The Journal of Laryngology & Otology

cambridge.org/jlo

Effects of mastoid and middle-ear volume on graft success and hearing outcomes in paediatric tympanoplasty

D Baklaci[1], E Bilgin[1], E K Çelik[2], A Kılıç[3], D Erdem[1] and S S Eliçora[1]

[1]Department of Otorhinolaryngology, School of Medicine, Bulent Ecevit University, Zonguldak, [2]Department of Otorhinolaryngology, Diskapi Training and Research Hospital, Ankara and [3]Department of Radiology, Kahramankazan State Hospital, Ankara, Turkey

Main Article

Dr D Baklaci takes responsibility for the integrity of the content of the paper

Cite this article: Baklaci D, Bilgin E, Çelik EK, Kılıç A, Erdem D, Eliçora SS. Effects of mastoid and middle-ear volume on graft success and hearing outcomes in paediatric tympanoplasty. *J Laryngol Otol* 2022;**136**: 404–409. https://doi.org/10.1017/S0022215121004400

Accepted: 14 June 2021
First published online: 7 January 2022

Key words:
Child; Tympanoplasty; Mastoid; Ear, Middle; Tomography

Author for correspondence:
Dr Deniz Baklaci, No: 44A/9,
Vatan Avenue, Zonguldak, Turkey
E-mail: doktorent@gmail.com

Abstract

Objective. To examine the effects of mastoid and middle-ear volume on the anatomical and functional success of type 1 tympanoplasty in paediatric patients.

Methods. This study included 45 paediatric patients who underwent type 1 cartilage tympanoplasty. Patients' demographic data, pre- and post-operative audiological evaluation results, and post-operative graft status were evaluated. Middle-ear and mastoid cavity volumes were calculated (in cubic centimetres) using temporal bone high-resolution computed tomography. Middle-ear and mastoid cavity volume values were compared between patients with and without post-operative anatomical and functional success.

Results. Anatomical success was achieved in 82.2 per cent of patients ($n = 37$), and functional success in 68.9 per cent ($n = 31$). When anatomical success and failure groups were compared, a statistically significant difference was found in mean mastoid volume ($p = 0.037$), while there was no significant difference in relation to mean middle-ear volume ($p = 0.827$). The comparison of functional success and failure groups revealed no significant difference in mean mastoid volume ($p = 0.492$) or middle-ear volume ($p = 0.941$).

Conclusion. The study showed that mastoid pneumatisation volume affects surgical success in paediatric tympanoplasty.

Introduction

Tympanoplasty is a common otological intervention, with the primary goals of a healthy middle-ear cavity and improved hearing. In the literature, various factors are reported to affect surgical outcomes in tympanoplasty, such as age, perforation size and location, condition of the contralateral ear, graft type, and middle-ear and mastoid bone pneumatisation.[1,2]

The middle ear is a very complex anatomical structure. It is a narrow chamber located in the tympanic part of the temporal bone, covered with mucosa, and contains air. It transmits vibrations from the outer-ear canal to the inner ear through the tympanic membrane and ossicles. At birth, the middle-ear cavity is filled with air. The main factor in the postnatal development of middle-ear volume is skull growth in the vertical axis. The middle-ear volume in adult individuals is 1.5 times larger than that in infants.[3] Although there is an increase in middle-ear volume with age, a strong correlation has not been shown between the two.[4] It has been reported that middle-ear volume is larger in males than in females.[5] The middle ear is posteriorly connected to mastoid cells through the aditus ad antrum. The mastoid air system is one of the most important structures for the functional balance of the middle ear. Mastoid air cells are the air reservoir for the middle ear and play an important role in the physiological functions of the middle ear by taking part in the regulation of heat and pressure.[6] The development of the mastoid air cell system is completed at an age of about 10 years in females and 15 years in males.[7,8]

While many studies have reported a success rate of 60–99 per cent for tympanoplasty in adults, this success range is reduced to 35–94 per cent for the paediatric age group.[9] Incomplete Eustachian tube function and continued development of mastoid pneumatisation in the paediatric group are considered to be the reasons for tympanoplasty failure.[10] The decrease in the degree of mastoid pneumatisation may adversely affect the transmission of sound waves through the middle ear and the prognosis of middle-ear disease.[2,11,12]

Mastoid pneumatisation has been calculated quantitatively using several methods based on water weight, acoustics and a pressurised transducer.[13–15] Recent and significant advances in computed tomography (CT) have provided better images of the anatomical features of the temporal bone.[6] For this purpose, multiplanar reconstruction is used.[6,8] This method allows simple and accurate measurements of the degree of mastoid and middle-ear pneumatisation.

To the best of our knowledge, there is no previously published study investigating the effects of mastoid and middle-ear pneumatisation volume, measured using high-

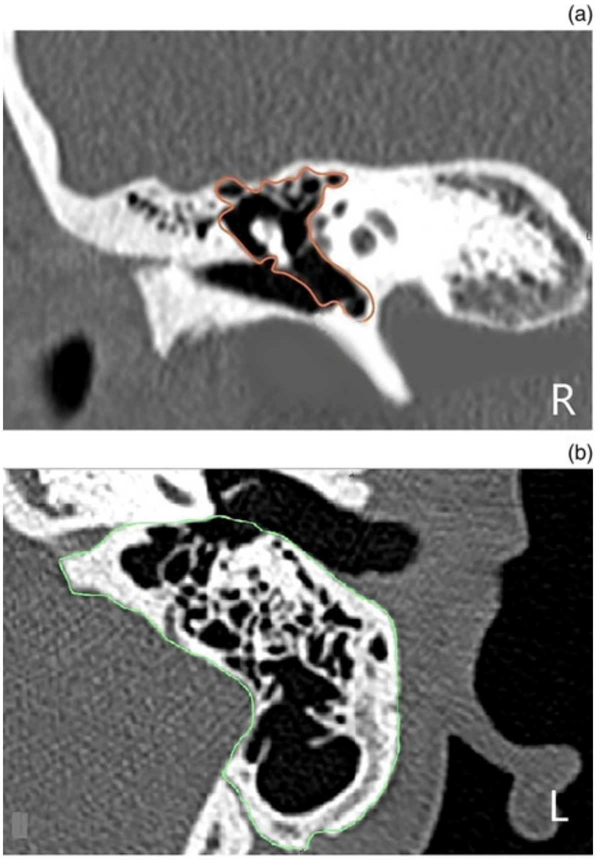

Fig. 1. Using the segmentation tool, regions of interest were manually drawn in each section in the axial and coronal planes, based on the conventional anatomical boundaries around the middle ear (a) and mastoid bone (b). R = right; L = left

resolution CT, on the success of tympanoplasty in paediatric patients. The current study aimed to reveal the effects of mastoid and middle-ear pneumatisation volume on the anatomical and functional success of type 1 tympanoplasty in paediatric patients.

Materials and methods

This retrospective study was conducted in a tertiary healthcare institution with the approval of the clinical research ethics committee (approval number: 2020/17-1). Written informed consent was obtained from the parents or guardians of the children prior to surgery. The study was conducted in accordance with the principles of the Declaration of Helsinki.

Forty-five paediatric patients who were diagnosed with chronic otitis media and who underwent type 1 cartilage tympanoplasty between January 2013 and January 2020 were included. Temporal bone high-resolution CT was performed on all patients to exclude middle-ear pathologies and ossicular chain defects and to determine the presence of soft tissue in the antrum requiring mastoidectomy. The side effects of radiation were explained to all parents prior to high-resolution CT, as was the reason why the high-resolution CT was planned.

The criteria for admission to the study were: the absence of ear drainage for the last three months prior to surgery, no evidence of inflammation, and the absence of ossicular pathology and mastoiditis on high-resolution CT images of the temporal bone. Patients were excluded from the study if they had: ossicular chain defects, cholesteatoma, tympanosclerosis, a history of previous ear surgery, refractory otorrhoea or craniofacial anomaly, and irregular follow-up records. Further excluded

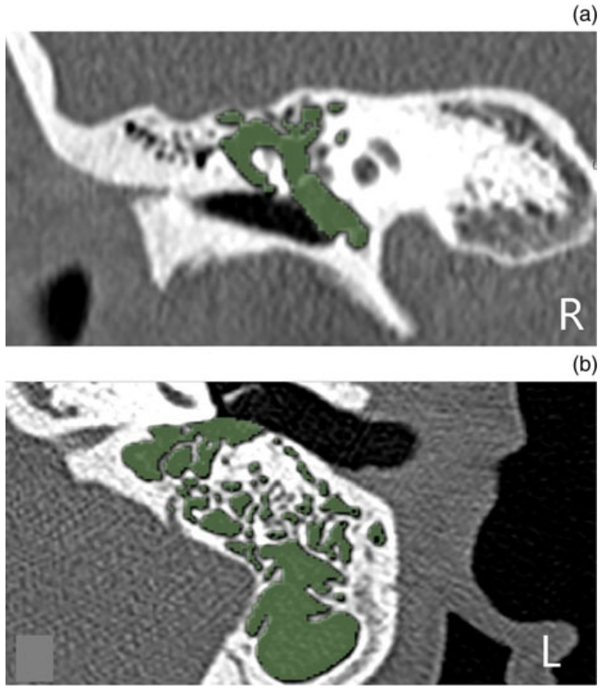

Fig. 2. Pneumatised areas were identified with the threshold algorithm for the air values, for the middle ear (a) and mastoid (b). R = right; L = left

were those without pre-operative audiological examination records or temporal bone high-resolution CT images.

For all the patients, in addition to age and gender, the audiological examination findings for the operated ears, the post-operative condition of the graft, and the middle-ear and mastoid volume, were recorded. The minimum post-operative follow-up period of the patients was six months.

Type 1 cartilage tympanoplasty was performed in all patients under general anaesthesia using the retroauricular approach and the overlay–underlay technique. Conchal cartilage was used as the graft tissue. Anatomical success was defined as an intact graft without perforation, lateralisation and a dry ear. The anatomical success of tympanoplasty was evaluated at the sixth post-operative month.

The pre- and post-operative pure tone audiometry tests of the patients were examined, and the bone conduction, air conduction and air–bone gap (ABG) values were recorded. The results of pure tone audiometry were calculated at four frequencies (0.5, 1, 2 and 3 kHz). The changes between the pre- and post-operative ABG values were evaluated. An ABG value of 20 dB HL or less was considered to indicate functional success.

High-resolution computed tomography

All CT images were evaluated by a specialist radiologist (AK). The high-resolution CT images were taken in the axial plane using a Toshiba Aquilion 64-slice CT device (Toshiba Medical, Tokyo, Japan) at 1 mm intervals, without intravenous contrast material administration. Coronal and sagittal multiplanar reconstruction images were constructed. Sections were obtained in such a way as to include the entire temporal bone and important surrounding structures.

Using the segmentation tool in the Horos picture archiving and communication system viewer software,[16] regions of interest were manually drawn in each section in the axial and coronal planes based on the conventional anatomical boundaries around the middle ear (Figure 1a) and mastoid bone

https://doi.org/10.1017/S0022215121004400 Published online by Cambridge University Press

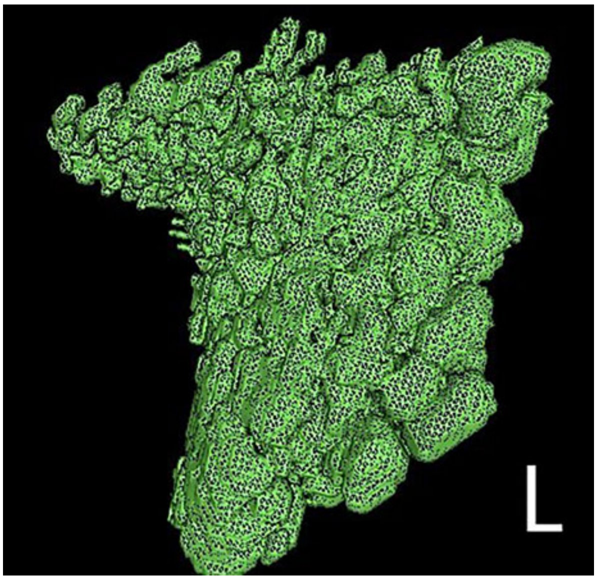

Fig. 3. Three-dimensional reconstruction of pneumatisation of a left mastoid bone. L = left

(Figure 1b). Pneumatised areas were then identified with the threshold algorithm for the air values (Figure 2a and b). Subsequently, manual corrections were performed in each section, and separate regions of interest were created for the air spaces in all sections. These areas were combined with the volume calculator in the Horos picture archiving and communication system viewer to determine the total air volume in cubic centimetres, and three-dimensional (3D) images of the air volume were obtained (Figure 3).

Statistical analysis

Mean, standard deviation, median, minimum and maximum values were used as descriptive statistics for continuous data, with percentages as discrete data. The Shapiro–Wilk test was conducted to examine the conformity of continuous data to the normal distribution. The Wilcoxon test was undertaken for the pre- and post-operative comparison of continuous data, and for comparison of the values between the operated and healthy sides. The Mann–Whitney U test was used to compare volume values according to graft and functional success. The IBM SPSS® Statistics version 20 software program was used for statistical analyses, and $p < 0.05$ was accepted as the statistical significance limit.

Results

The age of the 45 patients included in the study ranged from 8 to 18 years, with a mean value of 13.33 ± 3.05 years. Of the patients, 46.7 per cent were male and 53.3 per cent were female. Tympanoplasty was performed on the right ear in 42.2 per cent of patients and on the left ear in 57.8 per cent. Disease was unilateral in 77.8 per cent of patients ($n = 35$) and was bilateral in 22.2 per cent ($n = 10$) (Table 1).

The mean pre-operative bone conduction value was 5.87 ± 3.01 dB HL, and the mean post-operative bone conduction value was 6.16 ± 3.59 dB HL. There was no statistically significant difference between the pre- and post-operative bone conduction values ($p = 0.739$). The mean pre- and post-operative air conduction values were 28.13 ± 10.59 dB HL and 15.58 ± 9.24 dB HL, respectively, indicating a statistically significant difference ($p < 0.001$). The mean pre- and post-operative ABG values were 22.62 ± 9.91 dB HL and 9.42 ± 7.85 dB HL, respectively. A statistically significant difference was found between the pre- and post-operative ABG values ($p < 0.001$) (Table 2).

Table 1. Patient characteristics

Characteristics	Values
Age at operation (mean ± SD; years)	13.33 ± 3.05
Gender (*n* (%))	
– Male	21 (46.7)
– Female	24 (53.3)
Operated side (*n* (%))	
– Right	19 (42.2)
– Left	26 (57.8)
Laterality (*n* (%))	
– Unilateral	35 (77.8)
– Bilateral	10 (22.2)

SD = standard deviation

For the operated ears, the mean hearing gain value was 13.20 ± 9.71 dB HL. The mastoid volume in the operated ears ranged from 0.05 to 7.22 cm^3, with a mean of 1.89 ± 1.59 cm^3. The middle-ear volume of these ears varied between 0.28 and 0.65 cm^3, with a mean value of 0.47 ± 0.10 cm^3 (Table 3). Anatomical success was achieved in 82.2 per cent of the operated patients and functional success was achieved in 68.9 per cent (Table 4).

The mean mastoid volume was 2.09 ± 1.66 cm^3 for the patients with successful grafts and 0.98 ± 074 cm^3 for those in the graft failure group. A statistically significant difference was found between the mean mastoid volume values of the graft success and failure groups ($p = 0.037$). However, there was no difference between these two groups in terms of the mean middle-ear volume ($p = 0.827$) (Table 5).

When the functional success group was compared with the functional failure group, no statistically significant difference was observed in relation to the mean mastoid volume and middle-ear volume values ($p = 0.492$ and $p = 0.941$, respectively) (Table 6).

The mean mastoid volume of the operated ears was 1.89 ± 1.59 cm^3, and that of the intact ears was 2.63 ± 2.09 cm^3. A statistically significant difference was detected between the mastoid volume values of the operated and healthy sides ($p = 0.046$). The mean middle-ear volume values of the operated and intact ears were 0.47 ± 0.10 cm^3 and 0.47 ± 0.11 cm^3, respectively, revealing no statistically significant difference between the two sides ($p = 0.394$). The statistical comparison results of the post-operative bone conduction, air conduction and ABG values between the operated and healthy ears are given in Table 7.

Discussion

As a result of our study, we found that the mastoid pneumatisation volume of the ears with anatomical graft failure was smaller than those of the ears with anatomical graft success in patients who had undergone paediatric tympanoplasty. The mastoid pneumatisation system is a good air reservoir for the middle ear, and the function of the middle-ear cavity

Table 2. Comparison of pre- and post-operative bone conduction, air conduction and air–bone gap in operated ears

	Pre-operative		Post-operative		
Parameter	Mean ± SD	Median (range)	Mean ± SD	Median (range)	*P*-value
Bone conduction (dB HL)	5.87 ± 3.01	5 (0–10)	6.16 ± 3.59	5 (0–18)	0.739
Air conduction (dB HL)	28.13 ± 10.59	25 (13–55)	15.58 ± 9.24	13 (5–63)	<0.001
Air–bone gap (dB HL)	22.62 ± 9.91	21 (6–53)	9.42 ± 7.85	7 (0–45)	<0.001

SD = standard deviation

Table 3. Hearing gain, and mastoid and middle-ear volume in operated ears

Parameter	Mean ± SD	Median (range)
Hearing gain (dB HL)	13.20 ± 9.71	11 (7–40)
Mastoid volume (cm^3)	1.89 ± 1.59	1.56 (0.05–7.22)
Middle-ear volume (cm^3)	0.47 ± 0.10	0.48 (0.28–0.65)

SD = standard deviation

Table 4. Graft and functional success rates in operated ears

Success rates	Operated ears (*n* (%))
Graft success	
– Present	37 (82.2)
– Absent	8 (17.8)
Functional success	
– Present	31 (68.9)
– Absent	14 (31.1)

is closely related to the degree of pneumatisation of this system.[11,17] In addition to publications advocating that mastoid development is a genetically determined process, there are those reporting that various environmental factors such as infectious and serous otitis media can limit this development.[6,17,18] Aoki *et al.*[19] showed that the growth of mastoid cells and the transmucosal gas exchange function of the middle ear were closely related to histopathological changes in the middle-ear mucosa due to middle-ear infections.

The anatomical structure of mastoid cells poses a challenge to accurately measuring the volume; however, 3D measurement techniques have enabled the calculation of true volume. Casale *et al.*[20] compared the mastoid–middle-ear volume calculation technique in temporal bone high-resolution CT with tympanometry, and revealed that radiological measurements were more reliable in this calculation.

Although we identified several publications evaluating mastoid volume in healthy paediatric patients, there were only limited data on paediatric patients with chronic otitis media in this area. Hamada *et al.*[21] showed that severe inflammatory and infectious events in the middle-ear mucosa caused strong suppression of mastoid pneumatisation. Csakanyi *et al.*[11] reported that the mastoid volume of children with otitis media with effusion was smaller than that of healthy children (2.82 ± 1.51 ml *vs* 10.05 ± 5.3 ml). This is supported by the findings of our study, which revealed that the mean mastoid volume of the healthy ears (2.63 ± 2.09 cm^3) was significantly higher compared with that of the operated ears (1.89 ± 1.59 cm^3).

In contrast to mastoid volume, when we examined middle-ear volume on the intact and operated sides (0.47 ± 0.10 cm^3 and 0.47 ± 0.11 cm^3, respectively), we did not observe a significant difference. The middle-ear volume values we obtained were similar to the high-resolution CT measurements of healthy control groups reported in the literature.[4,22] The longer vertical elongation of the head being the main factor in the development of middle-ear volume, the middle ear being larger in men than in women, the absence of a significant difference between the middle-ear volume of healthy and diseased ears, and, lastly, the similarity between the previously reported middle-ear volume values of the completely healthy individuals and the data of our chronic otitis media patients suggest that the determinants of middle-ear volume may be genetic rather than environmental factors. Clearer conclusions will be drawn from further studies conducted with different ethnic groups and larger populations.

Although mastoid pneumatisation plays an important role in middle-ear functioning, different findings have been presented regarding the effect of reduced pneumatisation on tympanoplasty success. Holmquist and Bergström showed that the tympanoplasty success rate was high in ears with sufficient mastoid volume even if Eustachian tube function was impaired.[23] In a study conducted with paediatric patients, Merenda *et al.*[18] examined the effect of tympanometric volume on tympanoplasty success, and showed that a tympanometric volume of 3 cm^3 or above correlated with the success of this surgery. Thus, the authors recommended choosing the time for surgery when the tympanometric volume value was above 3 cm^3 in paediatric patients, to increase tympanoplasty success rates. However, in that study, the area evaluated as tympanometric volume included the external ear canal, middle-ear and mastoid cavity volume. Takahashi *et al.*[24] showed that the lack of mastoid pneumatisation and Eustachian tube mechanical obstruction on high-resolution CT imaging negatively affected tympanoplasty results. In contrast, Metin *et al.*[25] found no significant relationship between mastoid pneumatisation and graft success and hearing gain in patients undergoing type 1 tympanoplasty and antrostomy. Yegin *et al.*[2] examined the effect of mastoid pneumatisation on graft success in type 1 tympanoplasty in adult patients and concluded that the degree of mastoid pneumatisation did not affect the operation's success.

Our study draws attention to factors other than those described in the literature that could affect the success of tympanoplasty in paediatric patients with chronic otitis media. We found that mastoid volume was higher in patients with anatomically successful grafts; however, higher mastoid volume did not affect functional success in a statistically significant manner. Casale *et al.*[20] evaluated the relationship between mastoid–middle-ear volume and conductive hearing loss in patients with an isolated tympanic membrane perforation, and showed that hearing loss incidence was higher in ears

https://doi.org/10.1017/S0022215121004400 Published online by Cambridge University Press

Table 5. Comparison of mastoid and middle-ear volume in operated ears for graft success and failure groups

	Graft success*		Graft failure†		
Parameter	Mean ± SD	Median (range)	Mean ± SD	Median (range)	*P*-value
Mastoid volume (cm^3)	2.09 ± 1.66	1.79 (0.05–7.22)	0.98 ± 0.74	0.73 (0.21–2.11)	0.037
Middle-ear volume (cm^3)	0.47 ± 0.11	0.45 (0.28–0.65)	0.47 ± 0.06	0.48 (0.33–0.53)	0.827

*n = 37; †n = 8. SD = standard deviation

Table 6. Comparison of mastoid and middle-ear volume in operated ears for functional success and failure groups

	Functional success*		Functional failure†		
Operated ear parameters	Mean ± SD	Median (range)	Mean ± SD	Median (range)	*P*-value
Mastoid volume (cm^3)	1.50 ± 1.08	1.48 (0.05–3.51)	2.07 ± 1.76	1.84 (0.21–7.22)	0.492
Middle-ear volume (cm^3)	0.47 ± 0.11	0.47 (0.28–0.61)	0.47 ± 0.10	0.48 (0.29–0.65)	0.941

*n = 14; †n = 31. SD = standard deviation

Table 7. Comparison of post-operative parameters in operated and intact ears

	Operated ears		Intact ears		
Post-operative parameters	Mean ± SD	Median (range)	Mean ± SD	Median (range)	*P*-value
Bone conduction (dB HL)	6.16 ± 3.59	5 (0–18)	4.96 ± 2.30	5 (0–10)	0.021
Air conduction (dB HL)	15.58 ± 9.24	13 (5–63)	10.84 ± 6.17	10 (5–32)	0.001
Air–bone gap (dB HL)	9.42 ± 7.85	7 (0–45)	5.89 ± 6.31	5 (0–27)	0.001

SD = standard deviation

with a small mastoid–middle-ear volume compared to those with a large volume. Similarly, Mehta *et al.*[26] reported that the size of the middle-ear volume and the degree of hearing loss were inversely correlated, independently of other variables. However, in both studies, no data were presented concerning the effect of volume values measured in high-resolution CT on post-operative hearing outcomes. In this respect, we consider our study to have the features of a preliminary investigation guiding future research.

- The effects of mastoid and middle-ear volume on the anatomical and functional success of type 1 tympanoplasty in paediatric patients were examined
- Mastoid pneumatisation volume was a positive factor affecting surgical success in paediatric tympanoplasty
- Middle-ear volume had no significant effect on functional and anatomical success

This study has certain limitations. Because of its retrospective design, patients' records obtained from medical charts may have been inaccurate or missing. The limited number of patients and the absence of a completely healthy control group were other limiting factors. Patient- and disease-related factors that may affect anatomical and functional outcomes should also not be overlooked. Finally, we investigated the anatomical and functional outcomes only at the sixth post-operative month.

Conclusion

We determined that mastoid pneumatisation affected the anatomical success of cartilage tympanoplasty in paediatric patients. The middle-ear volume was not affected by middle-ear pathologies, and it had no effect on the anatomical and functional success of tympanoplasty. However, further studies are needed to evaluate the outcomes in larger patient groups over a longer follow-up period.

Competing interests. None declared

References

1 Zollner F. The principles of plastic surgery of the sound-conducting apparatus. *J Laryngol Otol* 1955;**69**:637–52
2 Yegin Y, Celik M, Simsek BM, Masallah B, Olgun B, Aylin K *et al.* Impact of the degree of the mastoid pneumatization on cartilage type 1 tympanoplasty success. *J Craniofac Surg* 2016;**27**:695–8
3 Virapongse C, Rothman SL, Kier EL, Sarwar M. Computed tomographic anatomy of the temporal bone. *AJR Am J Roentgenol* 1982;**139**:739–49
4 Kavakli A, Ogeturk M, Yildirim H, Karakas S, Karlidag T, Sarsilmaz M. Volume assessment of age-related conversion of the tympanic cavity by helical computerized tomography scanning. *Saudi Med J* 2004;**235**:1378–81
5 Ikui A, Sando I, Haginomori S, Sudo M. Postnatal development of the tympanic cavity: a computer-aided reconstruction and measurement study. *Acta Otolaryngol* 2000;**120**:375–9
6 Lee DH, Jun BC, Kim DG, Jung MK, Yeo SW. 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
7 Diamant M. Otitis and pneumatization of mastoid bone. *Acta Otolaryngol* 1940;**60**:11–14
8 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**:595–8
9 Inwood JL, Wallace HC, Clarke SE. Endaural or postaural incision for myringoplasty: does it make a difference to the patient? *Clin Otolaryngol Allied Sci* 2003;**28**:396–8

10 Kaya I, Benzer M, Gode S, Sahin F, Bilgen C, Kirazli T. Pediatric type 1 cartilage tympanoplasty outcomes: a comparison of short and long term hearing results. *Auris Nasus Larynx* 2018;**45**:722–7
11 Csakanyi Z, Katona G, Josvai E, Mohos F, Sziklai I. Volume and surface of the mastoid cell system in otitis media with effusion in children: a case-control study by three-dimensional reconstruction of computed tomographic images. *Otol Neurotol* 2011;**32**:64–70
12 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**:486–90
13 Silbiger H. Measurement of mastoid pneumatisation in man. *Acta Anat* 1950;**11**:215–45
14 Molvaer OI, Vallersnes FM, Kringlebotn M. The size of the middle ear and the mastoid air cell. *Acta Otolaryngol* 1978;**85**:24–32
15 Andreasson L, Mortensson W. Comparison between the area and the volume of the air-filled ear space. *Acta Radiol Diagn* 1975;**16**:347–52
16 Horos. In: https://horosproject.org/ [4 March 2022]
17 Kim HJ, Kim MJ, Jeon JH, Kim JM, Moon IS, Lee WS. Functional and practical outcomes of inlay butterfly cartilage tympanoplasty. *Otol Neurotol* 2014;**35**:1458–62
18 Merenda D, Koike K, Shafiei M, Ramadan H. Tympanometric volume: a predictor of success of tympanoplasty in children. *Otolaryngol Head Neck Surg* 2007;**136**:189–92
19 Aoki K, Mitani Y, Tuji T, Hamada Y, Utahashi H, Moriyama H. Relationship between middle ear pressure, mucosal lesion, and mastoid pneumatization. *Laryngoscope* 1998;**108**:1840–5
20 Casale G, Shaffrey E, Kesser BW. Correlation between hearing loss and middle ear volume in patients with a tympanic membrane perforation. *Laryngoscope* 2020;**130**:228–32
21 Hamada Y, Utahashi H, Aoki K. Physiological gas exchange in the middle ear cavity. *Int J Pediatr Otorhinolaryngol* 2002;**64**:41–9
22 Kurkcuoglu A, Kurkcuoglu SS, Inancli HM, Enoz M, Pelin C, Zagyapan R. Measurement of tympanic cavity volume by the Cavalieri principle in Turkish population. *Kulak Burun Bogaz Ihtis Derg* 2010;**20**:137–41
23 Holmquist J, Bergström B. The mastoid air cell system in ear surgery. *Arch Otolaryngol* 1978;**104**:127–9
24 Takahashi H, Sato H, Nakamura H, Naito Y, Umeki H. Correlation between middle-ear pressure-regulation functions and outcome of type-I tympanoplasty. *Auris Nasus Larynx* 2007;**34**:173–6
25 Metin M, Kaptan ZK, Dogan S, Yazici H, Bayraktar C, Gocmen H *et al.* Effect of preoperative mastoid ventilation on tympanoplasty success. *Int J Otolaryngol* 2014;**2014**:169123
26 Mehta RP, Rosowski JJ, Voss SE, O'Neil E, Merchant SN. Determinants of hearing loss in perforations of the tympanic membrane. *Otol Neurotol* 2006;**27**:136–43