

Morphometric analysis of male and female inner ear structures in Caucasian population using three-dimensional modeling and oriented bounding box

Análisis morfométrico de las estructuras del oído interno masculino y femenino en población caucásica utilizando modelado tridimensional y caja delimitadora orientada

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Abstract

Objectives: This study aims to determine the standard morphometric structure of male and female inner ear structures in the Caucasian population by analyzing computed tomography (CT) images of 130 people without hearing or balance complaints. **Methods:** Three-dimensional (3D) models of the semicircular canals (SC), vestibule, and cochlea were created using semi-automatic segmentation. Angles between SCs were calculated using oriented bounding boxes (OBB). Size, volume, radius of curvature, canal diameters, common crus dimensions, central bone island areas, and cochlear and vestibule volumes were measured. **Results:** Although significant deviations from 90° on a case-by-case basis were observed in SC pairs, no statistically significant deviation from orthogonality was detected. While there was no significant difference between SC angulations, there were significant gender differences between other inner ear morphometric measurements. **Conclusions:** This study has shown that reliable SC angulation measurements can be made on conventional CT images with the OBB method, which has not been used for this purpose before. Significant differences were found between inner ear morphometric measurements of Caucasian male and female populations.

Keywords: Computerized tomography. Cochlea. Inner ear. Labyrinth. Morphometry.

Resumen

Objetivo: Determinar la estructura morfométrica estándar de las estructuras del oído interno masculino y femenino en población caucásica mediante el análisis de imágenes de tomografía computarizada (TC) de 130 personas sin quejas de audición y equilibrio. **Métodos:** Se crearon modelos tridimensionales (3D) de los canales semicirculares (CS), el vestíbulo y la cóclea utilizando segmentación semiautomática. Se calcularon los ángulos entre los CS utilizando cajas delimitadoras orientadas (OBB). Se midieron el tamaño, el volumen, el radio de curvatura, los diámetros de los canales, las dimensiones del común cruz, las áreas centrales de la isla ósea y los volúmenes de cóclea y vestíbulo. **Resultados:** Aunque se observaron desviaciones significativas de 90° caso por caso en pares de CS, no se detectó ninguna desviación estadísticamente significativa de la ortogonalidad. Mientras que no hubo diferencia significativa entre las angulaciones de los CS, hubo diferencias de sexo significativas entre otras mediciones morfométricas del oído interno. **Conclusiones:** Este estudio demuestra que se pueden realizar mediciones confiables de la angulación de los CS en imágenes de TC convencionales con el método OBB, que antes no se había utilizado para este propósito. Se encontraron diferencias significativas entre las mediciones morfométricas del oído interno de las poblaciones masculina y femenina caucásicas.

Palabras clave: Tomografía computarizada. Cóclea. Oído interno. Laberinto. Morfometría.

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Introduction

The inner ear constitutes an integral component of the auditory and vestibular systems. It collaborates with central and ocular structures to facilitate the essential balance required for body positioning. The semicircular canals (SC), utricle, and saccule within the inner ear play a pivotal role not only in sustaining balance but also in coordinating movements. It is imperative to establish standardized morphometric measurements for these structures in order to differentiate between potential normal and pathological conditions.

Being surrounded by the hardest bony structure of the human body, it is difficult to evaluate the anatomy of the inner ear structures. While morphological studies have generally been performed on a small number of cadaveric specimens using microtomography computed tomography (micro-CT),¹⁻⁵ conventional multidetector CT (MDCT) and cone beam CT have also been used in a few studies.^{3,6,7} Conflicting results arose due to restricted case numbers, the application of diverse measurement techniques, and the failure to exclude pathologies from the study groups that could potentially influence the inner ear.

Multiple studies have explored the correlation between anatomical variations of the middle ear structures and diseases.⁸⁻¹⁰ Publications evaluating the morphological differences in inner ear structures and their potential associations with related diseases, however, are limited in number.¹¹⁻¹³ The primary goal of this study is to investigate whether the inner ear morphology could be reliably assessed using routine thin-slice MDCT images and delineate the normal anatomical boundaries by conducting morphometric measurements on inner ear structures within healthy female and male Caucasian populations. We believe that this study could serve as a foundation for future research aiming to explore the morphology-pathology relationship. To ensure a consistent and reproducible methodology, morphological measurements were conducted using three-dimensional planar reconstructions, whereas the analysis of angular relations was carried out employing segmentation and the oriented bounding box (OBB) methods.

Methods

Following approval from the institutional ethics committee (2022/52), patient records and Picture Archiving

and Communication System images of 250 individuals who underwent high-resolution paranasal CT imaging between January 1, 2020, and July 30, 2020, with an initial diagnosis of septum deviation, sinusitis, or concha mass, were retrospectively examined. Beyond pathologies that could impact normal inner ear development, including craniofacial developmental disorders and bone anomalies, a thorough investigation was conducted regarding any history of prior brain, ear, or maxillofacial surgery and/or trauma. This inquiry was facilitated through phone calls and a comprehensive review of medical records. Images with motion or metallic artifacts were excluded from the study. Consequently, a total of 128 patients (84 men and 44 women) ranging in age from 18 to 75 years were included in the study.

The paranasal high-resolution CT scans for all patients were conducted using the identical 64-slice multidetector CT scanner (Toshiba Aquilion 64, Otawara, Japan). The scans were performed with the head in a neutral position, utilizing settings of 120 kV tube voltage, 150 mA current, 0.65 pitch, 0.5 s rotation time, 1 mm slice thickness, 0.8 mm slice spacing, and a 256 × 256 matrix value. The raw data obtained were transferred to the 3D Slicer application (www.slicer.org) and the TeraRecon workstation (AquariusNET Workstation 4.4.7). These platforms enable advanced image processing and manipulation, utilizing the Digital Imaging and Communications in Medicine format.

Using the open-source 3D Slicer application, three-dimensional models of the SCs, vestibule, and cochlea were generated through a semi-automatic threshold segmentation process. Utilizing these models, each SC was individually assigned to a different segment. Subsequently, OBBs were constructed around each SC, facilitated by a Python code specifically developed for this study. Automated calculations were conducted to determine the planar angulation relationships among all three SCs on the same side, ipsilateral anterior SCs (ASC) and contralateral posterior SCs (PSC), and additionally, the lateral SC (LSC) of each side were computed using the OBB vectors (Fig. 1). The volumes of the SCs, vestibule, and cochlea were computed using the "Segment Statistics" module within the 3D Slicer program.

Measurements of the maximum heights of each SC, from the apical bony labyrinth to the central part of the vestibule wall, and the maximum lateral widths of the bony labyrinths (referred to as SC height and width) were obtained through multiplanar images. In addition, the central bone island areas (BIA) were also quantified

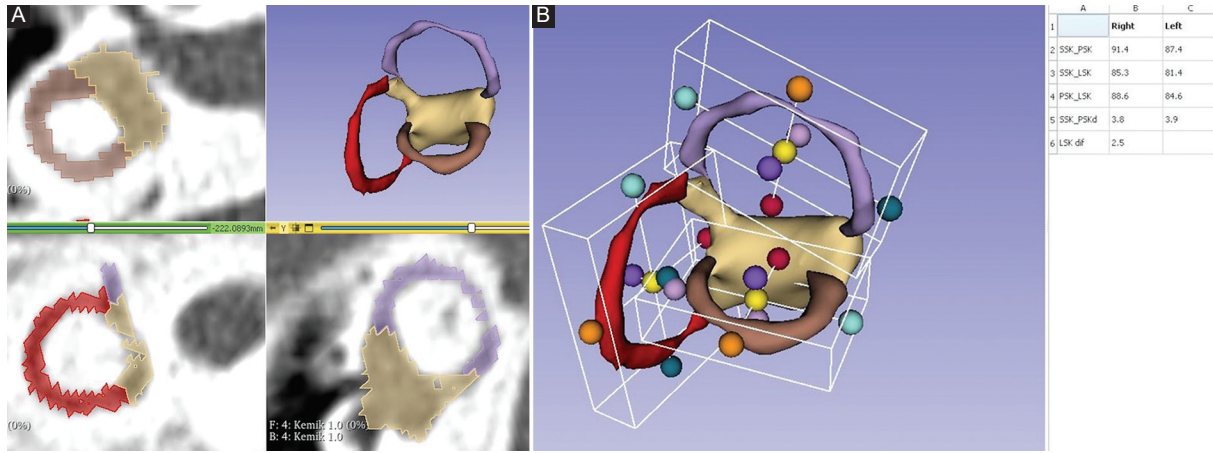


Figure 1. A: segmentation procedure of anterior, posterior, and lateral semicircular canals and vestibule using a semi-automatic threshold segmentation method. **B:** determination of the angles between semicircular canals utilizing oriented bounding boxes.

(Fig. 2A). The average SC diameters (CD) were measured by calculating the average inner bony labyrinth diameters of each SC from three standard points - one on each side and one at the apical region - as depicted in figure 2B. The length and width of the common crus were measured using two perpendicular planes from multiplanar images. The radius of curvature was computed using the formula " $0.5 \times (\text{SC height} + \text{SC width})/2$." All measurements were documented individually for both male and female subjects.

Informed consent was not sought from patients as it is not a requirement by our institutional ethics committee for retrospective studies. However, permission to utilize the medical imaging data of the patients was obtained from the chief physician.

Statistical analysis

The statistical analysis was conducted using the GNU PSPP application (<https://www.gnu.org/software/pspp/>). The Kolmogorov-Smirnov test was initially used to assess normal distribution. Subsequently, for normally distributed variables, the Student's t-test was employed, presenting results as mean values with corresponding standard deviations. For non-normally distributed variables, the Mann-Whitney U test was utilized, displaying results as median values along with the corresponding interquartile range values. A significance level of < 0.05 was adopted as the threshold p-value for determining statistical significance.

Results

The SC angulation values obtained through the OBB method are detailed in table 1 and illustrated in figure 3. Notably, there was no statistically significant difference in SC angulation between males and females. Angles of $< 90^\circ$ were observed between the ASC-PSC, ASC-LSC, and PSC-LSC pairs at rates of 63.3%, 54.4%, and 52.2%, respectively, with average angles of 89.28, 89.73, and 89.98°. No statistically significant deviation from orthogonality (90°) was observed in any SC pair except for the female ASC-PSC pair (mean $88.70 \pm 4.99^\circ$, $p = 0.0154$). Notably, it was determined that the contralateral ASC-PSC and LSC pairs exhibited non-parallel orientations, deviating by an average of 15° and 12.5° , respectively (Fig. 4).

Bony labyrinth heights and widths, mean canal diameters, SC volumes, radius of curvature values, and central BIA are outlined in table 2. Observations revealed that mean ASC heights and widths, and PSC heights were significantly higher in males ($p = 0.001$). Although the mean PSC width and LSC height showed higher measurements in males, no statistically significant differences were observed ($p = 0.13$ and $p = 0.11$). Interestingly, ASC and PSC canal diameters were significantly larger in women, while LSC canal diameters were similar in both genders. The calculated mean SC canal volumes were $13.12 \pm 3.12 \text{ mm}^3$ for ASC, $17.07 \pm 4.23 \text{ mm}^3$ for PSC, and $13.01 \pm 3.46 \text{ mm}^3$ for LSC (Fig. 5). All three measurements were notably higher

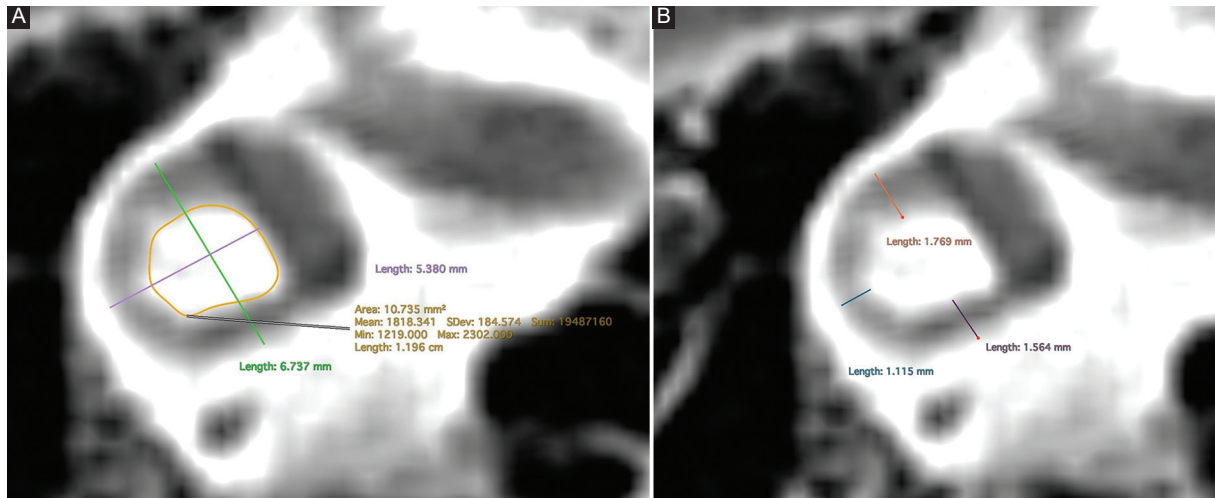


Figure 2. A: measurement of semicircular canal diameters and central bone island volume. **B:** determining the average width of the semicircular canal through measurements taken from three standardized locations.

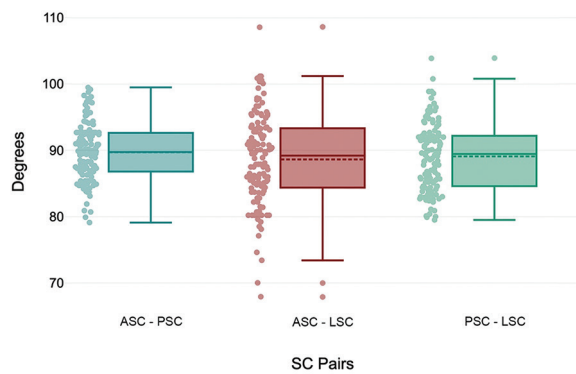


Figure 3. Boxplot displaying the angulations between each pair of semicircular canals. ASC: anterior semicircular canal; PSC: posterior semicircular canal; LSC: lateral semicircular canal.

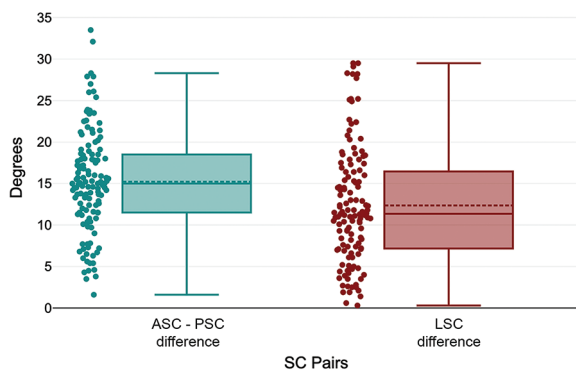


Figure 4. The boxplot illustrates the angles between synergistic pairs of semicircular canals. ASC: anterior semicircular canal; PSC: posterior semicircular canal; LSC: lateral semicircular canal.

Table 1. Angles between SCs

Parameters	Mean	SD	Min	Max	p	Orthogonality
ASC-PSC						
Male	89.60	3.93	77.2	98.1	0.108	p = 0.1889
Female	88.70	4.99	79.1	102.5		p = 0.0154*
ASC-LSC						
Male	89.54	6.56	70	107.4	0.581	p = 0.3647
Female	90.06	7.17	74.5	111.0		p = 0.9369
LSC-PSC						
Male	89.82	5.55	71.2	104.0	0.524	p = 0.6748
Female	90.27	5.04	78.6	103.9		p = 0.6126

*Significantly different from 90° (p < 0.05). Unit: degrees.

SCs: semicircular canals; ASC: anterior semicircular canal;

PSC: posterior semicircular canal; LSC: lateral semicircular canal.

in males. Moreover, the central BIA of all three SCs was notably larger in males compared to females. While the radius of curvature values of ASC and PSC were significantly larger in the male population, no significant gender-based differences were observed for LSCs (Table 2).

The common crus height and width measured 1.79 ± 0.40 mm and 1.76 ± 0.28 mm, respectively, across the entire case group. The common crus height was notably higher in males (p = 0.04), whereas the width was significantly higher in females (p = 0.001) (Table 3).

The mean cochlear volume was calculated as 68.62 ± 18.18 mm³, exhibiting a significant increase in males (p = 0.019). As for the vestibule volume, it averaged

Table 2. Morphometric data of the SCs

Parameters	Anterior SC			Posterior SC			Lateral SC		
	Median	IR	p	Mean	SD	p	Median	IR	p
Height									
Male	6.55	0.9	< 0.001*	6.75	0.48	< 0.001*	5.01	0.6	0.11
Female	6.10	0.8		6.33	1.09		4.95	0.5	
Width									
Male	8.50	0.6	< 0.001*	8.05	0.60	0.13	6.60	0.6	0.88
Female	8.25	0.8		7.86	0.64		6.60	0.6	
	Median	IR	p	Median	IR	p	Median	IR	p
CD									
Male	1.63	0.21	< 0.001*	1.79	0.20	< 0.001*	1.63	0.23	0.99
Female	1.73	0.21		1.94	0.24		1.62	0.20	
Volume (mm ³)									
Male	13.66	3.57	< 0.001*	18.01	4.60	< 0.001*	13.64	3.71	0.001*
Female	11.71	2.76		15.16	3.19		11.87	2.62	
RC									
Male	3.75	0.3	< 0.001*	3.72	0.3	< 0.001*	2.90	0.3	0.12
Female	3.58	0.3		3.53	0.4		2.87	0.2	
BIA (mm ²)									
Male	13.50	4.60	< 0.001*	17.22	4.85	< 0.001*	12.95	4.84	0.01*
Female	11.33	3.42		14.88	4.22		11.90	4.01	

*Significant difference between males and females (p < 0.05).

Unit: mm; CD: canal diameter; RC: radius of curvature; BIA: bone island area; IR: interquartile range; SCs: semicircular canals.

Table 3. Common crus measurements

Parameters	CC height	CC width	Height max-min	Width max-min	p
Male	1.80	1.70	3.4-1.0	2.3-1.0	0.04*
Female	1.60	1.85	3.8-1.0	3.5-1.2	< 0.001*

*Significant difference between males and females (p < 0.05).

Unit: mm.

68.91 ± 14.56 mm³ in women and 71.75 ± 11.67 mm³ in men, with no statistically significant difference observed between the genders (Table 4).

Discussion

The reliable results obtained when compared to micro-CT studies, considered the gold standard for inner ear morphology investigations, lead to the conclusion that, despite traditional CT images having lower resolution, accurate measurements can be acquired through segmentation processes and 3D reconstruction techniques.

In prior studies, SC angles were typically determined through manual or planar measurements.^{1,14,15}

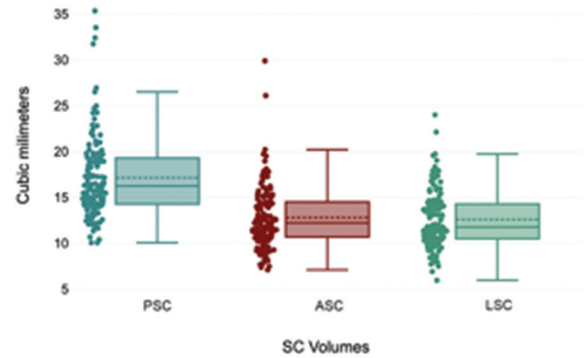


Figure 5. The boxplot of semicircular canal volumes. ASC: anterior semicircular canal; PSC: posterior semicircular canal; LSC: lateral semicircular canal.

These measurement methods may not be suitable for complex structures like human SCs that do not conform to a specific plane. To address this, the OBB method, which allows the assessment of the entire object, enables objective and reproducible measurements.

The OBB is a hexahedral rectangle that encompasses the target object, aligning its axes with the

Table 4. Cochlear and vestibular volumes

Parameters	Mean V	Standard deviation	p
Cochlea			
Male	70.57	18.14	0.019*
Female	65.05	17.81	
Vestibule			
Male	71.75	11.67	0.112

*Significant difference between males and females ($p < 0.05$).

Unit: mm³.

object's local coordinates. Initially introduced by Gottschalk in 1996 and employed within the RAPID system,¹⁶ the OBB method has gained popularity due to its ease of application and its ability to provide consistent results. It is extensively preferred for ascertaining the vector orientations of three-dimensional objects with complex geometries, specifically for collision detection purposes in virtual reality applications.¹⁷

Within the contemporary medical literature, there exists a limited number of studies that have employed the "oriented bounding box" technique. These studies share some common characteristics, including the usage of segmentation and machine learning algorithms, and in recent years, the number of such studies has shown a noticeable increase due to advancing artificial intelligence technology. He et al. investigated structural changes occurring in the corpus callosum of phenylketonuria patients in their study using segmentation and the OBB technique.¹⁸ Similarly, in another study utilizing both techniques, Plathow et al. assessed the volumes of lung nodules with complex shape characteristics and the degree of rotational movements occurring in the nodules due to breathing.¹⁹

Traditionally, human SCs have been assumed to be positioned at right angles to each other, a hypothesis supported by several textbooks and studies.^{1,20} Nevertheless, some publications report angulation differences, indicating a significant deviation from orthogonality between SCs. Blanks et al., in their examination of 10 skulls from various racial backgrounds, reported that the ipsilateral ASC and LSC were not oriented at right angles to each other, showing an average angle of $111.8 \pm 7.6^\circ$.²¹ In their study using multiplanar CT slices specifically oriented for each SC, Della Santina et al. reported a significant deviation from orthogonality between the ASC and PSC ($94.0 \pm 4.0^\circ$).²² In a micro-CT study conducted

on forty cadaver temporal bones, Lee et al. utilized three-dimensional SC models to measure angulations between the planes best oriented to each SC. They reported angles of $< 90^\circ$ between ASC-LSC and PSC-LSC, whereas they observed angles $> 90^\circ$ between the ASC-PSC in the majority of samples (30 out of 40 cases).¹ In our study, $< 90^\circ$ was observed between ASC-PSC, ASC-LSC, and PSC-LSC pairs in 63.3%, 54.4%, and 52.2%, respectively. The only measurement that presented a statistically significant difference from orthogonality is the female ASC-PSC angulation, which has also been identified as the only SC pair showing a significant deviation from orthogonality in the study by Della Santina et al.²² No statistically significant deviation was found in other SC pairs.

Conventionally, numerous books and reviews have established that synergistic SC pairs are parallel to each other and have similar sizes.^{4,20,23,24} Nevertheless, Blanks et al. reported deviations of up to 22° between human synergistic SC pairs.²¹ Corroborating this study, our findings suggest the possibility of angulations ranging from 12 to 20° between synergistic SC pairs.

There is limited literature available on gender-based differences in SC morphology.^{1,3,7} Since the size of the ASC and PSC has been linked to locomotor response time and sensitivity in animals,²⁵ it is reasonable to assume that a similar phenomenon may apply to human SCs.¹⁵ According to our measurements, all SC volumes were significantly larger in males, whereas females exhibited larger mean canal diameters for the ASC and PSC. In addition, ASC heights and widths were found to be significantly greater in males. These findings contrast with two prior studies that did not report statistically significant gender differences in labyrinth volumes.^{3,7} Another notable difference compared to previous studies was the common crus, which was found to be significantly longer in males, while widths were greater in females.¹

Additional measurements that showcased differences between male and female populations included all three BIAs and the radius of curvature values of the ASC and PSC, which were higher in males than in females ($p < 0.05$). In both genders, a smaller radius of curvature value was observed in the LSC (2.8 mm) compared to the ASC (3.8 mm) and PSC (3.79 mm). Spoor and Zonneveld indicated a larger radius of curvature (3.8 mm) for the PSC than the other SCs,⁴ whereas another study reported similar radius of curvature values for ASC and PSC (3.6 mm).¹ Similar to our findings, Hiller et al. reported

significantly larger cochlear volume measurements in males.³

Our study offers several advantages over previous research. Previous studies predominantly relied on modalities such as micro-CT and cone beam CT. These studies often assumed that the relatively low spatial resolution of diagnostic multidetector CT would render the image quality insufficient for measuring the minute structures of the vestibulocochlear system.^{1,3} While micro-CT studies on cadavers are esteemed as the gold standard due to their high image resolution, this approach has inherent limitations. For instance, micro-CT cannot be used *in vivo* on living humans, and the measurement results might be affected by volume changes caused by storage conditions in cadaveric specimens.⁵ While cone beam CT devices can generate high-resolution images, they do have their drawbacks. One significant limitation is the higher cost of these devices. In addition, the lack of soft-tissue resolution, longer acquisition times, and the scarcity of high-quality cone beam CT systems result in less widespread utilization of these devices.²⁶ In our study, a substantial study group was attainable as a routine imaging method was applied. It was deduced that by employing the segmentation process, multiplanar imaging, and the OBB method, measurements consistent with previous studies could be obtained using diagnostic CT images. Discrepancies between our findings and other studies may be attributed to variances in racial demographics within the study groups, the size of the study cohorts, and variations in the imaging modalities used.

Conclusions

This study stands out by introducing the OBB method to quantify SC angles within the largest study group in its field. It provides a detailed elucidation of the morphometric measurements of inner ear structures in both Caucasian females and males. Despite our findings indicating no significant gender differences in SC angles within the Caucasian population, distinct variations were observed in various other morphological parameters. The use of conventional computed tomography for morphometric analysis of inner ear structures enables thorough investigations, revealing morphological differences across genders and racial groups. The establishment of morphometric standards and the disclosure of inner ear variations have the potential to improve the success rate and safety of interventional procedures on the inner ear,

while also offering valuable insights for diagnosing hearing disorders and analyzing vestibulo-ocular reflex experiments.

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Conflicts of interest

The authors declare no conflicts of interest.

Ethical considerations

Protection of human subjects and animals. The authors declare that no experiments on humans or animals were performed for this research.

Confidentiality, informed consent, and ethical approval. This study does not involve personal patient data, medical records, or biological samples, and does not require ethical approval. SAGER guidelines do not apply. The study was approved by the Clinical Research Ethics Committee of our faculty (No. 2022/52), and all procedures followed were in accordance with the World Medical Association Declaration of Helsinki: ethical principles for medical research involving human subjects, 2013.

Declaration on the use of artificial intelligence. The authors declare that no generative artificial intelligence was used in the writing or creation of the content of this manuscript.

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