneumatized temporal bones and its surgical implications. Eur Arch Otorhinolaryngol 280:1089–1099

CHAPTER SIX
SYNTHESIS, CONCLUSION, AND RECOMMENDATION

6.1 Synthesis

Despite the postulation of the genetic and environmental theories of temporal bone pneumatization, the following controversies still exist: i) the relationship between the growth and size of mastoid air cells and chronic middle-ear diseases such as OM, either as a cause or consequence; ii) the influence of pneumatization on the morphology of temporal bone-related vasculatures such as SS, JB, and ICA and their morphometric relationship with ear regions; and iii) lack of consensus in the classification of temporal bone degree of pneumatization (Diamant, 1940; Todd, 1987; Koc *et al.,* 2003; Sirikci *et al.,* 2004; Han *et al.,* 2007; Friedmann *et al.,* 2011; Singh *et al.,* 2017; Singh *et al.,* 2019). Furthermore, studies on some of these controversies remain scarce, especially in South Africa. These controversies, therefore, necessitate finding the relationship between the size of air cells and age, the extent of influence of temporal bone pneumatization on temporal bone-related vessels, and proposing a simple classification of the degree of temporal bone pneumatization. The aim of this study was to assess the pneumatization of the temporal bone, investigating the volume of air cells developmentally (postnatal) with age, its degree of mastoid pneumatization, and its relationship with anatomical variations of some of its related vasculature utilizing HRCT scans in their finest slices that offers the greatest structural definition of temporal bone air cells, ear structures, and related vasculatures. A 3D reconstruction volumetric analysis of air cells was also utilized.

From the scoping review conducted, the development of temporal bone pneumatization postnatally was suggested to be classified into three stages: infantile, transitional, and adult stages. Limited studies (n= 9) were able to document the size of air cells with age in terms of area and volume (Diamant, 1940; Kawamura *et al.,* 1963; Rubensohn, 1965; Arora *et al.,* 1973; Qvarnberg, 1981; Chatterjee *et al.,* 1990; Isono *et al.,* 2003; Lee *et al.,* 2005; Hill, 2011). Information retrieved suggests that the size of air cells follows a linear growth pattern from age 1 to 6 years, followed by a rapid increase in size from age 6 years until puberty and slow, steady growth from puberty until early adulthood. However, this contradicts the review and reference study of Cinamon (2009), who suggested a slower increment in the size of air cells up to adult size at puberty but did not elaborate on the growth rate from puberty to early adulthood. Furthermore, information retrieved

from the scoping review also suggests variations in the size of temporal bone air cells with age according to sex and population group. These include females having larger air cells with a significant increase with age than males. These studies also suggested that the growth of air cells terminate at early puberty, late puberty, age 20, or the third decade of life (Diamant, 1940; Rubensohn 1965; Arora *et al.,* 1973; Chatterjee *et al.,* 1990; Isono *et al.,* 2003; Lee *et al.,* 2005).

However, some significant limitations were identified in the reviewed studies. Volumetric measurements, which likely give the foremost comprehensive insight into appreciating the estimate size of mastoid air cells over the surface area (because it measures 3D space), were limited to three studies (Isono *et al.,* 2003; Lee *et al.,* 2005; Hill, 2011). Of these three studies, information is still lacking on pediatric (up to age 5) air cell volume and in the three suggested stages of postnatal development of temporal bone pneumatization owing to the large age grouping employed by Lee *et al.* (2005) and inconsistent age grouping employed by Isono *et al.* (2003) and Hill (2011). In addition, none of these identified studies were conducted in Africa, a region with the second-largest prevalence of disabling hearing loss among children, of which chronic OM is a major cause.

6.1.1 The volume of temporal bone pneumatization from early childhood to early adulthood. The present study provided information on the volumetric size of air cells in healthy temporal bones at every stage of human postnatal development, ascertaining its growth rate and completion stage in adult life. The average volumes temporal bone pneumatization of infants, children, adolescents, and adults obtained in the South African population were higher than the previous reports (Jadhav *et al.,* 2014; Lee *et al.,* 2005; Hill, 2011; Isono *et al.,* 1999; Isono *et al.* 2003; Luntz *et al.* 2001; Koc *et al.* 2003; Kim *et al.* 2010). This discrepancy may be due to the different study population or technical characteristics since the present study utilized a 3D computer-based volumetric rendering technique on ≤ 0.6 mm slice thickness of CT images, giving more detailed volumetric information than previous literature.

The study also revealed that the average air cell volumetric size of temporal bone pneumatization in the South African population was higher than other age-related studies reported in Japanese, Korean, and Colombian populations (Isono *et al.,* 2003; Lee *et al.,* 2005; Hill, 2011). The temporal bone pneumatization with average volumes of 1920 mm^3 in pediatrics and 4510 mm^3 in young children indicates that pneumatization of the temporal bone is expected to follow a rapid growth during childhood. These augment the reports of Sethi *et al.* (2006) and Knipe and Hacking (2014)

that air cells are readily visible after birth and immediately begin to increase in size and extent. Any deviation from the normal size and growth rate of temporal bone pneumatization reported for this population during childhood could perhaps indicate pathology of the ME between the infantile stage (>2 years) and transitional stage (2-5 years). This is according to the environmental theory identifying that the degree of pathologic involvement of the ME during childhood influences the size and growth of mastoid pneumatization with age (Palva & Palva, 1966; Turgut & Tos, 1992; Han *et al.,* 2007).

As regards the growth rate in the size of air cells and cessation of pneumatization according to postnatal stages of human development in the study population, the volume of temporal bone pneumatization was observed to continue a significant linear increase until young adult stage I (19-25 years) and reduction in the volume of air cells, as well as a cessation in pneumatization in young adult stage II (26-35 years). This contradicts the previous reports about pneumatization terminating at puberty (Diamant, 1940; Arora *et al.,* 1973; Qvarnberg *et al.*, 1981). Although, these reports were identified to have utilized planimetric measurements, only giving information on the surface area of air cells, not volume. However, this concurs with the previous study that linked age-related changes to reduced air cells (Wright *et al.* 1987). Temporal bone pneumatization gives a protective function, acting as a shock absorber to direct trauma to the lateral skull base (Kang *et al.,* 2019). The reduction in air cells and termination of temporal bone pneumatization observed in young adult stage II diminishes its protective functions. This reflects the increased incidence of skull-based fractures (15.2%) among adults under 40 years of age (80.2% of the incidence) reported by Makolane *et al.* (2019) in South Africa following vehicle-pedestrian accidents, falls, and violence.

Also, a significant increase ($p<0.001$) in pneumatization volumes in different age groups relative to sex was observed in this study. The females showed a much earlier rapid increase in the volume of temporal bone pneumatization before the onset of puberty (6-9 years), which is similar to the report of Diamant (1940), which utilized surface area, and Hill (2011), that measured both surface area and volumes. This may, however, be linked to early puberty in females. However, the males were observed to have a larger increase in pneumatization at late puberty up to the young adult stage I, similar to the previous study by Chatterjee *et al.* (1990) that utilized planimetric measurements of temporal bone pneumatization. This implies that the development of temporal

bone pneumatization is more rapid in adolescent females, with the females first attaining adult size before adolescent males in the study population.

Furthermore, the present study also noted variations in the volume of air cells with age among population groups within the study population; Black South Africans (of indigenous African origin or Native group), White South Africans (of European ancestry), and Indian South Africans (of Asian descent). Although their pediatric volumes were about the same size with a rapid increase in volume during childhood development, the volume of temporal bone pneumatization was observed to increase significantly with age showing a rapid linear growth up to the young adult stage I among the Black South Africans. The significant increase in the volume of pneumatization observed from the young child to adult stage I conforms with the increase in the volume of paranasal air sinus in the same postnatal developmental stages in a South African population as reported by Rennie *et al.* (2017), with a correlation between pneumatization of mastoid air cells and paranasal air sinus been identified by Kim *et al.* (2010).

However, among the South African White and Indian population groups, the volume of temporal bone pneumatization followed a rapid increase from infant up to young child (3-5 years), followed by a slow increase up to the young adult stage I; thereafter, a plateau with no significant difference. This could be attributed to the small skull sizes, especially among the Indian South African population group, as the skull size influences the pneumatization of the temporal bone (Chatterjee *et al.,* 1990; Balzeau *et al.,*2006; Inal *et al.,* 2015). This augments the early study of Arora *et al.* (1973) among the Northern population of Indians that found the size of the temporal bone air cell system to have a value much less than that of the Swedish population, as reported by Diamant (1940). Arora *et al.* (1973) further assumed that this could be due to the smaller-sized cranial bones of the Indian sample. Although, there were no significant differences in the volume of temporal bone pneumatization within age groups among South African Indian and White population groups, a continuous increase in the pneumatization among these two population groups up to young adult stage II was observed and conformed with the previous study among the Korean population of Asian descent (Lee *et al.,* 2005).

6.1.2 Influence of pneumatization on the morphology of sigmoid sinus (SS), jugular bulb (JB), and internal carotid artery (ICA) and their morphometric relationship with ear regions.

Anatomical variations in the location and position of SS, JB, and ICA, closely related to the temporal bone and ear structures, are routinely encountered in clinical practice (Kawano *et al.,* 2000; Friedmann *et al.,* 2010). The variants of these vessels also have implications for the development of pathologic abnormalities such as encroachment on the structures of the ME or eroding into the inner ear and posing dangers in routine clinical practice and ear-related and mastoid surgeries (Schatz and Sade, 1990; Kawano *et al.,* 2000, Vachata *et al.,* 2010; Inal *et al.,* 2015). Among several factors, temporal bone pneumatization has been implicated as one of the factors influencing the relative morphology and location of blood vessels in relation to the ear regions (Sirikci *et al.,* 2004; Friedmann *et al.,* 2011; Osch *et al.,* 2019). Anatomical variations (morphologically and morphometrically) of these vessels were analyzed in the study population, and the degrees of temporal bone pneumatization were analyzed by evaluating air cells around the SS, according to Han *et al.* (2007).

In general, all degrees of pneumatization existed in the study population, with hyper-pneumatization having the highest incidence (37.9%) and hypo-pneumatization having the lowest incidence (15.2%), which is the same as reported by Tan *et al.* (2018) in the Singapore population. No significant difference was observed regarding age, laterality, and population group in the degree of pneumatization using this grading system. However, regarding sex, hyper-pneumatization was observed more in female temporal bones, while hypo-pneumatization was observed more in male temporal bones. This implies that males are more susceptible to temporal bone fractures, as indicated in the study of Makolane *et al.* (2019), which reported a male-to-female ratio of 3:1 in 15.2% incidence of lateral skull base fracture in the South African population.

The position and location of SS and JB to the EAC, ME, and IAC vary significantly ($p<0.05$) among individuals and between right and left ears, with significant associations ($p<0.05$, $p<0.01$) between degrees of pneumatization. All measured distances were highest in patients with hyper-pneumatized temporal bones. This was because distances between SS and JB and the selected ear regions were observed to be increased as pneumatization extends across each of the three parallel lines anterolaterally applied at angle 45^{o} that were utilized to classify the degree of pneumatization

in this study. According to Lima *et al.* (2013), mastoid surface area and volume follow a linear correlation. Hence, as pneumatization increases, the surface area also increases, which denotes the increase in distances observed between these vessels and ear regions as pneumatization increases. This novel finding could assist otologic surgeons in the positional relationship of these vessels with ear regions following a review of temporal bone and internal acoustic meatus CT images.

In the analysis of SS, JB and ICA variants, the SS and its variant shapes were observed in the different degrees of pneumatization. Although Ichijo *et al.* (1993) and Sirikci *et al.* (2004) in their studies found the half-moon-shaped SS to be the most common type of SS and ascribed it to a healthy and well-pneumatized mastoid, the present study identified the saucer-shaped SS to be more common in the study population with no significant association with age, sex, population group and degree of pneumatization. In contrast, half-moon-shaped SS was found more in patients with hypo-pneumatized temporal bone; however, there was no significant association with age, sex, population group and degree of pneumatization. The non-significant association between the degree of pneumatization and morphological shapes of the SS buttresses the suggestion of using the SS as a reference structure in classifying temporal bone pneumatization (Shatz & Sadé, 1990; Han *et al.,* 2007).

For JB and its anatomical variants, high jugular bulb (HJB) was the most common variant in this study population. This supports the claims of Friedmann *et al.* (2011) and Park *et al.* (2015) that HJB is the most common JB variant in a population. The HJB was significantly associated ($p<0.001$) with increasing pneumatization. An increase in the incidence of HJB was observed as pneumatization extends the three parallel lines, most significantly where pneumatization extends beyond the arbitrary line drawn at the most posterior point of SS (hyper-pneumatization) on the right (63.3%) and the left (51.4%). Like HJB, this study also observed a significant association between hyper-pneumatization and JB dehiscence.

The similarity in the significant association observed for HJB and JB dehiscence follows their anatomical relationship. According to Gaillard and Bickle (2008), HJB becomes a dehiscent JB when the sigmoid plate between high-riding JB and the ME is missing, allowing the JB to bulge into the ME cavity. This means that an individual with hyper-pneumatized temporal bone is at risk of having a dehiscent JB in the absence of the sigmoid plate, which is one of the common causes of pulsatile tinnitus (Erdogan *et al.,* 2017). Although JB abnormalities are rarely encountered

during ear surgeries, a high JB remains a recognized problem that can lead to brisk venous hemorrhage if the bulb is inadvertently opened (Fox *et al.,* 2017). Therefore, otologic surgeons should watch out for the possibility of a high-riding JB in patients with hyper-pneumatized temporal bones in the study population.

Also, the lower incidence of flat jugular bulb (FJB) compared to HJB observed in the study population with no association with age, sex and population groups contradicts the report of Vachata *et al.* (2010), who documented a higher incidence of FJB. However, the current study identified a significant association between decreasing pneumatization and the incidence of FJB, especially when pneumatization is limited to the first anteromedial line (i.e., hypo-pneumatization or nothing near this line). In this case, the mastoid contains more marrow than air cells (diploic) or may only contain dense bone, which could inhibit the formation of the bulb (Virapongse *et al.,* 1985; Hill, 2011).

The dehiscence of ICA was observed to occur with an incidence of 3.5% from the analyzed scans and was significantly associated with hyper-pneumatized (extensively pneumatized) temporal bone. In extensive pneumatized temporal bone, pneumatization spreads to the petrous apex, where the ICA is seen to exit the carotid canal into the foramen lacerum to enter the skull (Standring, 2008; Schmalfuss, 2018). This study found that the transition of the bony petrous into air cells in an extensive pneumatized could result in dehiscence of the ICA due to the loss of bony elements.

Notably, in Otolaryngology, most of these vascular variants can result in ear disturbances and dysfunction (Low *et al.,* 1995). Although ME disease such as chronic OM is one common cause of hearing loss, HJB, for instance, when associated with diverticulum or dehiscence high-riding JB, has been reported to result in sensorineural hearing loss, conducting hearing loss, and Meniere-like syndrome (a disorder of inner ear that can lead to dizzy spell and hearing loss common to the left ear) due to compression of the inner ear (Jahsdoerfer *et al.,* 1981; Hannell *et al.,* 1987; Low *et al.,* 1995; Hitier *et al.,* 2014; Koo *et al.,* 2018; John Hopkins Medicine, 2022). The high incidence of HJB and JB dehiscence reported in this study due to increased pneumatization, which is most common (hyper-pneumatization- 37.9%) in the study population, could also contribute to hearing impairment in children, teenagers, and adults in the South African population.

6.1.3 Classification of temporal bone degree of pneumatization using reference structures and landmarks.

The pneumatization of temporal bone is relevant in various clinical circumstances aside from its protective function and implication in the onsite of chronic ear disease. It plays an important role in surgical intervention in this region of the skull. These include surgical planning for bone conduction implants, active ME implants, and even cochlear implantation when assessing the space required for implant placement or predicting access to the ME via trans-mastoid, retro-facial approaches (Galal *et al.,* 2021). For instance, when considering implantable hearing devices, such as Bone Bridge devices, that require an approach through the mastoid, a certain volume of air cells is required for placement within the mastoid. In addition, poorly pneumatized or 'contracted' temporal bones may be associated with a low-lying tegmen mastoid, a relatively anteriorly placed SS, or a prominent JB, making the surgical approach increasingly precarious for otologic surgeons (Friedmann *et al.,* 2011; Galal *et al.,* 2021).

The present study utilized the SS as a reference structure on axial CT taken at the level of the (LSCC) to propose a simple, quick, and less burden classification of temporal bone degree of pneumatization. The use of SS as a reference conforms with the study of Shatz and Sadé (1990) and the suggestion of Han *et al.* (2007). With the use of a questionnaire, an inter-observer assessment was conducted among cohort otologists to compare how they correctly rate the degrees of mastoid pneumatization of the temporal bone axial CT images taken at the level of MIJ suggested by Han *et al.* (2007) and LSCC as proposed by the present study using SS as a reference structure and the two levels as landmarks. It is worth noting that participants were blinded to the fact that axial CT images included in the survey were limited to two levels. Hypo-, moderate-, good, and hyper-pneumatization were the terms for them to use in rating the degree of pneumatization of the temporal bone CT images.

More otologists were able to rate correctly axial CT images of temporal bone taken at the level of LSCC according to the respective degree of mastoid pneumatization (with participants with the highest work experience and professional status contributing more). This was significantly higher when compared to the number of otologists who correctly rated corresponding axial CT images of temporal bone taken at the level of the MIJ. Also, this survey found that otologists with the lowest year of experience and professional status could correctly rate the degree of mastoid

pneumatization of all axial CT images taken at the level of LSCC. This, however, reflects the simplicity and preciseness of this study's proposed classification system, as less experienced doctors could also utilize this system in classifying the degree of pneumatization of temporal bone. It also reflects a high correlation between mastoid pneumatization and SS at this level, as Shatz and Sadé (1990) reported. Hence, this classification method could be easily utilized when reviewing CT images of temporal bone before surgery, as well-pneumatized temporal bones are possibly skeletonizing or exposing critical structures such as ICA, facial nerve, and labyrinth.

Furthermore, the Likert chart used to assess participants' opinions on using SS as a reference structure in evaluating mastoid pneumatization observed a high positivity level of agreement. This, however, agrees with Han *et al.* (2007) on the utilization of the SS as a reference structure since evaluating air cells around the SS could interpret the entire pneumatization of the temporal bone and conform with the report of Yamakami *et al.* (2003) and Hindi *et al.* (2014).

6.2 Conclusion

The present study illustrated temporal bone pneumatization in its volumetric size regarding age in healthy subjects from 0 to 35 years, the classification of its degree of pneumatization, the incidence of related vascular variants, and the influence of pneumatization on these vascular variants in the South African population. Following an extensive literature review, it was evident that the current study utilized a more accurate method in evaluating temporal bone air cells and generally concludes that the pneumatization of a healthy temporal bone is expected to continue a significant linear increase up until at least the adult stage I (19-25 years) in the study population. In classifying the degree of temporal bone pneumatization, evaluating air cells around the SS on temporal bone axial CT images taken at the level of LSCC was observed to be simpler, concise, and less burden using hypo-, moderate, good, and hyper-pneumatization as rating terms. Finally**,** the current study also identified incidences of HJB, JB dehiscence, ICA dehiscence, and SS variant shapes in the study population and concludes that the degree of pneumatization influences only JB variants and ICA dehiscence, as well as the distances of SS and JB to ear regions.

6.3 Recommendations and future research

Following the clinical relevance of the technique employed in this study, i.e., CT imaging in its finest slices and advanced method, this study recommends its findings to be used in establishing a reference range of the expected size of temporal bone pneumatization in infants and children as

well as its development postnatally with age in the South African population. This study also recommends using the terms hypo, moderate, good, and hyper in classifying the degree of pneumatization of temporal bone by evaluating air cells around the SS on temporal bone axial CTs using the LSCC as a landmark among otologists. This will assist in the surgical planning of temporal bone-related surgeries when reviewing the mastoid pneumatization and vascular variants that could result in complications during and after surgical procedures.

Nevertheless, this study would like to suggest the following future studies: a comparative study between the pneumatization of temporal bones of healthy ears and temporal bones with middle-ear infection (or with any history of middle-ear disease) among infants/children; a study on the morphological shape (3D) of temporal bone pneumatization with age (from infants to adulthood); surveying the proposed classification system in a new group of clinicians (including radiologists and surgeons) who are taught the classification beforehand and correlating with clinical disease entities such as cholesteatoma or OM effusion or chronic OM.

6.4 Limitations of the study

A few limitations were encountered in this study:

- The inclusion criteria in this study limited the sample size of CT images, but the final sample size used was effective in detecting 80% power.
- The age group for adult stage II (26-35 years) was slightly too large. Unfortunately, this could not be sub-grouped as there is no assigned stage of human growth in literature at the time of this study that could allow any possible sub-grouping.

SUMMARY OF FINDINGS AND CONTRIBUTION TO KNOWLEDGE.

- During childhood development, the volume of temporal bone air cells increased rapidly in infants in the South African population. This makes provision for the lacking information regarding pediatric normal temporal bone pneumatization and could serve as a key indicator in probing the onset of ME infection in children in South Africa.
- At adult stage II (26-35 years), pneumatization of the temporal bone terminates as the volume of air cells begins to experience a decline. This reflects one of the causes of increased head trauma cases common in young adults from 26 years and beyond in the study population.

- Hyper-pneumatization was observed to be the most common degree of pneumatization in the study population and was strongly associated with incidences of HJB, JB dehiscence, and ICA dehiscence. These aberrant vasculatures are responsible for hearing dysfunction and, eventually, hearing loss with time, which could reflect the increased incidence of hearing problems in the study population.
- A high (31.85%) incidence of HJB was observed in this study population. This should be considered by otologic and head and neck surgeons when planning surgeries to avoid pitfalls detrimental to the outcome of the surgery.
- An increase in the degree of pneumatization also increases the distances of SS and JB to ear regions. Otologic surgeons should also take note of this when planning related surgeries.
- Classifying the degree of temporal bone pneumatization into hypo, moderate, good, and hyper by evaluating air cells around the SS at the level of LSCC on axial CT was found suitable and could be standardized among otologic surgeons.
- Finally, the inter-observer method used to validate this classification system's simplicity, conciseness, and accuracy is a novel approach and could serve as a template for further studies.

REFERENCES

Arora, M.M.L., Sain, U. & Sodhi, J.S. (1973). Mastoid pneumatization in children—a roentgenographic planimetric study. *Indian Journal of Otolaryngology,* 25:87–90

Balzeau, A, Girmaud-Herve, D. & Semah, F. (2006). Characteristics and variation of the temporal bone pneumatization in Asian Homo errectus. *EurASEAA, Bougon papers,* 21–27.

Bronoosh, P., Shakibafard, A., Mokhtare, M.R. & Rad, T.M. (2014). Temporal bone pneumatisation: A computed tomography study of pneumatized articular tubercle. *Clinical Radiology,* 69: 151–156.

Chatterjee, D., Ghosh, T.B. & Ghosh, B.B. (1990). Size variation of mastoid air cell system in Indian people at different age groups: a radio-graphic planimetric study. *Journal of Laryngology and Otology,* 104: 603–605.

Cinamon, U. (2009). The growth rate and size of the mastoid air cell system and mastoid bone: A review and reference. *European Archives Oto-Rhino-Laryngology,* 266(6): 781–786.

Demirel, O., Kaya, E. & Ucok, C.O. (2014). Evaluation of mastoid pneumatization using cone-beam computed tomography. *Oral Radiology*, 30: 92–97.

Diamant, M. (1940). Otitis and pneumatization of the mastoid bone. *Acta Otolaryngologica,* 41.

Erdogan, H., Arslan, S., Arslan, F.Z., Durmaz, M.S. & Cengiz, A. (2017). Dehiscent high jugular bulb. *Clinical Medical Image Library*, 3: 065.

Fox, R., Nash, R. & Tatler, T. (2017). Encountering a high jugular bulb during ear surgery. *Annals of the Royal College of Surgeons of England,* 99(1): 36–37.

Friedmann, D.R., Eubig, J., McGill, M., Babb, J.S., Pramanik, B.K. & Lalwani, A.K. (2011). Development of the jugular bulb: a radiologic study. *Otology and Neurology,* 32(8): 1389–1395.

Friedmann, D.R., Thuy, L.B., Pramanik, B.K. & Lalwani, A.K. (2010). Clinical Spectrum of Patients with Erosion of the Inner Ear by Jugular Bulb Abnormalities. *Laryngoscope*, 120: 365 – 372.

Fujii, N., Inui, Y. & Katada, K. (2010). Temporal bone: correlation of multiplanar reconstruction sections and three-dimensional computed tomography images. *Japanese Journal of Radiology,* 28(9): 637–648.

Gaillard, F. & Bickle, I. (2019). Dehiscent jugular bulb. Reference article, Radiopaedia.org. (Assessed on 28 Mar 2022).

Galal, A., Caruso, A., Lauda, L., Eldin, O.G., Baki, F. & Sanna, M. (2021). Effect of sigmoid sinus position on the difficulty and approaches to cochlear implantation surgery. *The Journal of International Advanced Otology,* 17(1):23–29.

Han, S.J., Song, M.H., Kim, J., Lee, W.S. & Lee, H.-K. (2007). Classification of temporal bone pneumatization based on sigmoid sinus using computed tomography. *Clinical Radiology,* 62: 1110 – 1118.

Hannell, G. & Fagan, P. A. (1987). The clinical significance of jugular bulb anomalies. *The Australian Journal of Otolaryngology,* 6(1): 46–49.

Hill, C. A. (2011). Ontogenetic change in temporal bone pneumatization in humans. *Anatomical Record,* 294(7): 1103–1115.

Hindi, K., Alazzawi, S., Raman, R., Prepageran, N. & Rahmat, K. (2014). Pneumatization of mastoid air cells, temporal bone, ethmoid and sphenoid sinuses: any correlation? *Indian Journal of Otolaryngology- Head and Neck Surgery*, 66: 429–436.

Hitier, M., Barbier, C., Marie-Aude, T., Moreau, S., Courtheoux, P. & Patron, V. (2014). New treatment of vertigo caused by jugular bulb abnormalities. *Surgical Innovation*, 21(4): 365-371.

Ichijo, H., Hosokawa, M. & Shinkawa, H. (1993) Differences in size and shape between the right and left sigmoid sinuses. *European Archives of Oto-Rhino-Laryngology,* 250:297–9.

Inal, M., Muluk, N.B., Dag, E., Arikan, O.K. & Kara, S.A. (2015). The pitfalls and important distances in temporal bones HRCT of the subjects with high jugular bulb- Preliminary Review. *Advanced Clinical Experimental Medicine*, 24(2): 315–325.

Isono, M., Murata, K., Azuma, H., Ishikawa, M. & Ito, A. (1999). Computerized assessment of the mastoid air cell system. *Auris Nasus Larynx,* 26: 139–145.

Isono, M., Ito, A., Nakayama, K., Miyashita, H., Saito, K. & Murata, K. (2003). Computerized assessment of developmental changes in the mastoid air cell system. *International Congress Series,* 1254: 487–491.

Jadhav, A.B., Fellows, D., Hand, A.R., Tadinada, A. & Lurie, A.G. (2014). Classification and volumetric analysis of temporal bone pneumatization using cone beam computed tomography. *Oral Surgery*, *Oral Medicine*, *Oral Pathology and Oral Radiology*, 117(3): 376–84.

Jahsdoerfer, R.A., Cail, W.S. & Cantrell, R.W. (1981). Endolymphatic duct obstruction from a jugular bulb diverticulum. *Annals of Otology, Rhinology & Laryngology,* 90: 619–623.

John Hopkins Medicine (2022). *Meniere disease: What is Meniere disease?* Retrieved from hopkinsmedicine.org/health/conditions-and-disease/menieres-disease.

Kawamura, S., Okabe, K., Mogi, S. & Terao, A. (1963). The normal development of the mastoid pneumatic cells. *Nippon Jibiinkoka Gakkai Kaiho,* 66: 909–912.

Kawano, H., Tono, T., Schachern, P.A., Paparella, M.M. & Komune, S. (2000). Petrous high jugular bulb: A histological study. *American Journal of Otolaryngology,* 21: 161–168.

Kim, J. Song, S.W., Cho, J-H., Chang, K-H. & Jun, B.C. (2010) Comparative study of the pneumatization of the mastoid air cells and paranasal sinuses using three-dimensional reconstruction of computed tomography scans. *Surgical and Radiologic Anatomy,* 32: 593–599.

Knipe, H. & Hacking, C. (2014 Mar 23) Mastoid air cells. Reference article, Radiopaedia.org. [revised 2021 Nov 19; accessed 2021 Dec 26]. Available from: https://doi.org/10.53347/rID-28366.

Koc¸ A., Ekinci, G., Bilgili, A.M., Akpinar, I.N., Yakut, H. & Han, T. (2003) Evaluation of the mastoid air cell system by high resolution computed tomography: three-dimensional multiplanar volume rendering technique. *The Journal of Laryngology & Otology*, 117**:** 595–598.

Koo, Y.H., Lee, J.Y., Lee, J.D. & Hong, H.S. (2018). Dehiscent high-riding jugular bulb presenting as conductive hearing loss: A case report. *Medicine (Baltimore)*, 97(26): e11067.

Lee, D.-H., Jun, B.-C., Kim, D.-G., Jung, M.-K. & Yeo, S.-W. (2005). Volume variation of mastoid pneumatization in different age groups: a study by three-dimensional reconstruction based on computed tomography images. *Surgical and Radiologic Anatomy,* 27: 37–42.

Lima, M.A.R., Farage, L., Cury, M.C.L. & Junior, F.B. (2013). Mastoid surface area-to-volume ratios in adult Brazilian individuals. *Brazilian Journal of Otorhinolaryngology,* 79(4): 446–453.

Low, W.K., Fenton, J.E., Fagan, P.A. & Gibson, W.P.R. (1995). The influence of race on the position of jugular bulb. *The Journal of Laryngology & Otology,* 109: 610–613.

Luntz. M., Malatskey, S., Tan, M. *et al.* (2001). Volume of mastoid pneumatization: three-dimensional reconstruction with ultrahigh-resolution computed tomography. *Annals of Otology, Rhinology and Laryngology,* 110: 486–490.

Osch, K.V., Allen, D., Gare, B., Hudson, T.J., Ladak, H. & Agrawal, S.K. (2019). Morphological analysis of sigmoid sinus anatomy: Clinical application to neurotological surgery. *Journal of Otolaryngology- Head and Neck Surgery,* 48:2.

Palva, T. & Palva, A. (1966). Size of the human mastoid air cell system. *Acta Otolaryngologica, (stockh),* 62: 237–251.

Park, J.J., Shen, A., Keil, S., Kuhl, C. & Westhofen, M. (2015). Jugular bulb abnormalities in patients with Meniere's disease using high-resolution computed tomography. *European Arch.ives of Oto-Rhino-Laryngology.,* 272(8): 1879–1884.

Qvarnberg, Y. (1981). Acute otitis media. A prospective clinical study of myringotomy and antimicrobial treatment. *Acta Otolaryngologica,* (Stockh) Suppl 375: 1–157.

Redleaf M. CT scan of the temporal bone. 2022 Jan 07 [accessed 2022 June 13]. Available from: emedicine.medscape.com/article/875593-overview.

Rennie, C.O., Haffajee, M.R. & Satyapal, K.S. (2017). Development of the paranasal air sinuses in a South African Population utilizing three-dimensional (3D) reconstruction model. *European Journal of Anatomy,* 21(3): 197–209.

Rubensohn, G. (1965) Mastoid pneumatization in children at various ages. *Acta Otolaryngologica,* (Stockh) 60: 11–14.

Schmalfuss, I.M. (2018). Petrous Apex. *In Chong. V, Skull Base Imaging (eds.).* Elsevier: Missouri, pp 233–245.

Schwab, S.A., Eberle, S., Adamietz, B., Kuefner, M.A., Kramer, M., Uder, M. *et al.* (2012). Comparison of 128-section single-shot technique with conventional spiral multi-section CT for imaging of the temporal bone. *AJNR American Journal of Neuroradiology*, 33(4): E55-E60.

Sethi, A., Singh, I., Agarwal, A.K. & Sareen, D. (2006). Pneumatization of mastoid air cells: Role of acquired factors. *International Journal of Morphology*, 24(1): 35–38.

Shatz, A. & Sadé, J. (1990). Correlation between mastoid pneumatization and position of the lateral sinus. *Annals of Otology, Rhinology & Laryngology,* 99(2):142–145.

Singh, V., Chaitanya, D.C., Chauchan, B.K.S. & Kumar, I.D.V. (2017). A comparative study of pneumatization of temporal bone. *Journal of the Anatomical Society of India,* 66: 78–81.

Singh, A., Kumar, I.D.V., Sikka, K., Verma, H. & Thakar, A. (2019). Study of sigmoid sinus variations in the temporal bone by micro dissection and its classification- a cadaveric study. *international archives of otorhinolaryngology,* 23: e311–e316.

Sirikci, A., Bayazit, Y.A., Kervancioglu, S., Ozer, E., Kanlikama, M. & Bayram, M. (2004). Assessment of mastoid air cells size versus sigmoid sinus variables with tomography-assisted digital image processing program and morphometry. *Surgical and Radiologic Anatomy,* 26: 145–148.

Standring, S. (2008). *Gray's Anatomy: The anatomical basis of clinical practice.* Edinburg: Churchill Livingstone.

Tan, D.A., Ng, J.H., Lim, S.A., Low, D.Y-M. & Yuen, H.W. (2018). Classification of temporal bone pneumatization of high-resolution computed tomography: Prevalence, patterns and implication. *Otolarynglogy-Head and Neck Surgery,* 1: 1–7.

Todd, N.W., Pitts, R.B., Braun, I.F. & Heindel, H. (1987). Mastoid size determined with lateral radiographs and computerized tomography. *Acta Otolaryngologica*, 103(5-6): 226–231.

Turgut, S. & Tos, M. (1992). Correlation between temporal bone pneumatization, location of lateral sinus and length of the mastoid process. *Journal of Laryngology and Otology,* 106: 485e9.

Vachata, P. Petrovicky, P. & Sames, M. (2010). An anatomical and radiological study of the high jugular bulb on high-resolution CT scans and alcohol-fixed skulls of adults. *Journal of Clinical Neuroscience,* 17: 473–478.

Virapongse, C., Sarwar, M., Bhimani, S., Sasak, C. & Shapiro, R. (1985). Computed tomographic anatomy of the temporal bone: 1. Normal pattern and morphology. *AJR America Journal of Roentgenology,* 145: 473–481.

Wright, A., Davis, A., Bredberg, G., Ulehlova´, L., Spencer, H., Bock, G., *et al.* (1987). Hair cell distributions in the normal human cochlea. A report of a European working group. *Acta Otolaryngologica*., 436: 15–24.

Yamakami, I., Uchino Y., Kobayashi, E. & Yamaura, A. (2003). Computed tomography evaluation of air cells in the petrous bone: relationship with postoperative cerebrospinal fluid rhinorrhea. *Neurologia Medico-Chirurgica. (Tokyo),* 24: 334–339.

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APPENDIX A

Ethical Approval

UNIVERSITY OF KWAZULU-NATAL
INYUVESI YAKWAZULU-NATALI

05 March 2021

Mr Okikioluwa Stephen Aladeyelu (219076039)
School of Lab Med & Medical Sc
Westville

Dear Mr Aladeyelu,

Protocol reference number: BREC/00002263/2020
Project title: Pneumatization of the temporal bone, its petromastoid part and related vasculature in a South African population from childhood to early adulthood: an anatomical and radiological study
Degree Purposes: PhD

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 05 March 2021 at Greys Hospital and IALCH only. Please ensure that outstanding site permissions are obtained and forwarded to BREC for approval before commencing research at a site.

This approval is subject to national and UKZN lockdown regulations, see (http://research.ukzn.ac.za/Libraries/BREC/BREC_Lockdown_Level_1_Guidelines.sflb.ashx). Based on feedback from some sites, we urge PIs to show sensitivity and exercise appropriate consideration at sites where personnel and service users appear stressed or overloaded.

This approval is valid for one year from 05 March 2021. To ensure uninterrupted approval of this study beyond the approval expiry date, an application for recertification must be submitted to BREC 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 (2006) (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 13 April 2021.

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

UNIVERSITY OF KWAZULU-NATAL
INYUVESI YAKWAZULU-NATALI

16 September 2021

Mr Okikioluwa Stephen Aladeyelu (219076039)
School of Laboratory Medicine & Medical Science
Westville

Dear Mr Aladeyelu,

Protocol reference number: BREC/00002263/2020
Project title: Pneumatization of the temporal bone, its petromastoid part and related vasculature in a South African population from childhood to early adulthood: an anatomical and radiological study
Degree Purposes: PhD

We wish to advise you that your response to BREC letter dated 19 August 2021 has been noted by a subcommittee of the Biomedical Research Ethics Committee. Your application for amendments (addition of questionnaire) received on 22 July 2021 for the above study has now been **approved** by a subcommittee of the Biomedical Research Ethics Committee

The committee will be advised of the above at its next meeting to be held on 12 October 2021.

Yours sincerely

[redacted]

Ms A Marimuthu
(for) Prof D Wassenaar
Chair: Biomedical Research Ethics Committee

UNIVERSITY OF KWAZULU-NATAL
INYUVESI YAKWAZULU-NATALI

16 September 2022

Mr Okikioluwa Stephen Aladeyelu (219076039)
School of Laboratory Medicine & Medical Science
Westville

Dear Mr Aladeyelu,

Protocol reference number: BREC/00002263/2020
Project title: Pneumatization of the temporal bone, its petromastoid part and related vasculature in a South African population from childhood to early adulthood: an anatomical and radiological study
Degree Purposes: PhD

RECERTIFICATION APPLICATION APPROVAL NOTICE

Approved:	**05 March 2022**
Expiration of Ethical Approval:	**04 March 2023**

I wish to advise you that your application for recertification received on 12 September 2022 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 11 October 2022.

Yours sincerely

[redacted]..

Ms A Marimuthu
(for) Prof D Wassenaar
Chair: Biomedical Research Ethics Committee

APPENDIX B

Department of Health Approval

KWAZULU-NATAL PROVINCE
HEALTH
REPUBLIC OF SOUTH AFRICA

DIRECTORATE:
Health Research & Knowledge Management Unit

Postal Address: Private Bag X9050
Physical Address: 330 Langalibalele Str; PM Burg; 3201
Tel: 0333953189/3123/2805 Fax: 033-3943782
Email address: hrkm@kznhealth.gov.za
www.kznhealth.gov.za

NHRD Ref: KZ_202102_026

Dear Mr O Aladeyelu
(UKZN)

Approval of research

1. The research proposal titled **'Pneumatization of the temporal bone, its petromastoid part and related vasculature in a South African population from childhood to early adulthood: an anatomical and radiological study'** was reviewed by the KwaZulu-Natal Department of Health (KZN-DoH).

   The proposal is hereby **approved** for research to be undertaken at Inkosi Albert Luthuli Central and Greys hospitals.

2. You are requested to take note of the following:

   a. *All research conducted in KwaZulu-Natal must comply with government regulations relating to Covid-19. These include but are not limited to: regulations concerning social distancing, the wearing of personal protective equipment, and limitations on meetings and social gatherings.*
   b. *Kindly liaise with the facility manager BEFORE your research begins in order to ensure that conditions in the facility are conducive to the conduct of your research. These include, but are not limited to, an assurance that the numbers of patients attending the facility are sufficient to support your sample size requirements, and that the space and physical infrastructure of the facility can accommodate the research team and any additional equipment required for the research.*
   c. *Please ensure that you provide your letter of ethics re-certification to this unit, when the current approval expires.*
   d. *Provide an interim progress report and final report (electronic and hard copies) when your research is complete to **HEALTH RESEARCH AND KNOWLEDGE MANAGEMENT, 10-102, PRIVATE BAG X9051, PIETERMARITZBURG, 3200** and e-mail an electronic copy to hrkm@kznhealth.gov.za*
   e. *Please note that the Department of Health shall not be held liable for any injury that occurs as a result of this study.*

For any additional information please contact Ms G Khumalo on 033-395 3189.

Yours Sincerely

[redacted]

Dr E Lutge
Chairperson, Health Research Committee
Date: 04/02/2021

APPENDIX C

Hospital Approvals

KWAZULU-NATAL PROVINCE
HEALTH
REPUBLIC OF SOUTH AFRICA

Private Bag X 9001, Pietermaritzburg, 3200
201 Town Bush Road, Northern Park, Pietermaritzburg, 3201
Tel: 0338973321 Fax: 0338973398

GREY'S HOSPITAL
OFFICE OF THE CEO

To:	**Mr. Okikioluwa Stephen Aladeyelu** **Discipline of Clinical Anatomy, UKZN**
From:	**Dr. K.B. Bilenge** **CEO - Greys Hospital**
Date:	**27 January 2021**
Re:	**Request for gatekeeper permission to conduct research at Grey's Hospital:** ***Pneumatization of the temporal bone, its petromastoid part and related vasculature in a South African population from childhood to early adulthood: an anatomical and radiological study***

Dear Mr. Aladeyelu

Your request to conduct research at Grey's Hospital refers.

Gatekeeper permission to conduct the above study is hereby granted under the following conditions:

- Final ethics approval is a prerequisite for conducting your study at our hospital. Once obtained, please submit a copy of the full and final ethics approval;
- You are also required to obtain approval for your study from the Provincial Department of Health KZN Health Research Unit **prior to commencement**. Once obtained, please submit a copy. You will find more information at: *http://www.kznhealth.gov.za/hrkm.htm*
- Confidentiality of hospital information, including staff and patient medical and/or contact information, must be kept at all times; **Patient/staff records are not to be removed from the hospital premises nor are you allowed to photocopy/ photograph them.**
- **You are to ensure that your data collection process will not interfere with the routine services at the hospital;**
- You are to ensure that hospital resources are not used to manage your data collection, e.g. hospital staff collecting and/or collating data; photocopying; telephone; facsimile, etc.;
- Informed consent is to be obtained from all participants in your study;
- Policies, guidelines and protocols of the Department of Health and Grey's Hospital must be adhered to at all times;
- Professional attitude and behaviour whilst dealing with research participants must be exhibited;
- The Department of Health, hospital and its staff will not be held responsible for any negative incidents and/or consequences, including injuries and illnesses that may be contracted on site, litigation matters, etc. that may arise as a result of your study or your presence on site.
- You are required to submit to this office a summary of study findings upon completion of your research.
- You are requested to make contact with **Dr. D. T. Reitz (HCD- Radiology)** at Grey's Hospital once you are ready to commence data collection.
- Please keep a copy of this approval on your person at all times whilst in the facility.

Supported by:

[redacted]

Dr L. Naidoo
Senior Manager: Medical Services

Supported by:

Dr. K. B. Bilenge
Hospital CEO

KWAZULU-NATAL PROVINCE
HEALTH
REPUBLIC OF SOUTH AFRICA

DIRECTORATE:

INKOSI ALBERT LUTHULI CENTRAL HOSPITAL
OFFICE OF THE MEDICAL MANAGER
Private Bag X03, Mayville, 4058
800 Vusi Mzimela (Bellair) Road, Mayville,4091
Tel: 031 240 1059 Fax: 031 240 1005 Email: Ursula.john@ialch.co.za

9 February 2021

Mr O S Aladeyelu (219076039)
School of Lab Med & Medical Sc
Westville

Dear Mr Aladeyelu

Re: Approved Research: Ref No: BREC/00002263/2020: Pneumatization of the temporal bone, its petromastoid part and related vasculature in South African population from childhood to early adulthood: and anatomical and radiological study.

As per the policy of the Provincial Health Research Committee (PHRC), you are hereby granted permission to conduct the above mentioned research once all relevant documentation has been submitted to PHRC inclusive of Full Ethical Approval.

Kindly note the following.

1. The research should adhere to all policies, procedures, protocols and guidelines of the KwaZulu-Natal Department of Health.
2. Research will only commence once the PHRC has granted approval to the researcher.
3. The researcher must ensure that the Medical Manager is informed before the commencement of the research by means of the approval letter by the chairperson of the PHRC.
4. The Medical Manager expects to be provided feedback on the findings of the research.
5. Kindly submit your research to:

   The Secretariat
   Health Research & Knowledge Management
   330 Langaliballe Street, Pietermaritzburg, 3200
   Private Bag X9501, Pietermaritzburg, 3201
   Tel: 033395-3123, Fax 033394-3782
   Email: hrkm@kznhealth.gov.za

Yours faithfully

.....

Dr A Harrichandparsad
Clinical Care Manager

KWAZULU-NATAL PROVINCE
HEALTH
REPUBLIC OF SOUTH AFRICA

DIRECTORATE:

INKOSI ALBERT LUTHULI CENTRAL HOSPITAL
OFFICE OF THE MEDICAL MANAGER
Private Bag X03, Mayville, 4058
800 Vusi Mzimela (Bellair) Road, Mayville,4091
Tel: 031 240 1059 Fax: 031 240 1005 Email: Ursula.john@ialch.co.za

Reference: BREC/00002263/2020
Enquiries: Medical Management

9 February 2021

Mr O S Aladeyelu (219076039)
School of lab Med & Medical Sc
Westville

Dear Mr O S Aladeyelu

RE: PERMISSION TO CONDUCT RESEARCH AT IALCH

I have pleasure in informing you that permission has been granted to you by the Medical Manager to conduct research on: **Pneumatization of the temporal bone, its petromastoid part and related vasculature in South African population from childhood to early adulthood: and anatomical and radiological study.**

Kindly take note of the following information before you continue:

1. Please ensure that you adhere to all the policies, procedures, protocols and guidelines of the Department of Health with regards to this research.
2. This research will only commence once this office has received confirmation from the Provincial Health Research Committee in the KZN Department of Health.
3. Kindly ensure that this office is informed before you commence your research.
4. The hospital will not provide any resources for this research.
5. You will be expected to provide feedback once your research is complete to the Medical Manager.

Y[redacted]

Dr A Harrichandparsad
Clinical Care Manager

APPENDIX D

Data Collection Sheet

MORPHOLOGY

Degree of Pneumatization

No.	Age	Sex	Race	Right				Left			
				Hypo	Moderate	Good	Hyper	Hypo	Moderate	Good	Hyper

Vascular Variants

-Jugular Bulb (JB)

No.	Age	Sex	Race	Right			Left		
				FJB	HJB	JB Dehiscence	FJB	HJB	JB Dehiscence

-Sigmoid Sinus (SS)

No.	Age	Sex	Race	Right					Left				
				SS-W (mm)	SS-D (mm)	Half-moon	Protrusive	Saucer	SS-W (mm)	SS-D (mm)	Half-moon	Protrusive	Saucer

-Internal Carotid Artery (ICA) Dehiscence

No.	Age	Sex	Race	Right	Left

MORPHOMETRY

Volume of air cell- 3D-volumetric reconstruction (mm^3)

No.	Age	Sex	Race	Right	Left

Vasculature (Linear) Measurement (mm)

No.	Age	Sex	Race	Right						Left					
				SS - EAC	SS – ME	SS – IAC	JB – IAC	JB – ME	JB – EAC	SS - EAC	SS – ME	SS – IAC	JB – IAC	JB – ME	JB – EAC

APPENDIX E

Questionnaire and Informed Consent

Section I: Demographic
Instruction: Please kindly tick in the box provided for each option

Discipline/Occupation: ( ) Ear, Nose & Throat Surgery ( ) Radiology

Years of Professional Experience: ( ) 1 to 5 years ( ) 6 to 10 years ( ) >11 years

Professional Status: ( ) Registrar ( ) Specialist

Relative otology burden in your typical work *(i.e., in your typical month of, what volume of your work involves otology and/or temporal bone review)*: ( ) < 20% ( ) 21 – 50% ( ) >51%

Section II: Classification

Instruction: Please kindly indicate your impression of the degree of pneumatization of the temporal bone in different images (axial section) of the temporal bone using the sigmoid sinus (SS) as reference with the classification terms provided below each image.

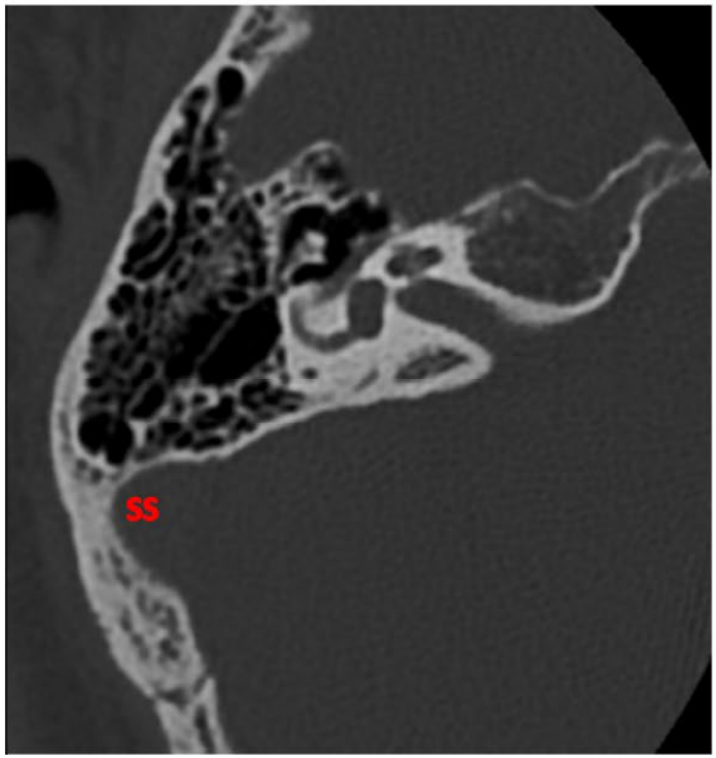

Image A

- ☐ **Hypo-Pneumatization**
- ☐ **Moderate pneumatization**
- ☐ **Good Pneumatization**
- ☐ **Hyper-pneumatization**

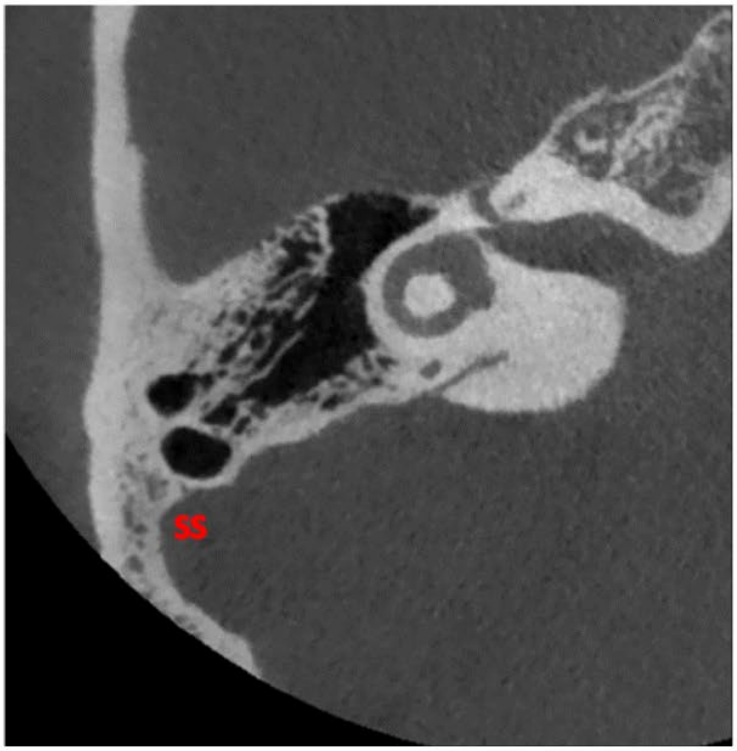

Image B

- ☐ **Hypo-Pneumatization**
- ☐ **Moderate pneumatization**
- ☐ **Good Pneumatization**
- ☐ **Hyper-pneumatization**

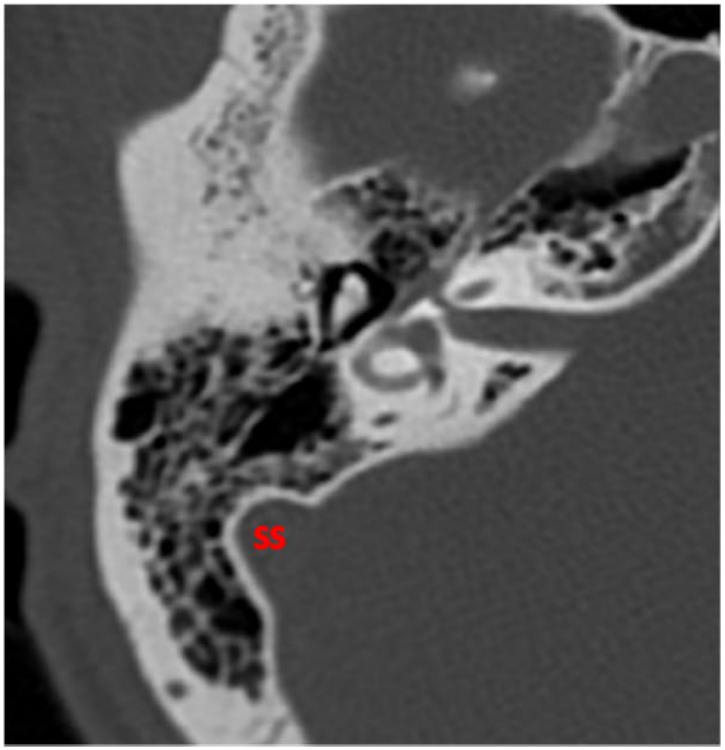

Image C

- **Hypo-Pneumatization**
- **Moderate pneumatization**
- **Good Pneumatization**
- **Hyper-pneumatization**

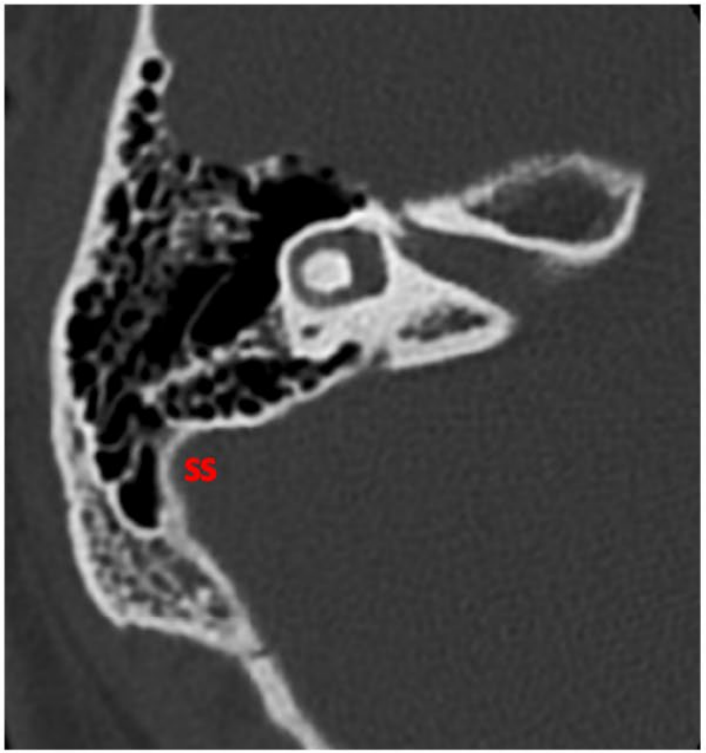

Image D

- **Hypo-Pneumatization**
- **Moderate pneumatization**
- **Good Pneumatization**
- **Hyper-pneumatization**

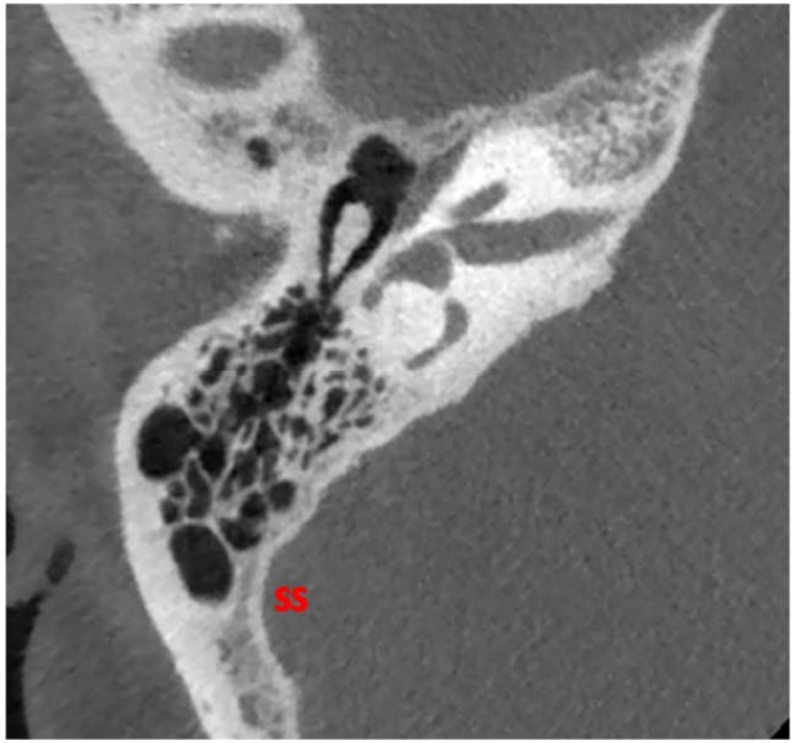

Image E

- **Hypo-Pneumatization**
- **Moderate pneumatization**
- **Good Pneumatization**
- **Hyper-pneumatization**

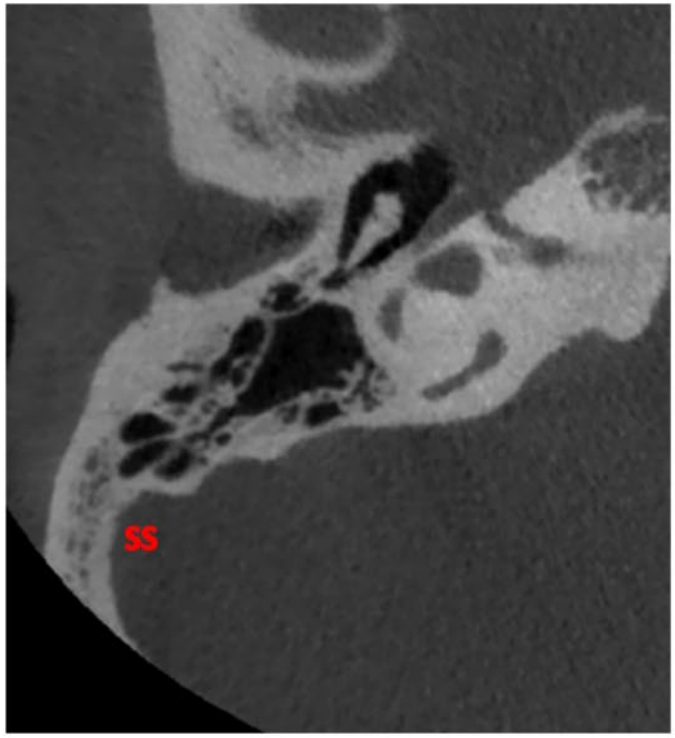

Image F

- **Hypo-Pneumatization**
- **Moderate pneumatization**
- **Good Pneumatization**
- **Hyper-pneumatization**

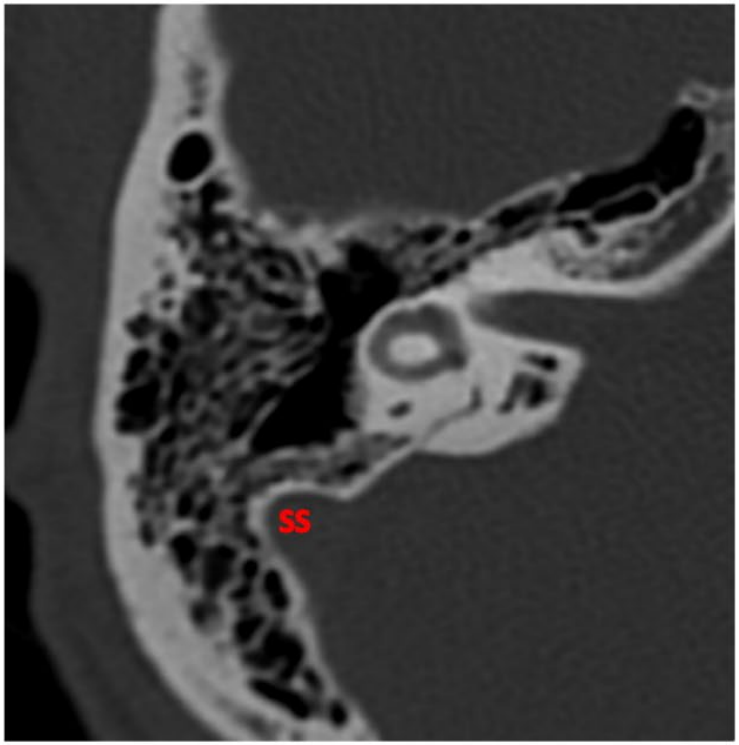

Image G

- **Hypo-Pneumatization**
- **Moderate pneumatization**
- **Good Pneumatization**
- **Hyper-pneumatization**

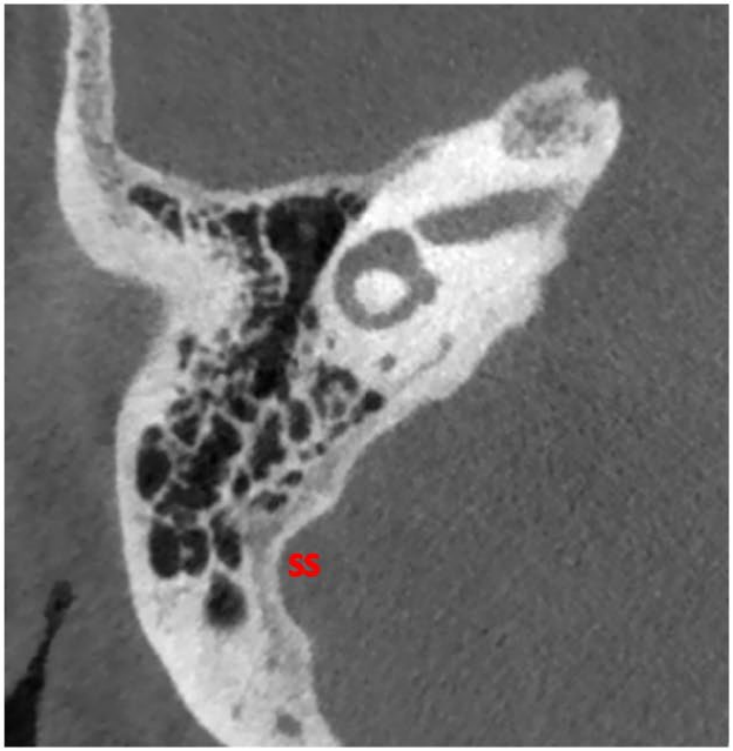

Image H

- **Hypo-Pneumatization**
- **Moderate pneumatization**
- **Good Pneumatization**
- **Hyper-pneumatization**

Section III: Self-Opinion
Instruction: Kindly provide your opinion on the following using the 5 Likert scale provided.

-From your classifications of images A to H in Section II, what is your level of agreement with the use of sigmoid sinus as a reference structure or landmark?

- ☐ **Strongly Disagree**
- ☐ **Disagree**
- ☐ **Neutral**
- ☐ **Agree**
- ☐ **Strongly Agree**

UKZN BIOMEDICAL RESEARCH ETHICS COMMITTEE

APPLICATION FOR ETHICS APPROVAL
For research with human participants (Biomedical)

INFORMED CONSENT RESOURCE TEMPLATE

Information Sheet and Consent to Participate in Research Study Entitled: "**Pneumatization of the temporal bone, its petromastoid part and related vasculature from childhood to early adulthood: an anatomical and radiological study**"

Date: 26th August 2021

My name is Okikioluwa Stephen Aladeyelu. I am A PhD candidate from the Programme of Clinical Anatomy, School of Laboratory Medicine and Medical Sciences, College of Health Sciences, University of KwaZulu-Natal (UKZN). My contact details are: cell; 0656975373, email; 219076039@stu.ukzn.ac.za or stephen4ureal@yahoo.com

You are being invited to consider participating in a study that involves assessing impressions of Otologists in classifying or rating the degree of pneumatization of temporal bone into hypo-, moderate-, good- or hyper-pneumatization, in relation to sigmoid sinus on axial CT images showing different patterns of pneumatization (presence of air cells). The study is expected to enroll a maximum of 25 Ents / Otologists. The aim and purpose of this research is to determine impressions of otologists in rating the degree of pneumatization of the temporal bone images in the questionnaire. This study will compare views and this will thereby help in developing a simple, quick and concise classification of the degree of temporal bone pneumatization at a glance. The study will involve self-completion of a questionnaire. It is anticipated that the duration of your participation if you choose to participate will not exceed 10 to 15 minutes.

There will be no risk or discomfort to you from participating except perhaps the time taken to complete the questionnaire. If you choose to participate in this study, the data from the questionnaire will be analyzed and reported anonymously so that there will be no individually identifiable information included in the final report or publications.

Ethical clearance, Authorization from KZN Department of Health

This study has been ethically reviewed and approved by the UKZN Biomedical research Ethics Committee (approval number BREC/00002263/2020). Authorization has been obtained from KZN Department of Health (KZ_202102_026) to conduct the study.

In the event of any problems or concerns/questions you may contact the researcher at cell; 0604147582, email; 219076039@stu.ukzn.ac.za or stephen4ureal@yahoo.com or my supervisors: Dr. C.O. Rennie, UKZN, Department of Clinical Anatomy, South Africa (rennie@ukzn.ac.za; +27828556206); Dr. A.L. Sibiya, UKZN, Department of Otorhinolaryngology, South Africa(sibiyaL1@ukzn.ac.za; +27837999309); and Dr. W.E. Mbatha, Specialist Head, Neck and Neuroradiologist, Lake, Smit and Partners Inc and Inkosi Albert Luthuli Central Hospital, South Africa (wandambatha@yahoo.com; +2788009999).

OR the UKZN Biomedical Research Ethics Committee, contact details as follows:

BIOMEDICAL RESEARCH ETHICS ADMINISTRATION
Research Office, Westville Campus
Govan Mbeki Building
Private Bag X 54001
Durban
4000
KwaZulu-Natal, SOUTH AFRICA
Tel: 27 31 2604769 - Fax: 27 31 2604609
Email: BREC@ukzn.ac.za

Participation in this research is voluntary and you may withdraw participation at any point. In the event of refusal/withdrawal of participation you will not incur penalty or loss of treatment or other benefit to which you are normally entitled. There are no potential consequences to you for withdrawal from the study.

No costs will be incurred by you as a result of participation in this study. There is no incentive or direct benefit to you for participating in the study. However indirect benefits may occur in that the findings of the study may be used in rating and classifying the degree of pneumatization which will assist in deciding surgical approaches to surgeries and can help avoid pitfalls and complications. The researcher may derive a benefit in the award of an academic qualification from UKZN through completion of a thesis and the results will be published in scientific journals or a book. However, your confidentiality will be protected as any publications will not include any individually identifiable information.

CONSENT

If you agree to voluntarily participate in this research project as described, please indicate your agreement by signing this consent form. Please retain this consent cover form for your reference.

I _____(Name) have been informed about the study entitled

"Pneumatization of the temporal bone, its petromastoid part and related vasculature from childhood to early adulthood: an anatomical and radiological study"

by Okikioluwa Stephen Aladeyelu.

I understand the purpose and procedures of the study.

I have been given an opportunity to answer questions about the study and have had answers to my satisfaction.

I declare that my participation in this study is entirely voluntary and that I may withdraw at any time without affecting any treatment or care that I would usually be entitled to.

I have been informed that there is no available compensation or medical treatment if injury occurs to me as a result of study-related procedures.

If I have any further questions/concerns or queries related to the study I understand that I may contact the researcher at cell; 0604147582, email; 219076039@stu.ukzn.ac.za or stephen4ureal@yahoo.com or the supervisors of the study: Dr. C.O. Rennie, UKZN, Department of Clinical Anatomy, South Africa (rennie@ukzn.ac.za; +27828556206); Dr. A.L. Sibiya, UKZN, Department of Otorhinolaryngology, South Africa(sibiyaL1@ukzn.ac.za; +27837999309); and Dr. W.E. Mbatha, Specialist Head, Neck and Neuroradiologist, Lake, Smit and Partners Inc and Inkosi Albert Luthuli Central Hospital, South Africa (wandambatha@yahoo.com; +2788009999). OR the UKZN Biomedical Research Ethics Committee,

If I have any questions or concerns about my rights as a study participant, or if I am concerned about an aspect of the study or the researchers then I may contact:

BIOMEDICAL RESEARCH ETHICS ADMINISTRATION
Research Office, Westville Campus
Govan Mbeki Building
Private Bag X 54001
Durban
4000
KwaZulu-Natal, SOUTH AFRICA
Tel: 27 31 2604769 - Fax: 27 31 2604609
Email: BREC@ukzn.ac.za

_____	_____
Signature of Participant	**Date**
_____	_____
Signature of Witness (Where applicable)	**Date**
_____	_____
Signature of Translator (Where applicable)	**Date**

APPENDIX F

CONFERENCE ATTENDANCE AND PRESENTATION

- *XXXVIII International Symposium on Morphological Sciences (ISMS) 5 – 8 August 2023*
  OKIKIOLUWA STEPHEN ALADEYELU, SAMUEL OLUWASEUN OLOJEDE, SODIQ KOLAWOLE LAWAL, WONDER-BOY EUMANE MBATHA, ANDILE LINDOKUHLE SIBIYA, CARMEN OLIVIA RENNIE. Influence of pneumatization on morphology of temporal bone-related vasculatures and ear regions.

- *The 57th South African Society Otolaryngology and Society of Rhinoplasty Surgeon South Africa (ENT/SORSSA) Congress, 26 – 31 October 2021.*
  OKIKIOLUWA STEPHEN ALADEYELU, WONDER-BOY EUMANE MBATHA, ANDILE LINDOKUHLE SIBIYA, CARMEN OLIVIA RENNIE. Inter-observer assessment of temporal bone pneumatization: Classifying the degree of pneumatization based on sigmoid sinus using computed tomography.

- *The 49th Annual Conference of the Anatomical Society of Southern Africa (ASSA/AVSA) 19 – 21 April 2022.*

- *The 48th Annual Conference of the Anatomical Society of Southern Africa (ASSA/AVSA) 19 – 21 April 2021.*

Pneumatization of the temporal bone, its petromastoid part and related vasculature in a South African population from early childhood to early adulthood: an anatomical and radiological study

ORIGINALITY REPORT

17%	12%	15%	0%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	www.ncbi.nlm.nih.gov Internet Source	5%
2	Okikioluwa Stephen Aladeyelu, Samuel Oluwaseun Olojede, Sodiq Kolawole Lawal, Matome Nadab Matshipi et al. "Three-dimensional volumetric analyses of temporal bone pneumatization from early childhood to early adulthood in a South African population", Folia Morphologica, 2023 Publication	2%
3	Abdel F. Allam. "V Pneumatization of the Temporal Bone", Annals of Otology, Rhinology & Laryngology, 2016 Publication	2%
4	www.researchgate.net Internet Source	1%
5	archive.org Internet Source	1%

6	Cheryl A. Hill. "Ontogenetic Change in Temporal Bone Pneumatization in Humans", The Anatomical Record Advances in Integrative Anatomy and Evolutionary Biology, 07/2011 Publication	1 %
7	link.springer.com Internet Source	1 %
8	D. Chatterjee, T. B. Ghosh, B. B. Ghosh. "Size variation of mastoid air cell system in Indian people at different age groups: a radiographic planimetric study", The Journal of Laryngology & Otology, 2007 Publication	1 %
9	journals.sagepub.com Internet Source	1 %
10	Vishram Singh, D. Krishna Chaitanya, B.K.S. Chauhan, I. David Victor Kumar. "A comparative study of pneumatization of Temporal bone", Journal of the Anatomical Society of India, 2017 Publication	1 %
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12	S.-J. Han, M.H. Song, J. Kim, W.-S. Lee, H.-K. Lee. "Classification of temporal bone pneumatization based on sigmoid sinus using	<1 %

	computed tomography", Clinical Radiology, 2007 Publication	
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Exclude quotes	On
Exclude bibliography	On