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Air spaces of the temporal bone: a morphometric analysis with clinical implications

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Background: *The main objective of the present study was to analyse the morphological variations of the air spaces of the temporal bone, that is, the pneumatized and air-filled spaces of the temporal bone cavities.*
Materials and methods: *A total of 99 sides were analysed. Temporal bone pneumatic spaces (TBPS) were defined as the free spaces inside the cavities of the temporal bone filled with air, excluding the volume of the structures present in the investigated region. Total volumes of TBPS were calculated as the sum of total volumes of mastoid air cells (MAC), tympanic cavity (TC), and external auditory canal (EAC). Analyses were performed considering the general population and the female and male subgroups.*
Results: *The overall results obtained on Polish population were set as follows: the median total volume of TBPS was demonstrated at 7882.58 mm^3 (lower quartile [LQ]: 6200.56 mm^3; higher quartile [HQ]: 10393.16 mm^3). The median volume of MAC was set at 5813.05 mm^3 (LQ: 4224.94 mm^3; HQ: 8181.81 mm^3). The median of the total volume of the EAC was demonstrated at 1294.36 mm^3 (LQ: 1099.68 mm^3; HQ: 1627.84 mm^3).*
Conclusions: *In the present study, the morphometric properties of the temporal bone cavities were analysed. The results showed that the total volume of the MAC was, on average, lower in women than in men. This should be taken into account when performing procedures on the mastoid, such as mastoidectomies. It is hoped that the results of this study can help reduce potential surgical complications associated with otological procedures.* (Folia Morphol 2023; 82, 4: 909–920)

Key words: temporal bone, temporal bone trauma, laryngeal anatomy and physiology, external ear

INTRODUCTION

The temporal bone is a complex structure that contains a network of pneumatic spaces and typically consists of four parts: squamous, petromastoid, tympanic, and styloid processes [40]. Pneumatization refers to the development of air-filled cavities in the bone, where the epithelium infiltrates the developing bone, resulting in the formation of air cell cavities [18]. The air cells are typically lined by a single layer of epithelium divided from bone by subepithelial

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connective tissue [33]. In 1969, Allam [2] was the first to; propose the classification of temporal bone pneumatization (TBP). He divided this system into: 1) mastoid pneumatization, 2) petrous pneumatization, and 3) accessory pneumatization (extending beyond the limits of the mastoid and petrous regions). Another classification of TBP was presented by Han et al. [17], which consisted of four groups according to the degree of pneumatization in relation to the sigmoid sinus: group 1 (hypopneumatization), group 2 (moderate pneumatization); group 3 (good pneumatization), and group 4 (hyperpneumatization). TBP begins prenatally, typically around 24 weeks of gestation [4, 33]. The process consists of three stages, which are the infantile, transitional, and adult stages. The development is usually completed at the age of 10 years in women and 15 years in men [13, 19].

The aeration of the temporal bone has many functions, such as reception of sound, preventing negative pressures, and avoiding changes in the middle ear mucosa, among others [23, 38, 44]. The extent to which pneumatization occurs in the temporal bone varies considerably, and numerous studies on TBP have been presented in the literature [10]. Gibelli et al. [16] conducted a study in which the degree of TBP was analysed. They emphasized that there are significant variations in the degree of pneumatization in some areas of the temporal bone, such as the petrous apex or the infralabyrinthine portion. In general, the squamous, petromastoid and tympanic parts are the most frequently pneumatized parts, but pneumatization may also be extended to the articular eminence of the zygomatic process [15]. These variations must be taken into account clinically, especially when planning surgical procedures in this area.

Air cavities of the temporal bone are areas of minimal resistance that allow the spreading of the pathologies within the temporal bone, e.g. cholesteatoma, cholesterol granuloma, and otitis media, among others [21, 37, 45]. Air cells can form connections with the surrounding cavities, such as mastoid air cells (MAC) connecting to the tympanic cavity (TC). However, this connection can be a pathway for infection to spread in cases of otitis media, resulting in possible mastoiditis [28]. On the other hand, increased TBP has been associated with fewer and less severe complications associated with temporal bone fractures [24, 28].

Having a good understanding of the variations in the morphometric properties of temporal bone cavities can help to choose the right surgical approach for various otorhinolaryngological procedures. Surgeons can apply this knowledge when performing procedures directly on the external acoustic canal (EAC) or on the tympanic membrane, such as myringoplasty [7]. There are different surgical approaches to choose from when performing this procedure. Similarly, knowledge of the morphometric characteristics of the mastoid cavity is necessary to perform mastoidectomies properly. Mastoidectomy is a common surgical procedure with multiple indications, and each mastoidectomy is unique due to variations in the TBP patterns [27].

Although many studies have investigated the degree of TBP, there is still a lack of data regarding the total volumes and morphometric properties of the different temporal bone cavities. Therefore, the main objective of the present retrospective study was to analyse the morphological variations of the air spaces of the temporal bone, i.e. the pneumatized and air-filled spaces of the temporal bone cavities. Additionally, the objective was to establish possible alliances and correlations between parameters, as well as to assess sexual dimorphism.

MATERIALS AND METHODS

A retrospective observational study was performed on 55 randomly selected computed tomography (CT) angiographies (CTA) of the head and neck region that were analysed in the Department of Radiology of Jagiellonian University Medical College, Krakow, Poland, in April 2022. In this study, CTAs were evaluated instead of CTs due to the greater availability of these results. All participants consciously agreed to the examination. The research protocol was submitted for evaluation and approved by the Bioethical Committee of Jagiellonian University, Krakow, Poland. Further stages of the study were carried out in accordance with the approved guidelines. The structure of the study group consisted of 99 temporal bones, of which 42 were from women and 57 from men, with a median age of 49.7. All patients were Polish. Each study was analysed bilaterally (110 cases). Exclusion criteria were established as follows: (1) head trauma affecting the air spaces of the ear and/or the surrounding anatomical area, (2) significant artifacts that prevented accurate and precise imaging and/or measurement (3) low quality and illegible images. Defects that met the exclusion criteria but included only one side of the CT, without interference with

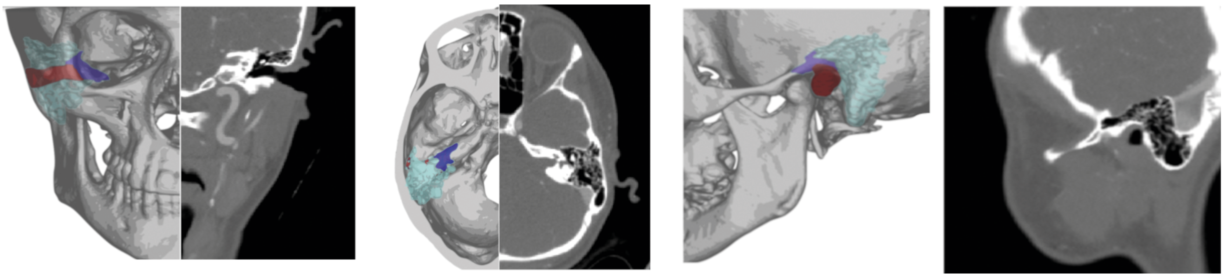

Figure 1. Three-dimensional representation of the studied region with computed tomography cross-section; red — external auditory canal; violet — tympanic cavity; turquoise — mastoid air cells.

the contralateral side, did not disqualify the entire CT, but only the affected side. Finally, a total of 99 sides were analysed.

Ethical approval

The research protocol was submitted for evaluation and approved by the Bioethical Committee of Jagiellonian University, Krakow, Poland.

CTA

The CTAs were performed on a 128-slice scanner CT (Philips Ingenuity CT, Philips Healthcare). The main CT imaging parameters were as follows: collimation/increment: 0.625/0.3 mm; tube current: 120 mAs; field of view: 210 mm; matrix size: 512 × × 512. All groups of patients received intravenous administration of contrast material at a dose of 1 mL/kg (standard dose). A non-ionic contrast medium (CM) containing 350 mg of iodine per mL was used (Jowersol 741 mg/mL, Optiray®, Guerbet, France). CT data acquisition was triggered using a real-time bolus-tracking technique (Philips Healthcare) with the region of interest placed in the ascending aorta. The CM was intravenously injected using a power injector at a flow rate of 5 mL/s. This was immediately followed by the injection of 40 mL of saline solution at the same flow rate. Following the injection of CM and saline, image acquisition was started automatically with a 2-s delay when the attenuation trigger value reached a threshold of 120 Hounsfield units (HU). Scanning was performed in the caudocranial direction.

Image processing

Biomedical data was processed by two experienced and independent investigators and a qualified senior radiologist was also consulted. Anonymised source files in DICOM format were imported into specialised software (Mimics Innovation Suite 22; Materialise, Plymouth, MI, USA). Individual multilayer graphic masks in the region of corresponding anatomical structures were created with built-in semiautomatic algorithms using technique of the maximum intensity projection based on the corresponding HU range. Additionally, in each study, a three-dimensional reconstruction was performed to obtain a better volume match. Any distortions that could have caused an error were manually removed.

Measurements

The exact representation of the measurements is illustrated in Figures 1 and 2. Each measurement was performed twice, with an accuracy to the second decimal place, and a mean result was established afterwards. In further statistics, the mean values were taken into account. In the present study, temporal bone pneumatic spaces (TBPS) were defined as the free spaces within the temporal bone cavities filled with air, excluding the volume of the structures presented in the investigated region. The total volumes of the TBPS were calculated as the sum of the total volumes of MAC, TC, and EAC. Then the percentage value of each component was calculated. MAC were designated as the enclosed spaces within the mastoid process of the temporal bone along with the canal leading to the entrance to the tympanic antrum, just above the epitympanic recess. Porous spaces that originated mainly from the MAC and extend beyond the mastoid process were also included. The TC was bounded by six entities: the medial labyrinthic wall, the lateral wall with the tympanic membrane taking into account its angle of inclination, the roof bounded by the tegmen tympani, the floor demarcating the TC from the jugular fossa, the posterior wall with a cutoff point just above the epitympanic recess, and the anterior wall including the bony portion of the Eustachian tube. All EAC parameters were determined in the normal sagittal plane. A point inside

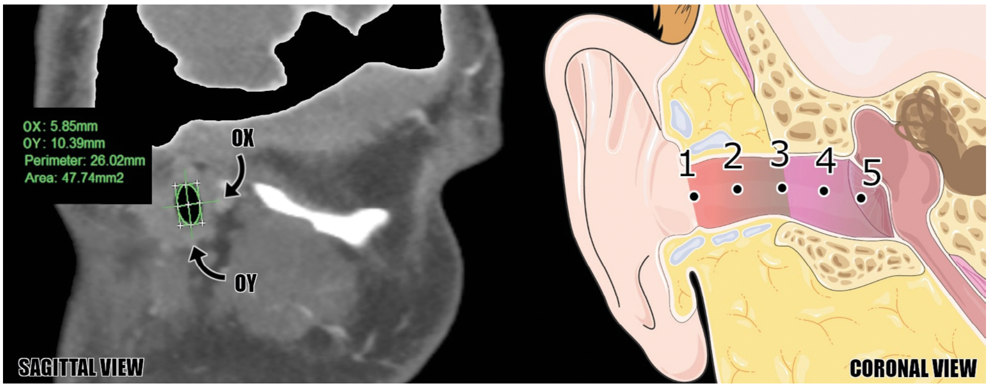

Figure 2. Location of measurement points for the external auditory canal (EAC) along with the evaluation method. OX and OY denote the horizontal and vertical axes. Point 1 corresponds to the distal end of the EAC. Point 3 corresponds to the transition from the bone (bEAC) to the cartilage (cEAC). Point 5 is at the proximal end of the EAC and indicates the origin of the bEAC itself, not the dimensions of the eardrum itself. Points 2 and 4 are placed halfway between points 1–3 and 3–5. The evaluation in the sagittal section on the left side of the figure is shown at measurement point 1; pink gradient — bEAC; reddish gradient — cEAC.

the canal, just behind the tragus, inside the concha cavity, where the section of the canal takes a constant elliptical, oval, or round shape, was chosen as the lateral border. The tympanic membrane was chosen as the medial border, taking into account its angle of inclination. Furthermore, the EAC was divided into two parts corresponding to cartilage (cEAC) and bone (bEAC). The point of transition from cartilage to bone was determined as complete closure of the perimeter of the visible round contour in the proper section. The volume and surface area corresponding to the epithelium lining the EAC was determined with cEAC and bEAC. Compared to volume, the surfaces did not encase the included ends of the EAC. The length of the EAC was provided as the centre line to the canal wall, taking into account its curvature. The EAC also defines five locations where selected morphological parameters were assessed. Taking into account the measurements in the sagittal plane, the X-plane measurements corresponded to a range of +45 to –45 degrees with respect to the horizontal line, while the Y-plane measurements corresponded to the same range in the vertical plane. X1/Y1 corresponds to the site of the lateral border of the EAC, X3/Y3 corresponds to the site corresponding to the cartilaginous-bone transition, and X5/Y5 corresponds to the site just distal to the appearance of the tympanic membrane where the bEAC perimeter visible in cross section opens. X2/Y2 was determined in the cEAC halfway between X1/Y1 and X3/Y3, while X4/Y4 was determined in the bEAC halfway between X3/Y3 and X5/Y5. Furthermore, the cross-sectional area and perimeter were labelled for each point.

Statistical analysis

Statistical analysis was performed with SATISTICA v13.1 (StatSoft Inc., Tulsa, OK, USA). The frequencies and percentages presented qualitative features. The Shapiro-Wilk test was used to assess the normal distribution. Quantitative features were presented by medians and higher and lower quartiles (HQ, LQ). Statistical significance was defined as $p < 0.05$. The Spearman rank correlation coefficient was used to determine possible correlations between parameters. U Mann-Whitney and Wilcoxon signed-rank tests were used to establish potential differences between two groups. To detect a simple correlation ($r = 0.3$) with 80% power and a 5% significance level (two-tailed; $\alpha = 0.05$; $\beta = 0.2$), the minimal sample size was set at 85 cases.

RESULTS

Baseline characteristics

Analysis was carried out from every side in a total of 99 TBPS of 49 patients, between 15 and 82 years of age (mean age: 50 years old; standard deviation: 19.3), of which 42 TBPS (42.4%) were from women and 57 (57.6%) from men. The left sides were analysed in 50 (50.5%) cases and the right sides in 49 (49.5%) cases. All further descriptions, which refer to the names of the categories mentioned in the materials and methods section, are illustrated in Figure 3.

EAC results

Data on EAC were collected in 30 categories. For each category, analyses were performed considering the general population and the female and male

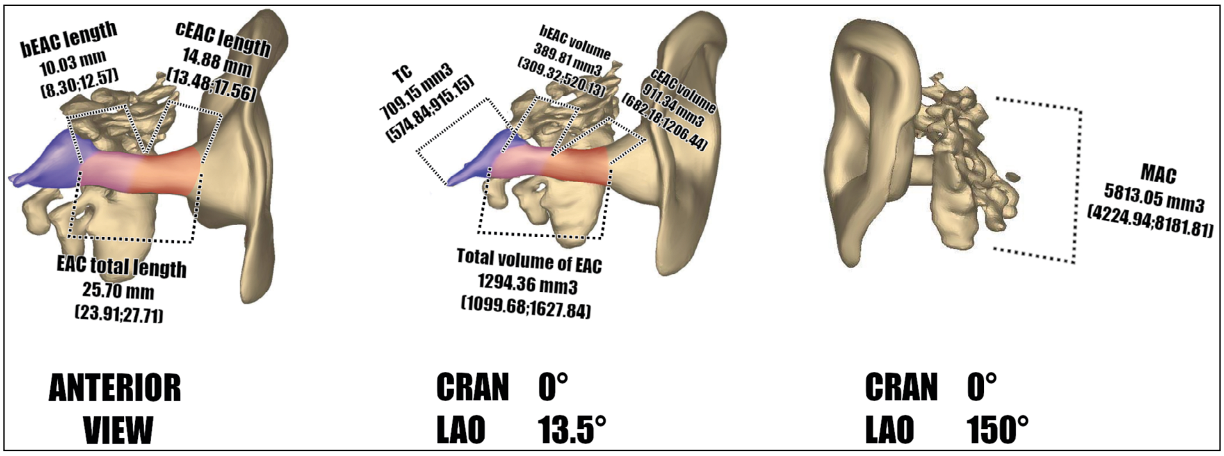

Figure 3. Results presented as a form of median with lower and higher quartile on a three-dimensional model. Pinna along with colours were added to emphasize the view; violet — tympanic cavity; pink gradient — bone external auditory canal; reddish gradient — cartilage external auditory canal; CRAN — cranial view; LAO — left anterior oblique view; rest abbreviations — see Table 1.

Table 1. Results of the measurements

Category	Median	LQ	HQ	Minimum	Maximum	Mean	SD
Total volume of TBPS [mm³]	7882.58	6200.56	10393.16	2111.74	22589.79	8606.67	3595.39
MAC [mm³]	5813.05	4224.94	8181.81	414.17	19528.21	6470.97	3442.69
TC [mm³]	709.15	574.84	915.15	345.95	1342.18	750.12	221.16
Total volume of EAC [mm³]	1294.36	1099.68	1627.84	658.12	2605.12	1385.59	403.76
EAC surface [mm²]	711.24	626.40	815.11	425.88	1247.51	735.60	154.33
cEAC volume [mm³]	911.34	682.18	1206.44	339.72	1962.02	960.87	342.50
cEAC surface [mm²]	448.88	370.53	550.72	218.82	823.29	464.82	123.32
cEAC-to-EAC volume ratio	0.70	0.62	0.76	0.43	0.88	0.69	0.11
bEAC volume [mm³]	389.81	309.32	520.13	150.14	1078.53	424.72	168.18
bEAC surface [mm²]	264.52	206.12	332.61	112.19	520.10	270.78	86.68
EAC total length [mm]	25.70	23.91	27.71	19.87	34.80	25.98	3.05
cEAC length [mm]	14.88	13.48	17.56	9.22	21.86	15.45	2.80
bEAC length [mm]	10.03	8.30	12.57	4.97	18.18	10.53	2.95

LQ — lower quartile; HQ — higher quartile; SD — standard deviation; TBPS — temporal bone pneumatic spaces; MAC — mastoid air cells; TC — tympanic cavity; EAC — external acoustic canal; cEAC — cartilage part of the external acoustic canal; bEAC — bony part of the external acoustic canal

subgroups. For the general population, the median total volume of EAC was determined at 1294.36 mm³ (LQ: 1099.68; HQ: 1627.84). The median surface of the EAC was set at 711.24 mm² (LQ: 626.40; HQ: 815.11). The median volume of cEAC was determined at 911.34 mm³ (LQ: 682.18; HQ: 1206.44). The median surface of the cEAC was set at 448.88 mm² (LQ: 370.53; HQ: 550.72). The median length of the cEAC was demonstrated at 14.88 mm (LQ: 13.48; HQ: 17.56). The median volume of bEAC was set at 389.81 mm³ (LQ: 309.32; HQ: 520.13). The median surface of the bEAC was demonstrated at 264.52 mm² (LQ: 206.12; HQ: 332.61). The median length of the bEAC was set to 10.03 mm (LQ: 8.30; HQ: 12.57). The of the EAC of the cartilage part surface was demonstrated at 64.00% of the EAC (LQ: 56.00%; HQ: 70.00%). The surface of the bone part of EAC was set at 36.00% of EAC (LQ: 30.00%; HQ: 44.00%). All the results mentioned above and more detailed values are presented in Table 1.

The median surface of the EAC was set at 75.75 mm² (LQ: 57.07; HQ: 89.94) at the site of its lateral border (X1/Y1); 44.82 mm² (LQ: 37.85; HQ: 53.97) in the cartilaginous-bone transition (X3/Y3); and 30.84 mm² (LQ: 26.59; HQ: 36.57) at the site just distal to the appearance of the tympanic membrane (X5/ /Y5). All mentioned above and more detailed results regarding all parameters are illustrated in Table 2.

Table 2. Results of the measurements

Category	Median	LQ	HQ	Minimum	Maximum	Mean	SD
EAC X1 [mm]	8.35	7.38	9.52	4.33	13.84	8.45	1.74
EAC Y1 [mm]	10.88	9.48	12.57	3.96	15.66	10.88	2.22
EAC P1 [mm^2]	31.13	27.94	34.16	15.78	39.44	30.63	4.61
EAC Area1 [mm^2]	75.75	57.07	86.94	19.28	119.77	72.46	20.44
EAC X2 [mm]	7.27	6.26	8.24	3.90	64.00	7.95	5.96
EAC Y2 [mm]	9.69	8.61	11.17	6.30	13.22	9.79	1.56
EAC P2 [mm^2]	26.51	24.40	29.68	2.03	37.41	27.02	4.63
EAC Area2 [mm^2]	53.27	43.79	65.47	25.84	109.30	56.91	17.45
EAC X3 [mm]	6.17	5.46	7.05	4.41	14.93	6.37	1.50
EAC Y3 [mm]	9.60	8.19	10.57	5.27	14.49	9.42	1.75
EAC P3 [mm^2]	25.08	22.53	27.18	16.07	37.36	25.16	3.84
EAC Area3 [mm^2]	44.82	37.85	53.97	20.00	98.43	47.31	14.44
EAC X4 [mm]	5.29	4.76	5.97	3.76	10.75	5.53	1.30
EAC Y4 [mm]	7.90	7.07	8.68	4.04	11.09	7.95	1.37
EAC P4 [mm^2]	20.88	19.52	23.08	14.87	32.31	21.44	2.82
EAC Area4 [mm^2]	32.43	27.68	39.88	16.86	82.25	34.33	9.84
EAC X5 [mm]	5.15	4.48	6.64	3.29	9.67	5.61	1.44
EAC Y5 [mm]	7.63	7.05	7.98	2.64	10.93	7.34	1.31
EAC P5 [mm^2]	20.40	19.17	21.90	14.91	29.03	20.58	2.56
EAC Area5 [mm^2]	30.84	26.59	36.57	14.51	66.79	31.97	9.46

LQ — lower quartile; HQ — higher quartile; SD — standard deviation; EAC — external auditory canal; Point 1 corresponds to the distal end of the EAC; Point 3 corresponds to the transition from the bEAC to cEAC part; Point 5 is located at the proximal end of the EAC; Points 2 and 4 were placed halfway between points 1-3 and 3-5; For detailed description of the points 1-5, please see the Materials and Methods section

Regarding all categories mentioned in Table 1, potential differences in EAC between men and women were analysed. The measurement results obtained from male cases were significantly higher in 8 of 10 categories ($p < 0.05$): (1) total volume of EAC, (2) surface of EAC, (3) volume of cEAC, (4) surface of cEAC, (5) volume of bEAC, (6) surface of bEAC, (7) total length of EAC, (8) length of cEAC. All results mentioned above and detailed values regarding sex differences are presented in Table 3.

Furthermore, potential correlations were established with respect to the EAC results between each of the categories. None of the EAC results correlated with age. However, some categories corresponded to each other. The correlations between the categories are summarized in Table 4.

Air spaces results

Data on the air spaces were collected in three categories. For each category, analyses were performed considering the general population and the female and male subgroups. For the general population, the median total volume of the TBPS was demonstrated at 7882.52 mm^3 (LQ: 6200.56; HQ: 10393.16). The median MAC volume was set to 5813 mm^3 (LQ: 4224.94; HQ: 8181.81). The medial TC volume was set at 709.15 mm^3 (LQ: 574.84; HQ: 915.15). All the results mentioned above and more detailed values are collected in Table 1.

Regarding the results of the measurements of the air spaces of the ear, potential differences between men and women were analysed. The measurement results obtained from male cases were significantly higher in 2 of 3 categories ($p < 0.05$): (1) total volume of TBPS and (2) volume of TC. All the aforementioned results and detailed values regarding sex differences are presented in Table 3.

Furthermore, potential correlations with the results of measurements of the airspaces of the ear were established between each of the categories. The total volume of TBPS was significantly inversely correlated with age ($R = -0.26$; $p < 0.05$). Furthermore, MAC volume was significantly inversely correlated with age ($R = -0.31$; $p < 0.05$). The correlations between the categories are summarized in Table 4.

Table 3. Results of measurements according to the sex of the patients. Highlighted in red are those parameters which were statistically significant ($p \leq 0.05$)

Category	Sex	Median	LQ	HQ	Minimum	Maximum	Mean	SD	P
Total volume of TBPS [mm^3]	Female	7262.26	6200.56	8869.95	3649.67	14291.01	7644.75	2307.27	0.04
	Male	8628.54	6340.25	11767.53	2111.74	22589.79	9315.45	4185.58	
MAC [mm^3]	Female	5646.36	4281.17	7007.97	1606.27	11752.44	5810.50	2174.48	0.22
	Male	6015.76	4224.94	9100.49	414.17	19528.21	6957.62	4087.92	
TC [mm^3]	Female	648.89	543.62	851.14	345.95	1342.18	705.17	231.57	0.05
	Male	745.42	619.30	915.15	439.09	1254.85	783.24	209.05	
Total volume of EAC [mm^3]	Female	1102.73	999.85	1253.41	658.12	1627.84	1129.08	220.13	0.00
	Male	1515.85	1290.45	1791.14	917.20	2605.12	1574.59	405.09	
EAC surface [mm^2]	Female	632.07	583.63	708.10	425.88	833.96	641.09	90.82	0.00
	Male	790.83	697.06	896.44	508.57	1247.51	805.24	154.95	
cEAC volume [mm^3]	Female	731.04	616.82	911.34	339.72	1401.31	767.36	238.29	0.00
	Male	1105.43	843.52	1356.76	499.86	1962.02	1103.46	339.01	
cEAC surface [mm^2]	Female	402.24	330.94	460.44	218.82	605.52	400.09	93.95	0.00
	Male	497.04	430.66	615.55	274.97	823.29	512.52	121.22	
cEAC-to-EAC surface ratio	Female	0.61	0.56	0.70	0.42	0.80	0.62	0.10	0.16
	Male	0.64	0.58	0.71	0.41	0.82	0.64	0.09	
bEAC volume [mm^3]	Female	367.57	276.82	425.72	150.14	636.59	361.73	111.45	0.00
	Male	430.10	318.20	584.28	198.75	1078.53	471.13	187.71	
bEAC surface [mm^2]	Female	258.55	196.04	282.63	112.19	382.16	241.00	64.99	0.01
	Male	272.88	216.06	360.77	139.76	520.10	292.72	94.34	
EAC total length [mm]	Female	24.05	22.50	26.10	19.87	30.00	24.36	2.51	0.00
	Male	26.98	25.18	28.79	20.72	34.80	27.17	2.87	
cEAC length [mm]	Female	14.25	12.44	16.01	9.22	18.70	14.06	2.32	0.00
	Male	16.38	14.45	18.74	9.86	21.86	16.47	2.69	
bEAC length [mm]	Female	9.64	8.38	11.93	4.97	16.65	10.30	2.87	0.50
	Male	10.21	8.21	12.77	5.91	18.18	10.70	3.02	

LQ — lower quartile; HQ — higher quartile; SD — standard deviation; TBPS — temporal bone pneumatic spaces; MAC — mastoid air cells; TC — tympanic cavity; EAC — external acoustic canal; cEAC — cartilage part of the external acoustic canal; bEAC — bony part of the external acoustic canal

DISCUSSION

Numerous studies have reported on the degree of pneumatization patterns of the temporal bone using CT. Dexian Tan et al. [12] conducted a study in which a classification of TBP was made on high-resolution CT. In the study, they concluded that the degree of TBP varies among the different compartments. They also indicated the existing significant association between age and sex with the degree of pneumatization of the petrous apex and the infralabyrinthine compartment. Another type of classification of TBP using CT was carried out by Han et al. [17]. However, the aforementioned study contained a classification that was based on the sigmoid sinus. In the study, they explained that when the sigmoid sinus at the level of the malleoincudal complex was used in the classification, there were statistically significant variations between the groups that correlated with the entire volume of the temporal bone. These results match what was found in the present study, that is, that variations in the morphology of the air spaces of the temporal bone are associated with sex and age.

Many imaging techniques for the evaluation of temporal bone cavities have been presented in the literature [35]. CT is the most common modality for assessing the bony anatomy of the temporal bone. In our study, CTAs were used to analyse the air spaces of the temporal bone. Although CT is a good option for conducting analyses of air-filled spaces of the temporal bone, comparable evaluation of the osseous components of the skull base and sinonasal anatomy is possible at a lower cost and radiation dose with cone-beam computed tomography (CBCT) [22]. Therefore, numerous studies have been conducted on

Table 4. Table gathers the R values obtained in the correlation analysis between categories. Highlighted in red are those in which the p value was smaller than 0.05

Category	Age	Total volume of TBPS [mm³]	MAC [mm³]	TC [mm³]	Total volume of EAC [mm³]	EAC surface [mm²]	cEAC volume [mm³]	cEAC surface [mm²]	cEAC-to-EAC surface ratio [%]	bEAC volume [mm³]	bEAC surface [mm²]	EAC total length [mm]	cEAC length [mm]	bEAC length [mm]
Age	1.00	–0.26	–0.31	–0.06	0.15	0.17	0.12	0.10	–0.09	0.14	0.17	0.18	0.05	0.17
Total volume of TBPS [mm³]	–0.26	1.00	0.98	0.58	0.07	0.17	–0.03	0.02	–0.13	0.18	0.21	0.26	0.05	0.19
MAC [mm³]	–0.31	0.98	1.00	0.50	–0.07	0.03	–0.16	–0.10	–0.15	0.11	0.14	0.17	–0.02	0.15
TC [mm³]	–0.06	0.58	0.50	1.00	0.30	0.39	0.15	0.19	–0.12	0.33	0.32	0.37	0.08	0.27
Total volume of EAC [mm³]	0.15	0.07	–0.07	0.30	1.00	0.92	0.90	0.86	0.29	0.40	0.32	0.60	0.59	0.08
EAC surface [mm²]	0.17	0.17	0.03	0.39	0.92	1.00	0.75	0.79	0.10	0.55	0.52	0.71	0.50	0.25
cEAC volume [mm³]	0.12	–0.03	–0.16	0.15	0.90	0.75	1.00	0.96	0.61	0.03	–0.04	0.39	0.71	–0.22
cEAC surface [mm²]	0.10	0.02	–0.10	0.19	0.86	0.79	0.96	1.00	0.65	0.02	–0.05	0.41	0.77	–0.26
cEAC-to-EAC surface ratio	–0.09	–0.13	–0.15	–0.12	0.29	0.10	0.61	0.65	1.00	–0.69	–0.77	–0.19	0.62	–0.76
bEAC volume [mm³]	0.14	0.18	0.11	0.33	0.40	0.55	0.03	0.02	–0.69	1.00	0.95	0.58	–0.12	0.70
bEAC surface [mm²]	0.17	0.21	0.14	0.32	0.32	0.52	–0.04	–0.05	–0.77	0.95	1.00	0.61	–0.20	0.80
EAC total length [mm]	0.18	0.26	0.17	0.37	0.60	0.71	0.39	0.41	–0.19	0.58	0.61	1.00	0.43	0.57
cEAC length [mm]	0.05	0.05	–0.02	0.08	0.59	0.50	0.71	0.77	0.62	–0.12	–0.20	0.43	1.00	–0.45
bEAC length [mm]	0.17	0.19	0.15	0.27	0.08	0.25	–0.22	–0.26	–0.76	0.70	0.80	0.57	–0.45	1.00

TBPS — temporal bone pneumatic spaces; MAC — mastoid air cells; TC — tympanic cavity; EAC — external acoustic canal; cEAC — cartilage part of the external acoustic canal; bEAC — bony part of the external acoustic canal

the TBP patterns with the use of CBCT [11, 14]. The image quality of the CBCT has also been described as superior to that of multiple-slice CT scans [36].

Knowledge about the morphology of the EAC is of great importance when performing procedures in that area, e.g. when performing myringoplasty. Myringoplasty is the term used for surgical repairs of minor perforations of the tympanic membrane. These perforations are most often caused by trauma, infections, or iatrogenic causes. Up to 80% of them are said to close spontaneously [1]. However, in some cases, myringoplasty is required. To access the tympanic membrane for myringoplasty, there are three recognised surgical approaches: permeatal, endaural, and postaural. Sharma et al. [39] conducted a prospective study on the different surgical approaches used when performing myringoplasty. In the study, they presented different results of myringoplasty when using these approaches. The highest success rate was found to be associated with the postaural approach (86.66%) and the lowest with the permeatal approach (73.33%). It was also stated that an issue with the permeatal approach was that it was only suitable in cases where the EAC was wide enough to allow complete visualisation of the tympanic membrane. Other studies have also stated the same [31]. The current study showed that there is sexual dimorphism in the morphometric properties of the EAC. Women, on average, had lower volumes, smaller total surface area, and shorter length of EAC. These results show that the permeatal approach might be less favourable in women than in men and that a different approach should be considered. Extensive knowledge of the morphology of the EAC is also important when treating squamous cell carcinoma (SCC) in that area. SCC is the most common primary type of cancer that affects the temporal bone, including the EAC [3]. The main form of therapy for cancers of the EAC and temporal bone is surgery. Nakagawa et al. [32] presented a study on the treatment of a SCC in the EAC. In the study, they performed a lateral bone resection of the tumour, not beyond the tympanic membrane. They concluded that radical surgery with preoperative chemoradiotherapy was effective in improving the estimated survival of patients with an advanced stage of SCC of the temporal bone. EAC cholesteatoma is an inflammatory process associated with ectopic proliferation of squamous tissue that results in osteolysis. It is a rare form of cholesteatoma first described by Toynbee in 1850 [42]. The typical location of this disease is the middle ear cavity, and the treatment modalities for EAC cholesteatomas vary and depend on the extent of the involvement. For smaller lesions localized to the EAC, debridement is suggested and for greater lesions, surgery is recommended [6].

Tympanosclerosis (TS) represents the deposition of hyalinised collagen in the TC and has been reported to be associated with chronic otitis media [30]. Deposition can occur in the tympanic membrane, the mucosa lining of the TC, the ossicular chain, and occasionally the mastoid [5]. However, in most cases, TS affects mainly the tympanic membrane. Intratympanic TS most commonly involves silent areas in the middle ear, with ossicular involvement seen in 30–40% of cases of intratympanic TS [29]. The severity of the impact of TS on hearing is determined primarily by the location and extent of TS plaques [5]. When TS plaques affect the mobility of the tympanic membrane, they have to be surgically removed. Larem et al. [29] presented a high success rate of tympanoplasty in the myringosclerosis ears with a postoperative air-bone gap $\leq$ 20 dB in 96.5% of cases. As mentioned above, the ossicle chain can also be affected by TS. This can lead to fixation of the incudo-malleal complex or fixation of stapes. Tympanoplasty has been generally accepted as the choice of procedure for hearing restoration in cases where TS involves the ossicular chain. This involves the removal of TS mass, followed by a reconstruction of the middle ear sound conductive mechanism [43]. In cases of fixation of the incudo-malleal complex, possible treatment may be the removal of the incus and the head of the malleus and the insertion of a partial ossicular replacement prosthesis [29]. Surgical interventions when the stapes is fixed are a manner of great controversy. Some authors state that stapedectomy is the more reliable treatment for stapes fixation [9, 46]. However, others report that this procedure carries an unacceptable risk of postoperative sensorineural hearing loss and that mobilisation of stapes could be a better option [41]. Knowledge of the morphology of the TC is crucial when performing procedures in this area. The results of the present study show that there is a sexual dimorphism in the morphometric properties of the TC. TC was shown to have, on average, a smaller total volume in women than in men. Kavakli et al. [26] investigated the differences in the volume of the TC between men and women. In the results study, the presented were similar to those in the present analysis. Therefore, surgeons should consider this when performing operations in this area.

The morphometric properties of the MAC are of great importance in order to understand their physiology and pathogenesis. These properties are mainly studied from a volumetric point of view because the mastoid cavity has been regarded as an air reservoir [34]. Colhoun et al. [10] conducted a CT-based study in which the area and volume measurements of the mastoid air spaces of 26 normal temporal bones of cadavers were analysed. In the study, the mean value of mastoid volume was measured at 8.4 ± 3.6 cm^3. Similarly, Park et al. [34] studied these properties in 24 normal ears, where the mean value of mastoid volume was 10.43 ± 6.66 cm^3. In the present study, the mean volume of MAC was measured to be 6.47 ± 3.44 cm^3, which is relatively lower than the two values mentioned above. Both of the cited studies were performed on cadavers, compared to the subjects used in this paper, which consisted of living patients. An explanation for this discrepancy may be that the extent of the contrast window was defined differently. This suggests that the boundary layers corresponding to the epithelium, for example, were chosen too restrictively, resulting in an underestimation of the measurement. Studies about the morphometric properties of the MAC based on CT have also been published in the literature. Karakas et al. [25] presented a morphometric examination of the MAC using CT. In the study, the mean value of the mastoid volume was 14.05 ± 7.24 cm^3, which is more than double the volume recorded in the present analysis. However, the results of the current study are very similar to those presented by Isono et al. [20], which were measured to be 6.3 cm^3 (no standard deviation was reported). The differences between the values might be due to many different factors, such as measuring techniques, the number of subjects used, or racially based differences.

Understanding the anatomy of the temporal bone is crucial when performing mastoid surgery. Mastoidectomy is a surgical procedure of the temporal bone in which postauricular air cells are opened by removing the bone that separates them. There are many indications for mastoidectomy to be performed, which can include cholesteatoma, acute mastoiditis, and chronic mastoiditis [8]. Mastoidectomy is also performed as a surgical approach for numerous otological procedures, such as facial nerve surgery, cochlear implantation, and labyrinthectomy [27]. In the present study, measurements and statistical analysis of MAC volume were performed. The sexual dimorphism was shown to occur in the total volume of the mastoid cavity. Women had, on average, smaller volumes of MAC than men. Additionally, a statistically significant correlation was found between mastoid cavity volume and age, where the volume of the mastoid cavity was shown to become lower with age. Therefore, these results should be taken into consideration when performing mastoidectomies or other procedures concerning the mastoid. The patients' age should be taken into account when performing these procedures, especially in older patients, since their mastoid cavity volumes might be lower.

Limitations of the study

However, this study is not without limitations. The authors of the current study did not have access to clinical data about the patients from whom the CTs were analysed. Despite statistically significant results, a study in a larger study group is still warranted to minimise potential bias and establish the most accurate parameters. Furthermore, this study is also burdened with a possible measurement error, as the results are only as good as the quality of the images analysed and the numerical accuracy of the software used.

CONCLUSIONS

The present study is the first to analyse the degree of pneumatization and the morphology of temporal bone cavities, with respect to different compartments, sides, sex, and age. The results showed that the total volume of the mastoid air cells was, on average, lower in women than in men. This should be taken into consideration when performing procedures on the mastoid, such as mastoidectomies. Furthermore, sexual dimorphism in the morphometric properties of the external auditory canal was found. Women, on average, had lower volumes, smaller total surface areas, and shorter external auditory canals. This study provides surgeons with crucial data that can surely be useful when performing otological procedures — which should be taken into consideration to avoid any unexpected complications.

Conflict of interest: None declared

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