Available online at www.sciencedirect.com

ScienceDirect

Journal of Otology 12 (2017) 125−131

www.journals.elsevier.com/journal-of-otology/

The anatomic determinants of conductive hearing loss secondary to tympanic membrane perforation

David J. Carpenter [a,*], Debara L. Tucci [a], David M. Kaylie [a], Dennis O. Frank-Ito [a,b,c]

[a] Division of Head and Neck Surgery & Communication Sciences, Department of Surgery, Duke University Medical Center, Durham, NC, USA
[b] Computational Biology & Bioinformatics PhD Program, Duke University, Durham, NC, USA
[c] Department of Mechanical Engineering and Materials Science, Duke University, Durham, NC, USA

Received 26 April 2017; revised 13 June 2017; accepted 22 June 2017

Abstract

Objectives: Recent studies have introduced middle ear volume (MEV) as a novel determinant of perforation-induced conductive hearing loss (CHL) in a mechanism driven by trans-tympanic membrane pressure differences. The primary aims of this preliminary report are to: 1) correlate CHL with perforation size; 2) describe the relationship between CHL and MEV; and 3) compare CHL across a range of cholesteatoma involvement.
Design: A retrospective pilot study was performed in 31 subjects with audiometry indicative of conductive hearing loss, temporal bone CT scans, and no prior middle ear surgery. Perforation size and MEV were analyzed with respect to CHL in a cohort of 10 perforated ears with no cholesteatoma. CHLs were compared in 3 groups defined by extent of cholesteatoma involvement.
Results: Ears with large and small perforations showed mean ABG values of 32.0 ± 15.7 dB and 16.0 ± 16.4 dB, respectively. A direct relationship was observed between MEV and CHL for ears with large perforations across all frequencies, whereas this relationship for small perforations was frequency-dependent. Finally, a statistically significant increase in CHL was found across ears with increasing cholesteatoma involvement at 1000 Hz ($\chi^2(2) = 9.786$, $p = 0.008$), 2000 Hz ($\chi^2(2) = 8.455$, $p = 0.015$), and 4000 Hz ($\chi^2(2) = 8.253$, $p = 0.016$).
Conclusions: These pilot data suggest that greater perforation-induced conductive hearing losses may be associated with larger perforation sizes and cholesteatoma. The correlation between MEV and CHL may require additional study.

Keywords: Perforation-induced hearing loss; Conductive hearing loss; Middle ear volume; Three-dimensional volume reconstruction

1. Introduction

Perforation of the tympanic membrane (TM), a common complication secondary to otitis media or trauma, results in varying degrees of conductive hearing loss (CHL) (Ibekwe et al., 2007; Voss et al., 2007). The threshold for performing tympanoplasty in the context of TM perforation depends on many factors; frequency of drainage, patient age, underlying medical conditions, and lifestyle needs must all be accounted for alongside the degree of CHL present. The incidence of TM perforation is currently unknown, though estimates suggest that 150,000 tympanoplasties are performed annually per 280 million people in the United States (McRackan and Brackmann, 2015).

CHL has been associated with greater perforation sizes, greater middle ear disease, and, most recently, smaller middle ear volume (MEV) (Gulya et al., 1990; Roland et al., 2001; Voss et al., 2001a,b,c; Mehta et al., 2006). In such reports, the correlation between MEV and CHL was determined using tympanometry to estimate MEV. In the context of TM

* Corresponding author. Duke Department of Head and Neck Surgery & Communication Sciences, Duke University Medical Center, Room 3561 − Blue Zone, Durham, NC, 27710, USA. Fax: +1 919 681 7949.

E-mail address: david.j.carpenter@duke.edu (D.J. Carpenter).

Peer review under responsibility of PLA General Hospital Department of Otolaryngology Head and Neck Surgery.

http://dx.doi.org/10.1016/j.joto.2017.06.001

perforation, however, estimating MEV has proved problematic. Commercially available tympanometers are often unable to record volumes above 7 mL (Mehta et al., 2006), though the average volume of a human middle ear, defined as the tympanic cavity and continuous mastoid air cells, is 6.5 mL ± 3.7 mL (Molvaer et al., 1978). Validation studies of tympanometry as a MEV estimation technique were limited to non-perforated middle ears, while TM perforation and middle ear disease were demonstrated to alter tympanometric MEV estimations (Molvaer et al., 1978; Lindeman and Holmquist, 1981; Shanks and Lilly, 1981; Rock, 1991; Mehta et al., 2006). Finally, observed disagreement between tympanometric and three-dimensional volume reconstruction (3DVR) MEV estimates were found to be a greater than differences between MEV quartiles, which previous studies have used instead of continuous MEV values to mitigate error in tympanometric MEV measurements (Carpenter, Tucci et al., 2017). Because MEV agreement was not present, studies using 3DVR rather than tympanometry to explore the correlation between MEV and CHL are warranted.

An increased understanding of perforation-induced CHL and its determinants is a necessary precursor to establishing preoperative guidelines for patients undergoing tympanoplasty. We hypothesize that 3DVR MEV values may correlate to CHL differently than the MEVs of previous studies that used tympanometric MEV values. This pilot study will help determine the clinical utility of perforation size measurements, tympanometry, and temporal bone CT scans.

2. Methods

2.1. Subjects

This is a retrospective study approved by the Duke University Health System Institutional Review Board (Pro00073436). A search was conducted of Duke University Medical Center medical records for patients ranging from 18 years to 89 years of age who had undergone both a temporal bone computed tomography (CT) scan and audiometry testing within 4 weeks of each other, prior to October 15th, 2015. Exclusion criteria included inadequate resolution on CT. From 78 subjects screened, we identified 31 perforated middle ears meeting our study criteria. Middle ears were classified into three groups: (1) perforated middle ears without evidence of cholesteatoma on temporal bone CT scan or operating notes (n = 10), (2) perforated middle ears with cholesteatoma per temporal bone CT scan with normal ossicular function per operating notes (n = 7), and (3) perforated middle ears with noted cholesteatoma with ossicular erosion per operating notes (n = 14).

2.2. Audiometric output

CHL secondary to tympanic membrane perforation was calculated from audiograms as the difference in decibels between air and bone conduction values at each given frequency: 500, 1000, 2000, and 4000 Hz. All audiometric data was taken from the pre-operative audiogram in closest proximity to the date of the pre-operative temporal bone CT scan. Audiograms and temporal bone CT scans were collected within 4 weeks of each other, both prior to middle ear surgery.

2.3. Perforation size

Pre-operative clinic notes were used to determine perforation size. Perforations with diameters <50% of the tympanic membrane diameter were defined as small perforations, while large perforations were defined by diameters ≥50% of the tympanic membrane diameter.

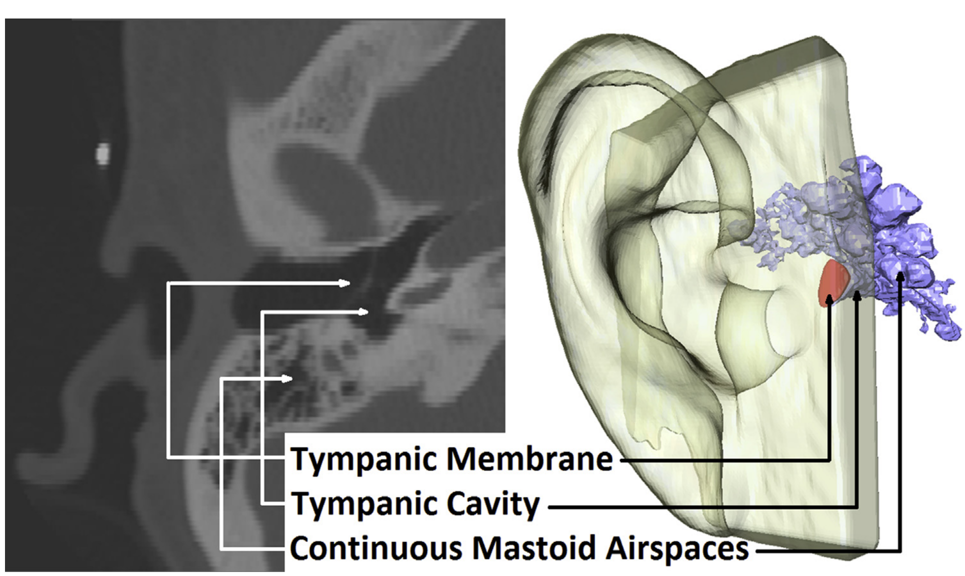

Fig. 1. Three-dimensional volume reconstruction of middle ear volume is shown above. Temporal bone CT scans (left) were reconstructed in medical imaging software Avizo™ (FEI Visualization Sciences Group, Burlington, MA; 2−4). Middle ear volume, defined as the tympanic cavity and continuous mastoid airspaces, was identified through locating the tympanic membrane on subject scans.

Table 1
General demographic information for each of the three cohorts.

	Perforation cohort (n = 10)	Cholesteatoma with ossicles intact (n = 7)	Cholesteatoma with ossicular erosion (n = 14)
Perforation size			
Large	5 (50%)	2 (29%)	–
Small	5 (50%)	5 (71%)	–
Age (yrs at time of CT scan)			
Mean	41	62	53
SD	17	15	14
Gender			
Male	5 (50%)	1	7 (50%)
Female	5 (50%)	6	7 (50%)
Ethnicity			
White	6 (60%)	3	11 (79%)
African American	1 (10%)	3	2 (14%)
Asian	3 (30%)	0	0 (0%)
Other	0 (0%)	1	1 (7%)
Air bone gap [dB; mean (SD)]			
500 Hz	24 (17)	35 (21)	38 (15)
1000 Hz	21 (16)	29 (22)	44 (9)
2000 Hz	12 (18)	18 (12)	29 (12)
4000 Hz	20 (15)	27 (14)	37 (9)

2.4. Three dimensional reconstruction

Images of CT scans were imported from the electronic health record into the imaging software, Avizo™ (FEI Visualization Sciences Group, Burlington, MA) for creation of 3D models of the middle ear. The middle ear was defined as the tympanic cavity and continuous mastoid airspaces (Fig. 1). All CT scans were de-identified in Avizo™ prior to any 3D model construction or further analysis. Structural analysis on each 3D model included middle ear volume (MEV) quantification and, where applicable, cholesteatoma quantification. A single investigator used a standardized approach to calculate MEV from temporal bone CT scans: the tympanic membrane (TM) was identified in the sagittal plane with all continuous airspaces medial to the TM (i.e. tympanic cavity and mastoid air cells) defined as −2000 to −609 Hounsfield units included in MEV values.

2.5. Statistical analysis

Descriptive statistics were used to analyze the effects of perforation size and middle ear volume (MEV) on conductive

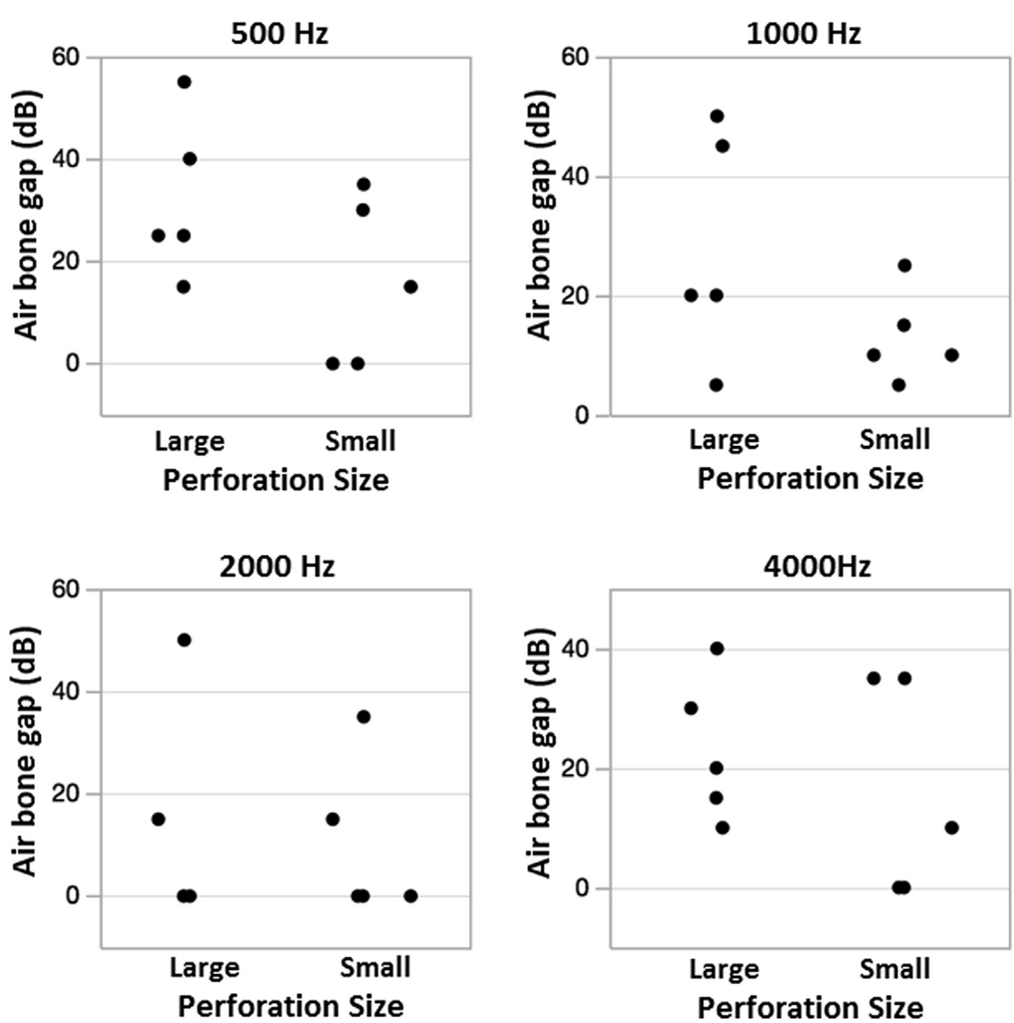

Fig. 2. Conductive hearing losses (dB) shown across audiometric frequencies of 500, 1000, 2000, and 4000 Hz for ears with large (n = 5) and small (n = 5) perforations.

hearing loss (Table 1). Subsequent analysis was divided into 3 aims. In Aim 1, conductive hearing loss (i.e. air bone gap on audiometry) was analyzed with respect to small- and large-sized perforations. In order to control for concurrent hearing losses caused by cholesteatoma, only group 1 subjects were included in Aim 1, which were subjects with perforated ears without evidence of cholesteatoma on temporal bone CT scan or operating notes. The relationship between middle ear volume and conductive hearing loss was explored in Aim 2, again limiting analysis to group 1 for the same reasons. Finally, Aim 3 examined the impact of cholesteatoma on perforation induced conductive hearing loss by comparing groups 1−3. For Aim 3, Kruskal−Wallis testing was performed using the SAS statistical software package JMP (Cary, NC) to analyze the correlation of cholesteatoma to perforation-induced conductive hearing loss across the three aforementioned study cohorts.

3. Results

3.1. Perforation size and conductive hearing loss

The effect of perforation size on conductive hearing loss (CHL) was examined in perforated ears without evidence of cholesteatoma. As demonstrated in Table 1, ears having large (n = 5) and small (n = 5) perforations showed aggregate mean ABG values (i.e. conductive hearing losses) of 32.00 ± 15.65 dB and 16.00 ± 16.36 dB across all listed frequencies, respectively. As seen in Fig. 2, there was no evidence of a significant trend toward greater conductive hearing losses (CHL) at lower frequencies in ears with larger perforations.

3.2. Middle ear volume and conductive hearing loss

The correlation of MEV to CHL was analyzed in perforated ears without evidence of cholesteatoma, while controlling for perforation size (Fig. 3). A direct relationship between MEV and CHL is suggested for ears with large perforations across all frequencies, whereas ears with small perforations exhibited a progressive shift from an indirect relationship between MEV and CHL at 500 and 1000 Hz to a direct relationship at 2000 and 4000 Hz.

3.3. Cholesteatoma in ears with small perforations

To evaluate the isolated effect of cholesteatoma on perforation-induced CHL, Groups 1 (n = 10), 2 (n = 7), and 3 (n = 14) were compared in terms of air bone gap (dB) at 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz. Per the Kruskal−Wallis H test, there was a significant difference in CHL between the three groups at 1000 Hz ($\chi^2(2) = 9.786$, $p = 0.008$), with a mean air bone gap of 9.95 dB for Group 1, 13.93 dB for Group 2, and 21.36 for Group 3. There was also a

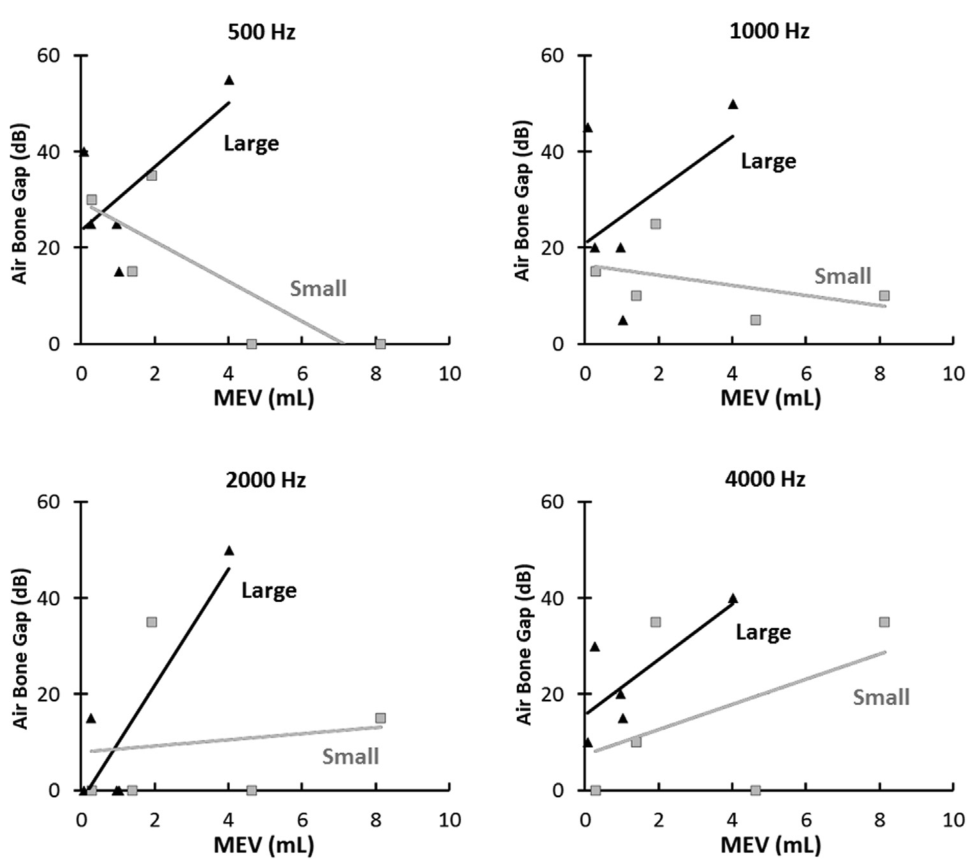

Fig. 3. The relationship between middle ear volume (mL) and conductive hearing loss (dB) shown between ears with large and small perforations across frequencies of 500, 1000, 2000, and 4000 Hz.

significant difference in CHL between the three groups at 2000 Hz ($\chi^2(2) = 8.455$, $p = 0.015$), with a mean air bone gap of 10.15 dB for Group 1, 14.64 dB for Group 2, and 20.86 for Group 3. Finally, there was a significant difference in CHL between Groups 1—3 at 4000 Hz ($\chi^2(2) = 8.253$, $p = 0.016$), with a mean air bone gap of 10.45 dB for Group 1, 14.21 dB for Group 2, and 20.86 for Group 3. Differences in air bone gap between Groups 1—3 were not significant at 500 Hz ($\chi^2(2) = 4.094$, $p = 0.129$). *Post hoc* Bonferroni testing demonstrated a significant difference between Groups 1 and 3 for CHL at audiometric frequencies of 1000 Hz ($p = 0.005$), 2000 Hz ($p = 0.022$), and 4000 Hz ($p = 0.016$). As seen in Table 1, CHL was greatest at 500 and 1000 Hz for all cohorts. When controlling for perforation size using only ears with small perforations, those with no cholesteatoma ($n = 5$) demonstrated a mean ABG value of 13.8 ± 10.4 dB, those with cholesteatoma and functional ossicles ($n = 5$) a mean ABG of 23.0 ± 10.2 dB, and those with cholesteatoma and ossicular dysfunction ($n = 5$) 37.1 ± 8.18 dB.

4. Discussion

4.1. Perforation size

Increased perforation size correlated with greater perforation-induced CHL particularly at lower frequencies (500 Hz and 1000 Hz). These data were consistent with those of prior studies (Ahmad and Ramani, 1979; Voss et al., 2001a,b,c; Merchant and Rosowski, 2003; Voss et al., 2007). This correlation between greater perforation size and greater CHL was anticipated, and justified the division of large and small perforation subsets in subsequent analysis of MEV and CHL. Analysis of perforation size was limited by operative descriptions obtained retrospective, which did not allow for further perforation quantification. However, perforation size is an uncontested determinant of perforation-induced CHL, and the primary aim of this analysis was simply to contextualize the decision to control for perforation size when correlating MEV with CHL within the given dataset.

4.2. Middle ear volume

A recent report of 42 ears with perforation-induced hearing loss demonstrated significant correlations of MEV with CHL (indirect; $p = 0.005$) (Park et al., 2015). Correlations to perforation size and MEV were analyzed across 4 categorical values without controlling for the other; the present report analyzes MEV as a continuous variable derived from 3-dimensional volume reconstruction while distinguishing between ears with large and small perforations. The resultant data, though limited in size, do not show the same indirect relationship between MEV and CHL seen in previous studies (Mehta et al., 2006; Voss et al., 2007), supporting the notion that MEV technique may significantly influence results

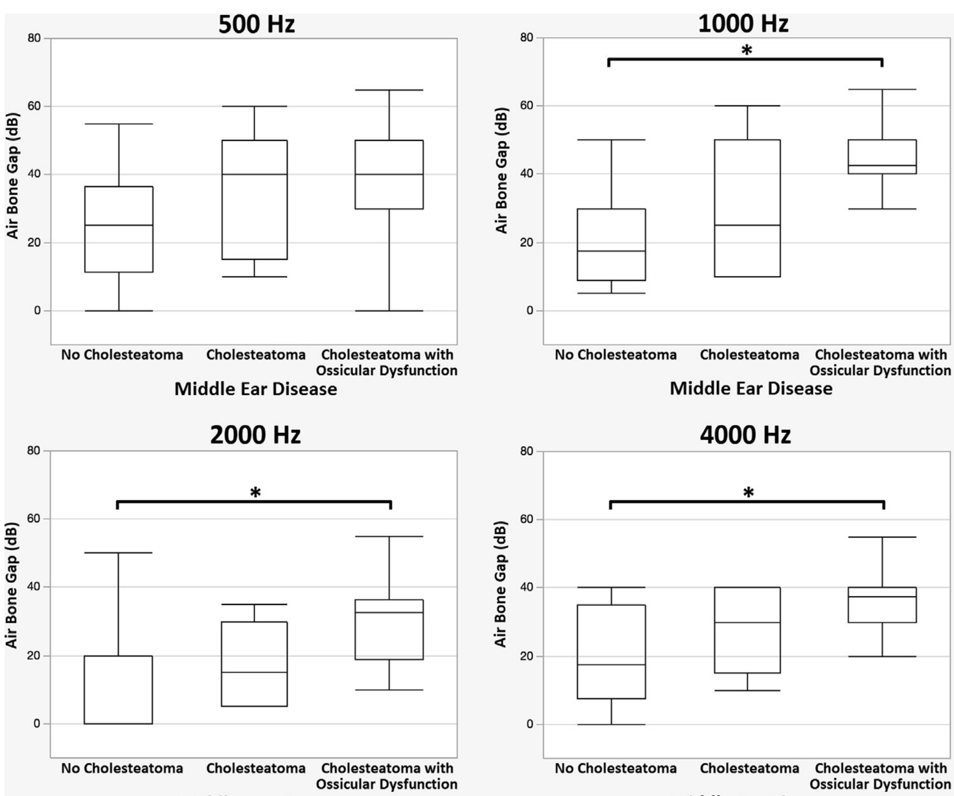

Fig. 4. Differentiates between perforation-induced hearing losses caused by cholesteatoma in the presence and absence of ossicular pathology. Conductive hearing losses are shown as conductive hearing loss (dB) across audiometric frequencies of 500, 1000, 2000, and 4000 Hz for ears with no cholesteatoma ($n = 10$), with cholesteatoma and functional ossicles, ($n = 7$), and with cholesteatoma and ossicular dysfunction ($n = 14$).

(Carpenter, Tucci et al. 2017). Follow-up studies should use 3DVR rather than tympanometry to measure MEV and its correlation to CHL.

4.3. Cholesteatoma

To the authors' knowledge, no previous studies have examined the impact of cholesteatoma in the specific context of perforation-induced CHL. Nevertheless, cholesteatoma is known to cause CHL via invasion and erosion of the ossicular chain (Noordzij et al., 1995; MacAndie and O'Reilly, 1999; de Azevedo et al., 2007; Costa, Rosito et al. 2008). The cohort with cholesteatoma and functioning ossicles (Group 2) exhibited mean CHL values that consistently fell between means for the groups with no middle ear disease (Group 1) and with cholesteatoma and ossicular dysfunction (Group 3; Table 1, Fig. 4). This may suggest that cholesteatoma contributes to the mechanism of perforation-induced CHL beyond what is currently understood about subsequent invasion and erosion of the ossicular chain.

5. Study limitations

Small sample sizes limit the applicability of these pilot data beyond hypothesis generation for a larger, multisite prospective study of middle ear volume as a determinant of perforation-induced CHL. Prior to October 2015, only 10 total patients at this medical center underwent temporal bone CT imaging for perforation-induced hearing loss in the absence of middle ear disease. The inclusion of cholesteatoma, while limited to analysis 4.3, may further confound analysis in that any surgery on the ear could alter MEV, while efforts to account for subtle ossicular abnormalities may be limited by CT scan resolution. In the absence of standardized pre-operative guidelines, reasons for obtaining temporal bone CT scans in the present cases may have been associated with clinical factors that could have confounded the relationships between CHL and perforation size, MEV, and middle ear disease. Furthermore, the need to dichotomize values limited analysis of perforation size. These limitations will be addressed by a future prospective study of CHL that expands the current cohort of patients with perforation-induced CHL as determined by the effect sizes of the present study.

6. Summary

Preliminary analysis of all patients in the past 10 years at this medical center with perforation-induced CHL may suggest that further studies of MEV as a determinant of CHL are warranted. These data provide effect sizes for future prospective studies, and highlight the need for standardization across techniques for assessing perforation size and MEV.

Ethical approval

This article does not contain any studies with human participants or animals performed by any of the authors.

Funding

Research reported in this article was supported by the National Institutes of Health under Award Numbers 5T32DC013018-03 and TL1TR001116. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

Author disclosure statement

Research reported in this article was supported by the National Institute on Deafness and Other Communication Disorders of the National Institutes of Health under Award Number 5T32DC013018-03 and by the National Center For Advancing Translational Sciences of the National Institutes of Health under Award Number TL1TR001116. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

Conflicts of interest

All authors declare no competing interests.

Acknowledgements

The authors thank ANSYS, Drs. Paolo Maccarini, Maragatha Kuchibhatla, and Murali Kadiramangalam (ANSYS Global Academic Program Director) for support. All authors gave final approval for publication.

References

Ahmad, S.W., Ramani, G.V., 1979. Hearing loss in perforations of the tympanic membrane. J. Laryngol. Otol. 93 (11), 1091–1098.

Carpenter, D.J., Tucci, D.L., Kaylie, D.M., Frank-Ito, D.O., 2017. Disagreement in middle ear volume estimation between tympanometry and three dimensional volume reconstruction in the context of tympanic membrane perforation. J. Otol. 12 (2), 74–79.

da Costa, S.S., Rosito, L.P.S., Dornelles, C., 2008. Sensorineural hearing loss in patients with chronic otitis media. Eur. Arch. Otorhinolaryngol. 266 (2), 221–224.

de Azevedo, A.F., Pinto, D.C.G., de Souza, N.J.A., Greco, D.B., Gonçalves, D.U., 2007. Sensorineural hearing loss in chronic suppurative otitis media with and without cholesteatoma. Braz. J. Otorhinolaryngol. 73 (5), 671–674.

Gulya, A.J., Minor, L.B., Glasscock, M.E., Poe, D., 1990. Glasscock-Shambaugh Surgery of the Ear. PMPH-USA.

Ibekwe, T.S., Ijaduola, G.T., Nwaorgu, O.G., 2007. Tympanic membrane perforation among adults in West Africa. Otol. Neurotol. 28 (3), 348–352.

Lindeman, P., Holmquist, J., 1981. Measurement of middle ear volume using the impedance audiometer. Am. J. Otol. 2 (4), 301–303.

MacAndie, C., O'Reilly, B.F., 1999. Sensorineural hearing loss in chronic otitis media. Clin. Otolaryngol. Allied Sci. 24 (3), 220–222.

McRackan, T.R., Brackmann, D.E., 2015. Otology, Neurotology, and Skull Base Surgery: Clinical Reference Guide. Plural Publishing.

Mehta, R.P., Rosowski, J.J., Voss, S.E., O'Neil, E., Merchant, S.N., 2006. Determinants of hearing loss in perforations of the tympanic membrane. Otol. Neurotol. 27 (2), 136–143.

Merchant, S.N., Rosowski, J.J., 2003. Auditory physiology. Surg. Ear 5, 59–82.

Molvaer, O.I., Vallersnes, F.M., Kringlebotn, M., 1978. The size of the middle ear and the mastoid air cell. Acta Otolaryngol. 85 (1–2), 24–32.

Noordzij, J.P., Dodson, E.E., Ruth, R.A., Arts, H.A., Lambert, P.R., 1995. Chronic otitis media and sensorineural hearing loss: is there a clinically significant relation? Otol. Neurotol. 16 (4), 420−423.
Park, H., Hong, S.N., Kim, H.S., Han, J.J., Chung, J., Seo, M.-W., Oh, S.-H., Chang, S.-O., Lee, J.H., 2015. Determinants of conductive hearing loss in tympanic membrane perforation. Clin. Exp. Otorhinolaryngol. 8 (2), 92−96.
Rock, E.H., 1991. The physical volume test in impedance audiometry. Ear Nose Throat J. 70 (4), 245−250.
Roland, N., McRae, R., McCombe, A., 2001. From chronic suppurative otitis media. Key Top. Otolaryngol. Head Neck Surg. 38−41.
Shanks, J.E., Lilly, D.J., 1981. An evaluation of tympanometric estimates of ear canal volume. J. Speech Hear Res. 24 (4), 557−566.
Voss, S.E., Rosowski, J.J., Merchant, S.N., Peake, W.T., 2001a. How do tympanic-membrane perforations affect human middle-ear sound transmission? Acta Otolaryngol. 121 (2), 169−173.
Voss, S.E., Rosowski, J.J., Merchant, S.N., Peake, W.T., 2001b. Middle-ear function with tympanic-membrane perforations. I. Measurements and mechanisms. J. Acoust. Soc. Am. 110 (3 Pt 1), 1432−1444.
Voss, S.E., Rosowski, J.J., Merchant, S.N., Peake, W.T., 2001c. Middle-ear function with tympanic-membrane perforations. II. A simple model. J. Acoust. Soc. Am. 110 (3 Pt 1), 1445−1452.
Voss, S.E., Rosowski, J.J., Merchant, S.N., Peake, W.T., 2007. Non-ossicular signal transmission in human middle ears: experimental assessment of the "acoustic route" with perforated tympanic membranes. J. Acoust. Soc. Am. 122 (4), 2135−2153.