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Disagreement in middle ear volume estimation between tympanometry and three-dimensional volume reconstruction in the context of tympanic membrane perforation

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Abstract

Introduction: Middle ear volume (MEV) is a clinically relevant parameter across middle ear diseases. MEV values between these techniques have never before been tested for agreement in ears with perforated tympanic membranes (TMs).
Methods: Middle ears were identified from 36 patients ranging 18–89 years of age with TM perforations who underwent tympanometry and temporal bone computed tomography (CT) between 2005 and 2015. MEVs calculated by both tympanometry and three-dimensional volume reconstruction (3DVR) were analyzed for agreement using Bland Altman plots. The differences between tympanometric and 3DVR MEV values for each given middle ear were characterized across MEV quartiles (1 = smallest; 4 = largest) and across increasing states of middle ear disease using Kruskal–Wallis and Wilcoxon testing with Bonferroni correction.
Results: Bland Altman plots demonstrated significant disagreement between MEV measurement techniques. Differences between tympanometric (T) and 3DVR MEV values were significantly greater with increasing average (i.e. (T+3DVR)/2)) MEV per linear regression ($p < 0.0001$). Significance was demonstrated between fourth and first average MEV quartiles ($p = 0.0024$), fourth and second quartiles ($p = 0.0024$), third and first quartiles ($p = 0.0048$), and third and second quartiles ($p = 0.048$). Absolute MEV difference was not significantly different across varying states of middle ear disease ($p = 0.44$).
Conclusion: Statistically and clinically significant disagreement was demonstrated between tympanometric and 3DVR MEV values. Studies that vary in MEV estimation techniques may be expected to demonstrate significantly different results. These preliminary results suggest that clinicians should endeavor to seek further confirmation when interpreting high tympanometric MEV values.

Keywords: Middle ear volume; Tympanometry; Three-dimensional volume reconstruction; Tympanic membrane perforation

1. Introduction

Middle ear volume (MEV), defined as the continuous volume occupied by the tympanic cavity and mastoid air cells, has been characterized in the setting of various middle ear pathologies using both tympanometry and three-dimensional volume reconstruction (3DVR). Determining MEV size by tympanometry has proved clinically useful in various settings. Clinical indications for tympanometry include screening for

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middle ear disease as well as determining the presence of tympanic membrane (TM) perforation following an indeterminate otologic exam. Using tympanometry, greater MEV was shown to directly relate to Eustachian tubal function and successful closure of dry, central TM perforations (Holmquist, 1970; Neel et al., 1977). Secretory middle ear pathologies were subsequently shown to recur more commonly in ears with smaller MEVs (Sederberg-Olsen et al., 1983). More recently, using tympanometry, smaller MEV has been correlated to conductive hearing loss secondary to TM perforation (Voss et al., 2001; Mehta et al., 2006; Voss et al., 2007).

3DVR of computed tomography (CT) scans has since emerged as a gold standard for MEV estimation for studies of middle ear anatomy. The correlation of MEV to TM perforation-induced conductive hearing loss, first identified by studies using tympanometry, has been expanded by those using 3DVR (Park et al., 2015). Novel applications for MEV have also emerged, such as determining surgical candidacy in patients with aural atresia (Osborn et al., 2011).

Statistical agreement in MEV between widely available tympanometry and precise 3DVR techniques has never been assessed in the context of tympanic membrane (TM) perforation. Characterizing agreement in MEV values between tympanometry and 3DVR is the primary objective of this study, secondarily determining whether agreement is influenced by middle ear disease states or sizes. It is hypothesized that MEV will differ between tympanometry and 3DVR for middle ears with TM perforations. Characterizing the agreement between MEV techniques will address limitations in the current literature surrounding MEV, and will provide context for clinicians who face the challenge of incorporating MEV estimations in their assessment of middle ear disease.

2. Methods

2.1. Subjects

This is a retrospective study approved by the Duke University Health System Institutional Review Board (IRB). A search was conducted of Duke University Medical Center medical records for all patients ranging from 18 to 89 years of age with perforated tympanic membranes (TMs) who underwent tympanometry up to one month prior to a standard-of-care temporal bone computed tomography (CT) between October 15th, 2005 and October 15th, 2015. One patient with inadequate CT resolution was excluded. 36 qualifying patients met study criteria.

2.2. Three dimensional volume reconstruction

Images of temporal bone CT scans were imported from the electronic health record into the medical imaging software, Avizo™ (FEI Visualization Sciences Group, Burlington, MA) for creation of three-dimensional (3D) models of the middle ear. All CT scans were de-identified in Avizo™ prior to any 3D model construction or further analysis. Imaging parameters included a section thickness of 0.6 mm, 512 × 512 matrix, rotation time of 1 s, and exposure time of 1825 ms. Patients were in the head first-supine position with 0 gantry tilt. Digital imaging and communications in medicine (DICOM) images had 512 rows, 631 columns, and a pixel spacing of 0.176 by 0.176 mm. Middle ear volume (MEV) was defined as the continuous, non-opacified airspaces of the middle ear cavity and mastoid air cells of the temporal bone.

A single investigator performed all 3DVR calculations blinded to tympanometric MEV values. To identify MEV on 3DVR, the TM was located using a previously validated approach (Patki et al., 2016) as the most lateral sagittal image where the temporal bone demonstrated a continuous circumference around the airspace, which denoted the boundary between the external auditory canal and middle ear (Fig. 1). MEV was defined as all continuous airspaces medial to the TM, including the tympanic cavity and mastoid airspaces. When directly measuring MEV, a cutoff of −2000 to −609 Hounsfield units was used to standardize opacification.

2.3. Disease cohorts

Middle ears were grouped into disease cohorts to account for the potential effects of impaired TM and ossicular function on calculated MEV values. TM perforation may be associated with cholesteatoma or not. When present, cholesteatoma may erode the ossicular chain. Therefore, grouping by "perforated" middle ears (P; n = 8) with TM perforations and without cholesteatoma or ossicular dysfunction, middle ears (PC; n = 7) with TM perforations and cholesteatoma but without ossicular dysfunction, and middle ears (PCO; n = 21) with TM perforations, cholesteatoma, and ossicular dysfunction provided an approximate categorization by severity of middle ear disease.

2.4. Analysis of agreement

MEV difference was defined as the tympanometric MEV value (MEV_T) minus the 3DVR MEV value (MEV_{3DVR}), and average MEV was defined as the sum of MEV_T and MEV_{3DVR} divided by 2. Linear regression of absolute MEV difference against average MEV values was performed to provide statistical context to subsequent Altman Bland plots. Per (Bland and Altman, 1986), MEV difference was plotted with 1.96 standard deviation boundaries with respect to average MEV. The line of equality (MEV difference = 0) and clinically acceptable thresholds for agreement were provided for comparison. Because prior studies have analyzed MEV as quartiles to mitigate errors in MEV measurement rather than as a continuous variable (Mehta et al., 2006; Park et al., 2015), the clinically acceptable threshold for MEV difference was set *a priori* at ±1.27 mL because this value was the averaged difference from the median to the inner-quartile boundaries for average MEV of the sample set.

A second Bland and Altman plot was constructed for all MEV values using a correction factor that accounts for external auditory canal (EAC) volume. Primary analysis did not include this correction factor because the majority of