Multifrequency Tympanometry: Effects of Ear Canal Volume Compensation on Middle Ear Resonance

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Abstract
Sweep frequency tympanograms compensating for ear canal volume at 200 and −400 daPa were obtained on 106 ears of 53 subjects during four different sessions. Resonance frequencies were obtained and analyzed to determine normative data, resonance differences between the compensation methods, and the interaction effect of running consecutive tympanograms. There were no gender or interaural differences for either compensation method. Although statistically significant, the compensation method by order interaction found between the first and second runs of tympanograms was not clinically significant. Compensation at 200 daPa was recommended when using sweep frequency tympanometry. Mean resonance frequency difference of the two compensation methods was 400 Hz. Large intersubject variability emphasized the need for audiologists to use proper compensation norms when examining middle ear resonance.

Key Words: Ear canal compensation, immittance, middle ear, tympanometry, multifrequency tympanometry, resonance

Multifrequency tympanometry may be used to estimate the resonance frequency of the middle ear. Experimental data have shown that middle ear pathologies alter tympanometric shapes at high frequencies and shift the resonance frequency of the middle ear transmission system. For example, increases in stiffness due to otosclerosis can shift middle ear resonance to a higher than normal frequency, and increases in mass (or lack of stiffness) due to ossicular discontinuity can shift middle ear resonance to a lower than normal frequency (Colletti, 1975, 1976, 1977; van Camp et al, 1983; Funasaka et al, 1984; van Camp and Vogeleer, 1986; Funasaka and Kumakawa, 1988; Shanks et al, 1988).

Resonance can be measured from acoustic susceptance or phase angle values after compensating for ear canal volume (Shanks et al, 1993). To compensate for ear canal volume, the susceptance at high positive or at high negative ear canal pressure is subtracted from all tympanometric values. A higher resonance frequency for negative ear canal pressure is attributed to normal tympanometric asymmetry, where there is lower admittance under negative pressure settings than under positive pressure settings (Margolis and Smith, 1977; Vanpeperstraete et al, 1979; Shanks and Lilly, 1981).

Multifrequency tympanometry can be performed with either the sweep pressure or sweep frequency method. The sweep pressure method holds the probe tone constant and sweeps the pressure. The sweep frequency method holds the pressure constant at specified intervals and sweeps the probe tone frequencies.

Shanks et al (1993) examined the effects of ear canal volume compensation on estimates of middle ear resonance using sweep frequency tympanometry. They evaluated the methods currently used on two acoustic immittance instruments with multifrequency capabilities. The Grason-Stadler Model 1733 middle ear analyzer Version 2 (GSI 33) plots the tympanometric peak to tail differences in acoustic susceptance, as a function of probe tone frequency. The Virtual Model 310 digital impedance...
instrument (Virtual 310) plots peak compensated phase angle as a function of probe tone frequency. Shanks et al concluded that the methods described above give comparable results. The mean middle ear resonance estimate was 817 Hz for measurements compensated at 200 daPa and was greater than 1052 Hz for compensation at -350 daPa. Twelve of their 26 subjects reached resonance above their cutoff frequency of 1243 Hz when ear canal compensation was at -350 daPa; therefore, an exact mean could not be reported.

Margolis and Goycoolea (1993) provided normative multifrequency data as obtained on the Virtual 310 for both sweep pressure and sweep frequency tympanometry. For the sweep frequency method, they reported a mean resonance of 1135 Hz for tympanograms compensated at 200 daPa and 1315 Hz for compensation at negative ear canal pressure (approximately -500 daPa). Margolis and Goycoolea reported that two or fewer subjects of 28 had resonance frequencies above their cutoff frequency of 2000 Hz for each method examined. Similar data obtained on the GSI 33 have not been reported. Reported differences of mean resonance frequencies compensated at positive and negative ear canal pressures ranged from 140 to 300 Hz (Margolis and Goycoolea, 1993; Shanks et al, 1984). It is not known if these resonance differences are consistent across subjects.

The GSI 33 compensates for ear canal volume based on the direction of pressure change as the tympanogram is run. That is, if the tympanogram is run in the positive to negative direction, it compensates from the positive tail, and vice versa. In order to examine resonance differences as a function of ear canal volume compensation using the GSI 33, two multiple frequency tympanograms must be obtained. In a clinical setting, both tympanograms would be recorded in one session. When these tympanograms are run consecutively, the middle ear resonance for the second tympanogram may change from the effects of multiple sweeps (Wilson et al, 1984). The results may also be affected by the interaction of running one tympanogram from a positive to negative direction and another from a negative to positive direction. This interaction would not occur on the Virtual 310 as ear canal volume compensation may be performed after the tympanogram is run.

The purposes of this study were to (1) provide normative data for multifrequency tympanometry as obtained on the GSI 33, (2) examine the differences in resonance frequency obtained from sweep frequency tympanograms compensated at both positive and negative ear canal pressures, and (3) examine the interaction effect of running consecutive multifrequency tympanograms at both positive and negative ear canal pressures.

METHOD

Fifty-three adults (106 ears) 18 to 25 years of age served in this study (25 males, 28 females). Each subject had normal hearing sensitivity (≤ 10 dB HL re: ANSI, 1989), a negative otoscopic exam, no reported history of chronic middle ear problems, and normal 226-Hz tympanometric peak pressures (100 to -150 daPa). Each subject attended a 15-minute session on 4 different days, with no more than 2 weeks passing between the first and the last session.

At each session, two sets of multifrequency data for each ear were collected with either ear canal volume compensation at -400 daPa first, followed by compensation at 200 daPa, or vice versa. The probe was left in the ear between test runs but the ear canal was vented. Initial ear order and compensation methods were randomly chosen for each subject. The order of the conditions was then counterbalanced among subjects. This rotation of trials provided four estimates of resonance from susceptance compensated at -400 daPa for each subject and four estimates compensated at 200 daPa. Trials 1 and 3 and trails 2 and 4 were identical, yielding test-retest data for all of the conditions examined.

The multiple frequency procedure incorporated in the GSI 33 is based on the sweep frequency tympanometry method. The GSI 33 first swept the probe tone from 250 to 2000 Hz in 50-Hz steps, while staying at the start pressure (200 daPa or -400 daPa). Susceptance and phase measurements from each frequency were stored in memory. An admittance tympanogram (226 Hz) was run with a sweep pressure rate of 50 daPa/sec and a pressure range of -400 to 200 daPa. This tympanogram was needed to obtain the tympanometric peak pressure (TPP). A second probe tone sweep was performed at TPP and the susceptance and phase measurements again were stored in memory.

Differences in susceptance and phase values between the first and second sweep of frequencies were calculated and plotted as a function of frequency. As the GSI 33 measured susceptance and phase in 50-Hz steps, the resonance frequency was marked by the equipment as the measured frequency that was closest to 0 mmhos.
Because of the step size, the calculated resonance frequency should be within 50 Hz of resonance frequencies up to 1000 Hz. For resonance frequencies from 1050 to 2000 Hz, the variation should not exceed 100 Hz (5% of the resonance frequency). Though phase measurements were taken, they were not used in the calculation of the resonance frequency (see Shanks et al, 1993 for a discussion).

All equipment was calibrated before the study began and weekly during data collection and met ANSI standards (ANSI 1987, 1989).

RESULTS AND DISCUSSION

Resonance Frequency

A multivariate analysis of variance (MANOVA) was performed on resonance frequency for ear, gender, compensation method, and order (p < .05). Results are displayed in Table 1. Mean resonance frequencies for ear canal volume compensated at 200 daPa were significantly lower than the mean resonance frequencies compensated at -400 daPa. Mean, median, mode, and 90 percent normal range data for the two compensation methods are shown in Table 2.

The mean resonance frequency with ear canal volume compensated at 200 daPa is 908 Hz with a 90 percent range of 650 to 1300 Hz. These results are in close agreement with other studies (Hanks and Rose, 1993; Shanks et al, 1993). Margolis and Goycoolea (1993) obtained a wider 90 percent range (800-2000 Hz) using a slightly different sweep frequency tympanometry method than the present study. Differences between the results may be due, in part, to intersubject variability and to the different step sizes that were used to measure resonance. The current study used 50-Hz steps, Shanks et al used 113-Hz steps, and Margolis and Goycoolea used 1/6-octave steps. For example, a middle ear resonance around 925 Hz could be classified as 900 or 950 Hz in the current study, 1000 Hz by Margolis and Goycoolea, and 1017 Hz by Shanks et al.

Mean resonance frequency with ear canal volume compensated at -400 daPa for the current study is 1318 Hz, the same as that found by Margolis and Goycoolea (1993). The 90 percent range is 900 to 1750 Hz. Ninety percent ranges obtained with ear canal volume compensated at negative pressure settings from other studies are more variable than those compensated at positive pressure settings (Funasaka et al, 1984; Margolis and Goycoolea, 1993; Shanks et al, 1993). All of the 90 percent ranges, however, are skewed toward the higher frequencies. A higher resonance frequency for negative ear canal pressure is attributed to normal tympanometric asymmetry, where there is lower admittance under negative pressure settings than under positive pressure settings (Margolis and Smith, 1977; Vanpeperstraete et al, 1979; Shanks and Lilly, 1981).

Differences in the results could be due to several factors. First, ear canal pressures used to compensate for ear canal volume were different, ranging from -200 to -500 daPa. The estimate of ear canal volume would be larger for tympanograms compensated at -200 daPa than at -500 daPa. This would result in lower estimates of resonance frequency at -200 daPa than at -500 daPa. Second, as discussed above, the frequency step size used to obtain resonance frequencies was different among the studies and would affect the estimate of the resonance frequency. Third, there is a great deal of variability in the asymmetry of tympanograms among subjects. The estimate of ear canal volume would change based on the amount of asymmetry, thus changing the resonance frequency estimate.

Test-Retest Reliability

Table 3 displays the Pearson $r$ correlations for resonance frequency as a function of compensation method by presentation order. Results
Table 2 Means (Standard Deviations), Medians, Modes, and Normal Ranges for Resonance Frequency as a Function of Compensation Method by Presentation Order

<table>
<thead>
<tr>
<th>Method (daPa)</th>
<th>Frequency (Hz)</th>
<th>Median</th>
<th>Mode</th>
<th>Normal Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 first</td>
<td>908 (188)</td>
<td>900</td>
<td>950</td>
<td>650-1300</td>
</tr>
<tr>
<td>200 second</td>
<td>924 (188)</td>
<td>900</td>
<td>800</td>
<td>650-1300</td>
</tr>
<tr>
<td>200 combined</td>
<td>916 (188)</td>
<td>900</td>
<td>950</td>
<td>650-1300</td>
</tr>
<tr>
<td>-400 first</td>
<td>1318 (308)</td>
<td>1300</td>
<td>1000</td>
<td>900-1750</td>
</tr>
<tr>
<td>-400 second</td>
<td>1286 (317)</td>
<td>1250</td>
<td>950</td>
<td>850-1850</td>
</tr>
<tr>
<td>-400 combined</td>
<td>1302 (312)</td>
<td>1250</td>
<td>1000</td>
<td>900-1800</td>
</tr>
</tbody>
</table>

indicated that resonance frequencies obtained with ear canal volume compensated at either 200 daPa or -400 daPa were very reliable. The reliability coefficients obtained in the present study are identical to or higher than those reported by Margolis and Goycoolea (1993) for sweep frequency tympanometry.

Table 4 presents means, medians, and 90 percent ranges for the differences in resonance frequency as a function of ear canal volume compensation. All of the descriptive data are identical between the first and second repetitions, indicating very small differences in resonance frequency between trials.

Resonance Differences between Compensation Methods

The mean difference in ear canal resonance frequency for the two compensation methods is approximately 400 Hz (Table 4). The majority of this difference may be accounted for by ear canal volume compensation, as has been discussed earlier (Shanks et al, 1993). The remaining difference may be accounted for by the effects of sweep direction and multiple sweeps (Vanpeperstraete et al, 1979; Osguthorpe and Lam, 1981; Wilson et al, 1984; Shanks and Wilson, 1986).

Figure 1 displays the distribution of resonance frequency differences obtained for the two compensation methods (averaged across repetitions). The resonance frequency compensation differences ranged from 0 to 1300 Hz. Some subjects had markedly different resonance frequencies for the two compensation methods. This may be attributed, in part, to the method used to calculate resonance. As the GSI 33 plots the difference in susceptance as a function of frequency, the plot can be either steep or flat. The resonance frequency is marked at the first measured frequency that is closest to 0 mmhos. Other points may be equally as close to 0 mmhos along the frequency continuum.

For example, one subject had a resonance difference of 1000 Hz. For the tympanogram that was compensated at 200 daPa, the frequency plot was very flat and near zero from approximately 700 Hz to 1500 Hz. The GSI 33 chose 800 Hz as the resonance frequency. For the tympanogram compensated at -400 daPa, the frequency plot was also very flat but above zero until 1700 Hz, the frequency which the GSI 33 calculated as the resonance frequency. Calculated resonance frequencies on subsequent days for the tympanograms compensated at 200 daPa were 1050, 850, and 700 Hz. Calculated resonance frequencies on subsequent days for the tympanograms compensated at -400 daPa were 1650, 1750, and 1750 Hz. These variabilities caused by the instrumentation were also noted by Valvik et al (1994).

Some subjects had similar resonance frequencies for the two compensation methods. Their tympanograms were very symmetric, or conversely, asymmetric, near the positive tail. This asymmetry near the positive tail is attributable to lower admittance under positive pressure settings than under negative pressure (Margolis and Popelka, 1977). The large variability

Table 3 Test–Retest Reliability Coefficients (Pearson r) from All Subjects (106 Ears)

<table>
<thead>
<tr>
<th>Resonance Frequency</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 daPa first</td>
<td>.92</td>
</tr>
<tr>
<td>200 daPa second</td>
<td>.95</td>
</tr>
<tr>
<td>-400 daPa first</td>
<td>.90</td>
</tr>
<tr>
<td>-400 daPa second</td>
<td>.92</td>
</tr>
</tbody>
</table>
Table 4 Means (Standard Deviations) and 90% Ranges for Resonance Frequency Differences (Hz) between Compensation Methods

<table>
<thead>
<tr>
<th>Compensation Method by Presentation Order Interaction</th>
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| The interaction between compensation method and order was significant. This interaction (Fig. 2) indicated that resonance frequency increased when the -400 daPa pressure was first, and decreased when the -400 daPa pressure was second. The mean difference in resonance frequency for ear canal volume compensated at 200 daPa is 16 Hz, whereas the mean difference for ear canal volume compensated at -400 daPa is 32 Hz. These differences are less than the 50-Hz increment used to calculate the resonance frequency and would not affect clinical decisions made regarding the presence or absence of pathology.

Preferred Compensation Method for Clinical Use

The following variables were examined before recommending one compensation method for clinical use: test–retest reliability, intersubject variability, and 90 percent range. Both compensation methods were very reliable, with compensation at 200 daPa slightly more reliable. Intersubject variability was lower for compensation at 200 daPa. The 90 percent range should allow for detection of abnormally high (increased stiffness of the middle ear) or abnormally low (increased mass of the middle ear) resonance frequencies. The available probe frequencies on the GSI 33 range from 250 to 2000 Hz. A 90 percent range that extended to either limit would not be useful in detecting abnormalities. Based on the above variables, multifrequency tympanometry compensated at 200 daPa is recommended for clinical use for the GSI 33.

SUMMARY AND CONCLUSIONS

Sweep frequency tympanograms compensating for ear canal volume at 200 and -400 daPa were obtained on 106 ears of 53 subjects during four different sessions. Resonance frequencies were obtained and analyzed in order to determine normative data (including test–retest reliability), resonance differences between the compensation methods, and the interaction effect of running consecutive tympanograms using different compensation methods.

Results indicated that there were no gender or interaural differences for resonance frequency for either compensation method. Compensation
at 200 daPa is preferred for obtaining resonance frequencies using sweep frequency tympanometry on the GSI 33. Test–retest data indicated high reliability between trials. Although statistically significant, the interaction between compensation method and order was not clinically significant.

Resonance frequency differences obtained from the two compensation methods are extremely variable and emphasize the need for audiologists to use the proper compensation norms when examining middle ear resonance.

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REFERENCES


