Research Article

Effects of Pressure Sweep Factors on Acoustic Immittance Measures in Ears with Normal/Low and High Acoustic Admittance

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Abstract

Normal middle-ear function has a tympanometric peak pressure (TPP) of ~0 daPa, with a sharp decline as the air pressure withdraws away from 0 daPa. However, there is no information about variations in the TPP because of changes in pressure sweep direction and sweep rate in ears with different acoustic admittance values. This study investigated the effects of pressure sweep direction and rate on the TPP and acoustic admittance values in individuals with high- and normal-/low acoustic admittance middle-ears (25 ears with healthy middle-ear acoustic admittance [Group I] and 19 ears with high middle-ear acoustic admittance [Group II]). We explored changes in ipsilateral acoustic reflex thresholds (ARTs) monitored with the obtained TPPs. Tympanometry was performed under four experimental conditions in two pressure directions (conventional and reverse) and at two pressure rates (high and low). In addition, we measured ipsilateral ARTs at octave frequencies from 500 to 4000 Hz for the obtained TPPs. We observed significant differences in the TPPs, but not in acoustic admittance measures, in both groups. Analysis of ipsilateral ARTs monitored at different TPPs showed significant differences between the four experimental conditions in Group II at octave frequencies >1000 Hz but not in Group I. Low (better) ARTs were elicited with lower variability at a TPP obtained in the conventional pressure sweep direction but at a low pressure sweep rate of 50 daPa/s. Therefore, tympanometric measurements are suggested to be performed at a low pressure sweep rate and in a conventional pressure sweep direction, especially for people with increased acoustic admittance.

INTRODUCTION

The middle-ear is an essential part of the auditory system as it compensates for the impedance mismatch between the acoustic energy in the environment and cochlear fluids in the inner ear (Moore, 2012). For more than two decades, acoustic immittance measures, such as tympanometry and acoustic reflex determination, are clinically used to objectively evaluate the optimal function of the middle-ear. These measures help to distinguish between normal and pathological conditions and also help make differential diagnoses among several conductive pathological conditions.

During tympanometry, the pressure in the external ear canal is systematically varied and the tympanic membrane acoustic admittance is estimated by computing the reflected acoustic energy, which is used to determine middle-ear functioning. The air pressure which coincides with the peak acoustic admittance (i.e. at highest acoustic admittance or low impedance) is called the tympanometric peak pressure (TPP). Clinically, tympanograms are obtained at a 226 Hz probe tone, with the air pressure swept from +200 to −400 daPa at a pressure sweep rate of 200 daPa/s. Normal middle-ear function has a TPP of ~0 daPa, with a sharp decline as the air pressure withdraws away from 0 daPa. Middle-ear disorders affect the tympanogram shape (American Speech-Language-Hearing Association, 1988; Stach, 1998). In addition to its diagnostic value, the TPP is also used in other sub-measures of immittance audiometry. For example, the TPP is used to measure acoustic reflex thresholds (ARTs) to better monitor subtle changes in acoustic admittance because of the stapedius muscle reflex (Stach, 1998).

Various factors, such as the probe signal frequency, changes in the pressure sweep direction and the pressure sweep rate, significantly affect tympanometric results and, consequently, ART measurements. Variations occur in acoustic admittance at the tympanic membrane because of changes in the rate of air pressure (Gaihede, 1999; Kobayashi, Okitsu & Takasaka, 1987; Margolis & Heller, 1987; Shanks & Wilson, 1986). For example, increasing the pressure sweep rate from 200 to 400 daPa/s increases acoustic admittance and changes the TPP complexity (Margolis & Heller, 1987). Even in normal ears, as the pressure sweep rate increases, acoustic admittance increases and the TPP peak shifts towards a more negative pressure (Feldman, Fria, Palfrey & Dellecker, 1984). Shanks and Wilson (1984) reported an increase in the TPP, peak acoustic admittance and conductance by increasing the pressure sweep rate from 12.5 to 50 daPa/s with probe tones of 226 and 678 Hz. In addition, changes in the pressure sweep direction brings about a change in the tympanogram amplitude and shape. Mainly, the conventional direction (positive to negative) results in a higher acoustic admittance compared to the reverse direction (negative to positive) and shows more complex notching (Alberti & Jerger, 1974; Margolis & Smith, 1977; Van Camp, Creten, Vanpeperstraete & Van de Heyning, 1980; Wilson, Shanks & Kaplan, 1984). Therefore, these factors must be considered when diagnosing middle-ear disorders (Creten & Van Camp, 1974; Koebsell & Margolis, 1986; Margolis & Heller, 1987; Shanks & Wilson, 1986).

Most of the studies cited earlier have revealed tympanometric measurement variability associated with pressure sweep direction and rate mainly in individuals with normal middle-ear function. Only few studies have been performed on individuals with middle-ear disorders. For example, Feldman et al. (1984) reported a change in the tympanogram classification in ~25% of 27 children with different middle-ear disorders by changing the pressure sweep rate. Gaihede, Bramstoft, Thomsen and Fogh (2005) carried out bidirectional tympanometry in 57 children with serous otitis media and found higher TPP differences in these children.

In addition, few studies have explored the effects of tympanometric measurement variations on ART measurements. In presence of a reflex-eliciting signal, subtle change in acoustic admittance at the tympanic membrane is measured as acoustic reflex. Only minimal changes are noted in the measured ARTs if the external air pressure varied within a range of +80 mm H2O with reference to the TPP (Rizzo & Greenberg, 1979). DiGiovanni and Ries (2007) monitored ARTs at seven different pressure values with reference to the TPP and found that a pressure of −50 daPa (relative to the TPP) has better ARTs, especially in individuals with high peak-compensated static acoustic admittance. The TPP can overestimate the middle-ear pressure by 30–70 daPa at higher pressure sweep speeds, especially for individuals with small middle-ear volumes or hypermobile tympanic membranes (Renvall & Holmquist, 1976). Similar results are also found for changes in the pressure sweep direction, especially in children with secretory otitis media (Gaihede et al., 2005). Sun, Shaver and Harader (2013) reported a hypercorrection of the acoustic admittance and gradient in middle ears with negative pressure.

These findings indicate a lack of firm information about TPP variations due to changes in pressure sweep direction and rate in individuals with different acoustic admittance values. Therefore, further studies monitoring the ARTs of the TPP (measured using different pressure sweep factors on tympanometry procedures) in these individuals are required. This study measured the effects of pressure sweep direction (conventional, +200 to −400 daPa; reverse, −400 to +200 daPa) and rate (200 and 50 daPa/s) on the TPP and determined the effect of such TPP on the ARTs of individuals with normal middle-ear function and those with high middle-ear acoustic admittance.

METHODS

Participants

We enrolled 44 individuals aged 15–65 years in this study. They were divided into two groups on the basis of acoustic admittance values obtained using tympanometry at a 226 Hz probe tone. Group I comprised 25 individuals (12 males and 13 females) with an average age of 19.95 years (standard deviation [SD] = 1.56 years). Of these, 17 had an A-type (0.5–1.75 mmho) tympanogram and 8 had an A_S-type (<0.5 mmho) tympanogram with conventional 226 Hz tympanometry. All 25 individuals had normal hearing sensitivity on pure tone audiometry and acoustic reflexes at all octave frequencies between 500 and 4000 Hz in the tested ear, with no reported otologic difficulties for the past 5 years of testing. Group II comprised 19 individuals (10 males and 9 females) with an average age of 33.3 years (SD = 14.68 years) with high middle-ear acoustic admittance, that is, an A_D-type tympanogram (>1.75 mmho), but a clear presence of normal or elevated acoustic reflexes at all octave frequencies between 500 and 4000 Hz.

We selected one ear per individual at random for performing experiments and for inclusion in data analysis. The study was conducted in an academic institution at the audiology department. The 44 individuals voluntarily participated and provided informed consent prior to enrolment in the study. The procedures used complied with the tenets of the 2013 Declaration of Helsinki and were in accordance with the ethical guidelines for bio-behavioural research involving human subjects recommended by the institution's ethical committee.

Procedure

After hearing assessments (i.e. pure tone audiometry and acoustic immittance evaluation) and otoscopic examination, all participants were asked to sit comfortably in an armchair located in sound-treated acoustic room. They were instructed to remain quiet, without any head movements, during the measurement in order to avoid any variations in tympanometric values. A probe tube was inserted into the ear canal to obtain an airtight seal in order to record the tympanogram and ART. To reduce the risk of disturbing the probe tube's airtight seal, we allowed intermittent breaks between the testing procedures but only when a participant insisted. We used a calibrated Grason-Stadler (GSI) Tympstar version 2 Immittance metre (GSI, Eden Prairie, MN, USA) to measure the TPP, acoustic admittance and ipsilateral ART at octave frequencies between 500 and 4000 Hz. Tympanometric measurements were performed under four different experimental conditions: Condition 1 (forward sweep direction at high rate [FSHR]) involved measuring the TPP and acoustic admittance in the conventional pressure sweep direction (+200 to −400 daPa) at a pressure sweep rate of 200 daPa/s. Condition 2 (reverse sweep direction at high rate [RSHR]) involved measuring the TPP and acoustic admittance in the reverse pressure sweep direction (−400 to +200 daPa) at a pressure sweep rate of 200 daPa/s. Condition 3 (forward sweep direction at low rate [FSLR]) involved measuring the TPP and acoustic admittance in the conventional pressure sweep direction (+200 to −400 daPa) at a pressure sweep rate of 50 daPa/s. Condition 4 (reverse sweep direction at low rate [RSLR]) involved measuring the TPP and acoustic admittance in the reverse pressure sweep direction (−400 to +200 daPa) at a pressure sweep rate of 50 daPa/s.

We estimated ipsilateral ARTs at octave frequencies between 500 and 4000 Hz at the measured TPP under each of the four experimental conditions. The ART was defined as the lowest stimulus level which produced a minimum stimulus-associated change of 0.03 mmho in the acoustic admittance. We used a step size of 2 dB hearing level (HL) to measure the ART. Measurements under different experimental conditions were performed in a pseudo-randomised manner (sequential rotation among four experimental conditions from one participant to the next) in order to minimise order effects. We documented the TPP, static acoustic admittance and ipsilateral ART at four octave frequencies between 500 and 4000 Hz in each experimental condition for all the participants for further analysis.

Statistical analyses

The collected data were analysed for the effects of the pressure sweep direction and rate on the TPP and ART separately for each group using SPSS Statistics version 21 (IBM Corporation, Armonk, NY, USA). Clear differences existed in the static acoustic admittance values between groups and also in averaged hearing threshold levels (which might lead to clear differences between ARTs), thus we did not perform between-group comparisons. The Shapiro–Wilk test of normality showed that the data obtained on some of the parameters under each experimental condition for both groups did not follow a uniform bell-shaped curve (< 0.05); therefore, we used the nonparametric Friedman test of differences among repeated measures to compute the statistical significance of the differences between the experimental conditions. In addition, when data were significantly different between experimental conditions, we used Wilcoxon's signed-ranks test to test the differences.

RESULTS

Tympanometric peak pressure measurements

TPP data obtained from each group under different experimental conditions were averaged separately, and Table 1 lists the descriptive parameters. In both groups, the RSHR and RSLR yielded a lower TPP compared to the FSHR and FSLR.

With regard to TPP measurements in Group I, we found a statistically significant difference among the four experimental conditions ($\chi^2 = 45.47$; $P < 0.01$). Among individual pairs of experimental conditions, we found significant between-condition differences ($P < 0.01$) for all pairs of experimental conditions, except between the FSLR and the RSLR ($Z = -1.04$; $P = 0.16$). The highest positive TPP was obtained with the conventional procedure (FSHR), while the lowest TPP was obtained in the RSHR condition (Table 1). However, we found no significant difference in the TPPs between experimental conditions of FSLR and RSLR. In addition, reversing the pressure sweep direction decreased the TPP by an average 26.58 daPa at a pressure sweep rate of 200 daPa/s and only 1.6 daPa at a pressure sweep rate of 50 daPa/s for Group I.

In Group II, we found a significant difference among the four experimental conditions ($\chi^2 = 49.52$; $P < 0.01$). In addition, we found significant between-condition differences ($P < 0.01$) for all pairs of experimental conditions. Similar to the results for Group I, the highest positive TPP was obtained with the conventional procedure (FSHR), while the lowest TPP was obtained in the RSHR condition. Therefore, for individuals with high acoustic admittance, reversing the pressure sweep direction decreased the TPP by an average 40.79 daPa at a pressure sweep rate of 200 daPa/s and only by 10.79 daPa at a pressure sweep rate of 50 daPa/s.

These results indicated that both pressure sweep direction and pressure sweep rate significantly affect the TPP in individuals with high acoustic admittance.

Static acoustic admittance measurements

Static acousticadmittance data obtained from each group under different experimental conditions were averaged separately, and Table 1 lists the descriptive parameters. In Group I, we found a significant difference among the experimental conditions

Table 1: Mean (SD) values of the static acoustic admittance and tympannometric peak pressure for both groups I and II under all experimental conditions.

Condition	Tympanometric peak pressure (daPa)		Static acoustic admittance (mmho)	
	Group I(normal/low acoustic admittance)	Group II(high acoustic admittance)	Group I(normal/low acoustic admittance)	Group II (high acoustic admittance)
Condition 1 - FSHR	16.00 (13.07)	22.89 (12.40)	0.63 (0.28)	2.51 (0.72)
Condition 2 - RSHR	−10.58 (14.97)	−17.89 (13.16)	0.67 (0.24)	2.67 (0.86)
Condition 3 - FSLR	2.20 (8.91)	4.74 (10.07)	0.58 (0.24)	2.67 (0.72)
Condition 4 - RSLR	0.60 (7.12)	−6.05 (5.16)	0.59 (0.22)	2.61 (0.68)

Note: SD, standard deviation; FSHR, forward sweep direction at high rate; RSHR, reverse sweep direction at high rate; FSLR, forward sweep direction at low rate; RSLR, reverse sweep direction at low rate.

(χ^2= 13.58; P < 0.01). We found a significantly higher acoustic admittance in the RSHR compared to the FSLR (Z = −2.40; P = 0.016) and the RSLR (Z = −2.46; P = 0.014). These results indicated that the acoustic admittance obtained in the reverse pressure sweep direction at a pressure sweep rate of 200 daPa/s is significantly higher compared to that obtained at a pressure sweep rate of 50 daPa/s. We did not observe any significant difference in the static acoustic admittance among the four experimental conditions for Group II (χ^2= 5.62; P = 0.131). These results indicated that neither pressure sweep direction nor pressure sweep rate has a significant effect on acoustic admittance in individuals with high acoustic admittance.

Acoustic reflex measurement

Figure 1 depicts ipsilateral ARTs measured under each of the four experimental conditions in Group I. The ARTs of Group I were similar across all experimental conditions at all tested octave frequencies and were distributed within a 10 dB HL range. The ARTs monitored under in the four experimental conditions at each of the four octave frequencies (500–4000 Hz) for Group I were significantly different at 500 Hz (χ^2 = 9.06; P = 0.03) and 1000 Hz (χ^2= 7.95; P = 0.05). No significant differences were observed at 2000 Hz (χ^2= 3.57; P = 0.31) and 4000 Hz (χ^2= 0.69; P = 0.88). In addition, the ART obtained at 500 Hz in the FSHR was significantly higher than that obtained in RSHR (Z = −2.02; P = 0.04), while the ART obtained at 1000 Hz in the FSLR was significantly higher compared to the RSHR (Z = −2.49; P = 0.01) and the RSLR (Z = −2.12; P = 0.03). These results indicated that ipsilateral ARTs are sensitive to the pressure monitored only at 500 and 1000 Hz in individuals with normal/low acoustic admittance. In addition, individuals with normal/low static admittance showed lowest (better) ARTs measured at a peak pressure obtained by sweeping the pressure from −400 to +200 daPa and at a pressure sweep rate of 200 daPa/s.

In Group II, the ARTs varied more than a range of 10 dB HL at each octave frequency, with a large variation across frequencies (Figure 2). The differences in ARTs among the four experimental conditions for Group II were significant at all tested octave frequencies: 500 Hz (χ^2= 9.84; P = 0.02), 1000 Hz (χ^2= 14.83; p < 0.01), 2000 Hz (χ^2= 9.41; P = 0.02) and 4000 Hz (χ^2= 13; p < 0.01). In addition, the ART obtained at 500 Hz in the FSLR was significantly lower compared to the FSHR (Z = −2.65; p < 0.01), while the ART obtained at 1000 Hz in the FSHR was significantly higher compared to other experimental conditions (P ≤ 0.05); there were no significant differences between RSHR, FSLR and RSLR. At 2000 Hz, the ART obtained in the FSHR was significantly higher compared to the RSHR (Z = −3.11; P < 0.01) and the FSLR (Z = −2.34; P = 0.02), and the ART obtained in the RSLR was significantly higher compared to the FSLR (Z = −2.23; P = 0.03). Similarly, the ART obtained at 4000 Hz in the FSHR was significantly higher compared to the RSHR (Z = −2.86; P < 0.01) and FSLR (Z = −2.68; P = 0.01). Among all the experimental conditions studied, the lowest ARTs were measured at a pressure obtained in the reverse pressure sweep direction and at a pressure sweep rate of 200 daPa/s. These results indicated that the ARTs measured at a pressure in the conventional pressure sweep direction at a pressure sweep rate of 200 daPa/s are ~6.75 dB higher than the ARTs measured at the TPP in the reverse pressure sweep direction at octave frequencies >500 Hz.

Figure 2 indicates lower inter-subject variations in the measured ARTs if monitored at a TPP yielded with lower pressure sweep rate (FSLR and RSLR). The FSLR resulted in lower ARTs at all octave frequencies (lowered/bettered by ~4.22 dB at 500 Hz, ~4.74 dB at 1000 Hz, ~3.95 dB at 2000 Hz and ~3.68 dB at 4000 Hz) compared to the FSHR (conventional method).

DISCUSSION

This study evaluated the effects of two pressure sweep directions and rates with two different groups of participants (normal/low and high acoustic admittance). Our results under different experimental conditions were similar to previous investigations (Shanks & Wilson, 1986). Overall, the effects

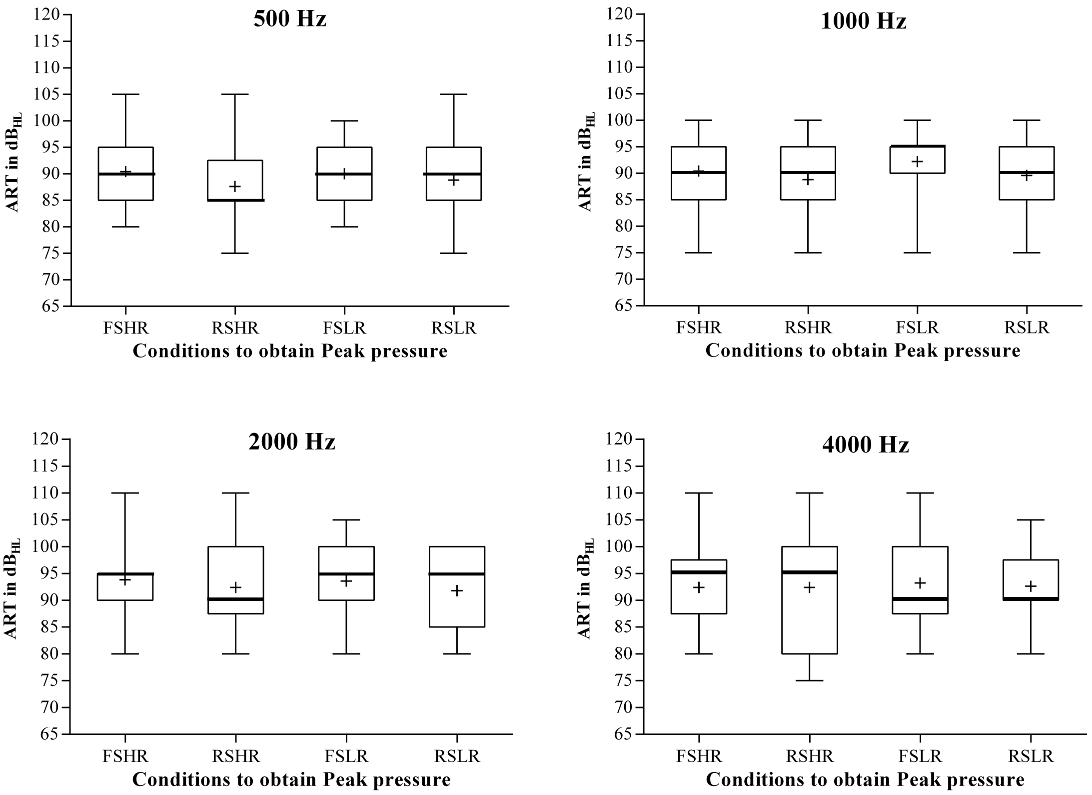

*Figure 1: ART in individuals with normal/low acoustic admittance. Data are represented as box plots with whiskers ('+' represents the mean value, and the mid-line represents the median value) across different experimental conditions at different octave frequencies. *The maximum value at 2000 Hz (RSLR) lies on the edge of the box plot. ART, acoustic reflex threshold; FSHR, forward sweep direction at high rate; RSHR, reverse sweep direction at high rate; FSLR, forward sweep direction at low rate; RSLR, reverse sweep direction at low rate; HL, hearing level.*

of these parameters on the TPP were different for the two groups. More positive TPPs were obtained when the pressure swept from positive to negative during tympanometry compared to the reverse direction. In addition, the TPP was closer to 0 daPa when the pressure sweep rate was low. However, the difference in the TPP measured in two different pressure sweep directions was higher in Group II and higher at an increased pressure sweep rate. Therefore, the TPP change across different conditions can have a significant effect on the measured ARTs, especially in individuals with high acoustic admittance. Consequently, considering the presence or absence of ARTs and the effect of pressure-related factors becomes crucial for differential diagnosis, especially in individuals with high acoustic admittance (mainly to differentiate between a thin tympanic membrane and ossicular chain discontinuity). Our results would provide some direction to monitoring the effect of pressure-related factors on the TPP and further monitoring ARTs.

Studies on a change in the pressure sweep direction have reported a significant effect of a change in the pressure sweep rate on the TPP (Hergils, Magnuson & Falk, 1990; Kobayashi et al., 1987; Shanks & Wilson, 1986; Therkildsen & Gaihede, 2005). Our results are also consistent with previous studies which used high probe tone frequencies, especially at a higher pressure sweep rate of 200 daPa/s (Bian, 2014; Kim, 2003). Although the TPP varies, the static acoustic admittance values obtained in different pressure sweep directions and rates are not significantly different between normal-/low- and high acoustic admittance individuals. These findings are in agreement with previous studies which have reported that a change in the pressure sweep direction and rate does not affect middle-ear acoustic admittance (Bian, 2014; Kim, 2003). Pressure-related factors do not have a significant effect on acoustic admittance.

In Group II, we obtained better ARTs in a reverse pressure sweep direction and a pressure sweep rate of 200 daPa/s (RSHR, condition 2). However, with regard to within-group comparisons, the ARTs measured in the RSHR showed high across-subject variations. Fewer variations were observed in the ARTs measured in the FSLR (condition 3). Therefore, individuals with high acoustic admittance, slight pressure changes in the external ear canal during acoustic reflex monitoring across different octave frequencies have a significant effect on ARTs. In addition, at a pressure sweep rate of 50 daPa/s, the TPPs mea-

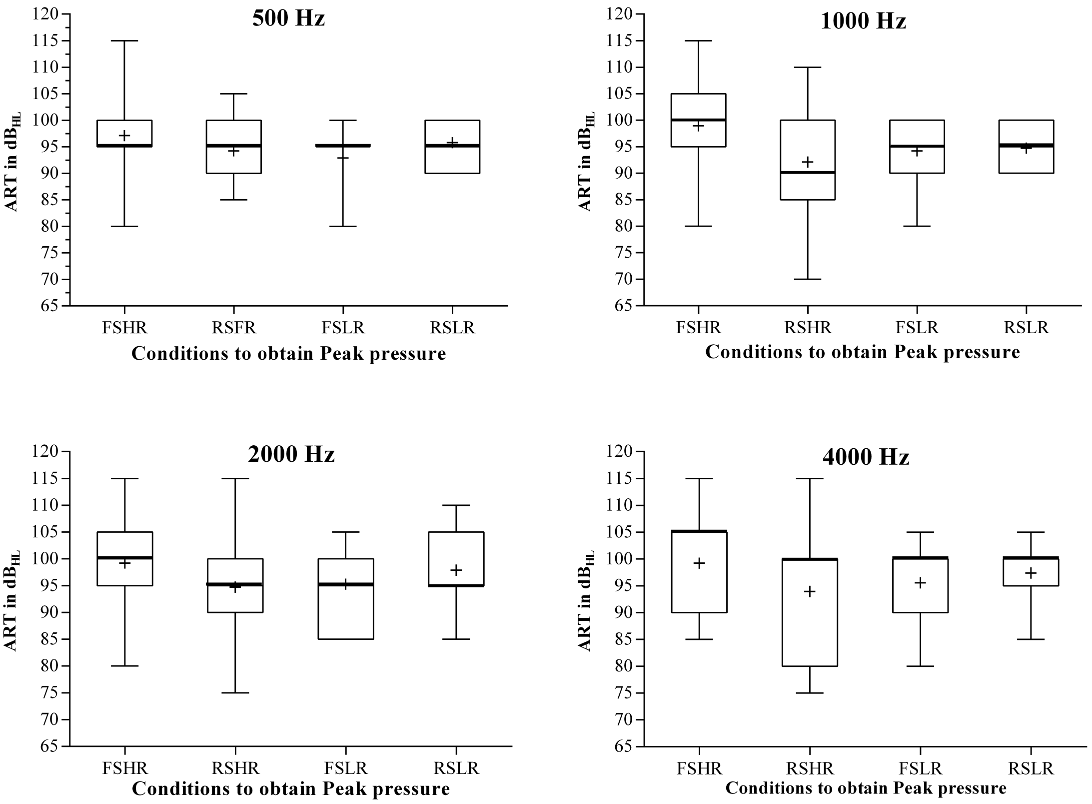

*Figure 2: ARTs in individuals with high acoustic admittance. Data are represented as box plots with Tukey whiskers ('+' represents the value, and the mid-line represents the median value) across different experimental conditions at different octave frequencies. *The extreme data values (error bars) at 500 Hz (RSLR), 1000 Hz (FSLR and RSLR) and 2000 Hz (FSLR) lie on the edge of the box plot. The box plot at 500 Hz (FSLR) is not visible as most of the data coincided with the median value. ART, acoustic reflex threshold; FSHR, forward sweep direction at high rate; RSHR, reverse sweep direction at high rate; FSLR, forward sweep direction at low rate; RSLR, reverse sweep direction at low rate; HL, hearing level.*

sured with a change in the pressure sweep direction do not significantly alter ARTs. These findings are in agreement with previous studies in which a negative pressure shift of >–50 daPa relative to the TPP significantly increased ipsilateral ARTs in subjects with high acoustic admittance (DiGiovanni & Ries, 2007; Martin & Coombes, 1974; Rizzo & Greenberg, 1979). Studies have also reported a significant increase in ARTs at pressures >=±80 daPa (Rizzo & Greenberg, 1979).

In clinical practice, tympanometry is commonly used to determine the middle-ear status in order to identify middle-ear disorders. However, the sensitivity and specificity of tympanometry at a 226 Hz probe tone are poor (Browning, Swan & Gatehouse, 1985; Kaf, 2011; Shahnaz & Polka, 1997). Bhatta and Adhikari (2008) reported that type A_S and A_D tympanograms have poor sensitivity and specificity in identifying middle-ear disorders, and thus additional test tools confirm diagnosis. Better ARTs monitored at TPPs yielded by a lower pressure sweep rate along with lesser inter-individual variations. This reduces clinician bias in confirming the presence of ARTs and, therefore, improves the sensitivity of the test to some extent. Overall, in individuals with high acoustic admittance, slight pressure changes in the external ear canal during acoustic reflex monitoring can have a significant effect on ARTs.

CONCLUSIONS

We recommend that a lower pressure sweep rate (50 daPa/s) and a conventional pressure sweep direction (positive to negative pressure) be used to measure the TPP during clinical evaluation, especially while testing individuals with increased acoustic admittance. Such measured TPPs can be used to monitor acoustic reflexes with more stability and obtain better results. This could improve the sensitivity of acoustic immittance measurements and confirmation of middle-ear disorders to some extent. However, further research with an outsized sample is required to generalise the findings and utilising them in routine clinical practice. The future studies can consider taking a large number of participants in order to analyse the consistency of the results obtained. Further similar studies on individuals with high acoustic admittance and no ARTs using a conventional pressure sweep could validate this study's results to determine clinical applicability.

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