

# Distinguishing Healthy from Otosclerotic Ears: Effect of Probe-Tone Frequency on Static Immittance

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## Abstract

The diagnostic utility of static immittance (SI) with respect to distinguishing healthy from otosclerotic ears was investigated at different probe-tone frequencies in 68 healthy ears and 36 ears with surgically confirmed otosclerosis. Because one effect of otosclerosis is to shift the resonant frequency of the middle ear to higher values as a result of increased stiffness of the middle ear system, it was hypothesized that SI measured at higher probe-tone frequencies may provide a better distinction between healthy and otosclerotic ears. As expected, the results of this study indicate that SI measured at higher probe-tone frequencies is superior to a standard low probe tone in the detection of otosclerotic ears. Through systematic and objective comparisons of relevant probe-tone frequencies using both group statistics and test performance analysis, the present study suggests 630 Hz as an optimum probe-tone frequency for measuring SI with respect to distinguishing healthy ears from otosclerotic ears.

**Key Words:** Immittance, middle ear, otosclerosis, resonance, tympanometry

**Abbreviations:** AUC = area under the curve; B = susceptance;  $F45^\circ$  = frequency corresponding to admittance phase angle of 45 degrees; G = conductance; ROC = receiver operating characteristic; SI = static immittance; Y = admittance

## Sumario

La utilidad diagnóstica de la compliancia estática (SI) para distinguir entre oídos saludables y otoposcleróticos fue investigada para diferentes frecuencias de la sonda de prueba en 68 oídos sanos y en 36 oídos con una otoposclerosis confirmada quirúrgicamente. Dado que un efecto de la otoposclerosis es el cambio de la frecuencia de resonancia del oído medio a valores más altos como resultado del incremento en la rigidez del sistema del oído medio, se estableció la hipótesis de que las SI medidas con frecuencias más agudas de la sonda de prueba, podría aportar una mejor distinción entre oídos sanos y oídos otoposcleróticos. A través de comparaciones sistemáticas y objetivas de frecuencias relevantes en relación al tono de la sonda de prueba y utilizando estadística grupal y pruebas de análisis de rendimiento, el presente estudio sugiere que 630 Hz es una frecuencia óptima para el tono de prueba a la hora de medir SI, tratando de distinguir entre oídos saludables y otoposcleróticos.

**Palabras Clave:** Compliancia, oído medio, otoposclerosis, resonancia, timpanometría

**Abreviaturas:** AUC = área bajo la curva; B = susceptancia;  $F45^\circ$  = frecuencia correspondiente al ángulo de fase de 45 grados de la admitancia; G = conductancia; ROC = características operativas del receptor; SI = compliancia estática; Y = admitancia

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**T**ympanometry is a noninvasive and quick method for assessing middle ear function. In this technique, a pliable probe is sealed in the outer ear. Sound is presented while the air pressure is changed within the ear canal. The sound pressure level monitored at the probe tip provides an index of the ease with which acoustic energy flows into the middle ear system, which is referred to as acoustic admittance (Y). Tympanometry is typically conducted at a standard probe-tone frequency of 226 Hz.

At the low probe-tone frequency used in standard tympanometry, the normal middle ear system is stiffness dominated, and stiffness susceptance contributes more to overall Y than mass susceptance and conductance (G, the frictional element). Tympanometry performed at a low probe-tone frequency of 226 Hz has proved its validity in identifying various disorders of the middle ear (e.g., effusion or abnormal air pressures within the middle ear cavity), tympanic membrane abnormalities (e.g., atrophic scarring, retraction, or perforation), and eustachian tube malfunction (Lilly, 1984). However, standard tympanometry has often failed to distinguish normal middle ears from ears with lesions that specifically affect the ossicular chain, such as otosclerosis (Colletti, 1975, 1976, 1977; Lilly, 1984; Browning et al, 1985; Shahnaz and Polka, 1997). One major effect of otosclerosis is to increase the stiffness of the middle ear system resulting in a shift of the middle ear resonant frequency to the higher values. For this reason, it has been suggested that tympanometry performed using a higher probe-tone frequency, close to the resonant frequency or frequency corresponding to Y phase angle of 45 degrees ( $F_{45^\circ}$ ) of the normal human middle ear system, may be more informative in identifying otosclerosis (Liden et al, 1974; Shahnaz and Polka, 1997; Margolis and Hunter, 1999).

Early results reported by Burke and Nilges (1970) support the idea that tympanometry conducted using higher probe-tone frequency provides useful information for identifying an otosclerotic ear. They compared 18 normal with 18 surgically confirmed otosclerotic ears using absolute impedance measurements (Zwislocki Acoustic Bridge Model 3) at 125, 250, 500, 750, 1000, and 1500 Hz for each subject. By comparing a range of  $\pm 1$  SD, compliance measures revealed a good separation between normal and otosclerotic ears for probe-tone frequencies below 750 Hz. When a resistance range of  $\pm 1$  SD at a low (125 Hz) and a high probe-tone frequency (1500 Hz) for normal and otosclerotic ears were

compared, otosclerotic ears revealed a prominent difference between 125 Hz and 1500 Hz, whereas the normal group showed only a slight difference between these two frequencies. They reported a difference of 300  $\Omega$  or greater to be characteristic of otosclerotic ears in their sample. With this cutoff alone, 89 percent of ears in normal and otosclerotic ears were correctly classified as normal and otosclerotic ears (sensitivity and specificity of 89%).

A number of later studies, however, have failed to show that tympanometry aids in the identification of otosclerosis. For example, Liden and colleagues (1970) compared tympanograms obtained using 220-Hz, 625-Hz, and 800-Hz probe tones in 100 normal ears, 29 otosclerotic ears, and 27 ears with sensorineural impairment. They did not find any statistical differences between these three groups with respect to static impedance, tympanometric peak pressure, tympanometric width, or difference in sound pressure level (SPL) between the two end points (i.e., pressure extremes). They concluded that a normal tympanometric configuration is evident in otosclerotic ears.

A later study by Jerger and colleagues (1974) reported impedance measurements obtained using a standard low probe-tone frequency in 60 patients with a diagnosis of otosclerosis. They found that 95 percent of the otosclerotic ears had a normal type A tympanogram. Although the median (50th percentile) static Y was lower in otosclerotic ears than in normal ears, the overlap between the two groups was so great that only a small percentage of otosclerotic ears fell below the 10th percentile of the normal group. Thus, despite a small group difference, the extensive overlap between normal and otosclerotic ears severely limits the diagnostic utility of low-frequency tympanometry for identification of otosclerosis. This general finding is well supported in the literature (Alberti and Kristensen, 1970; Jerger, 1970; Dempsey, 1975; Shahnaz and Polka, 1997).

Muchnik and colleagues (1989) examined the clinical validity of static immittance (SI) values obtained at two probe-tone frequencies, 220 Hz and 660 Hz, in 42 confirmed otosclerotic ears. SI was measured for Y, susceptance (B), and G. The results were compared with the normative values of static Y established by Himmelfarb and colleagues (1977). No attempt was made to control for pathologies other than otosclerosis. The results for the 220-Hz probe tone revealed low Y values for 14 ears, normal values in 19 ears, and high Y in 9 ears. For the

660-Hz probe tone, low Y was found in 14 ears, normal values in 17 ears, and high Y values in 11 ears. These results suggest that changing the probe-tone frequency or focusing analysis on immittance components does not improve our ability to identify otosclerosis using tympanometry.

In contrast to the majority of the studies, results reported by Jacobson and Mahoney (1977) are in agreement with those of Burke and Nilges (1970) showing that tympanometry conducted using a high-frequency probe tone can aid in the identification of otosclerosis. They compared static B and G obtained using two probe-tone frequencies, 220 Hz and 660 Hz, in 28 surgically confirmed otosclerotic ears and 60 normal ears. None of the otosclerotic ears had any other pathology as confirmed by otomicroscopy and surgery. The results revealed significantly lower SI for otosclerotic ears than for normal ears on all four measures. They found that both friction and stiffness were higher in about three-fourths of the otosclerotic ears than in the normal ears. Furthermore, static B had 80 percent predictive accuracy<sup>1</sup> for otosclerosis. The predictive value increased to 100 percent for static G at 660 Hz probe-tone frequency. They claim that the failure to find reliable differences in previous studies is attributed to (1) the exclusive use of single-component impedance instrumentation, (2) contamination of the typical otosclerotic tympanograms with hypermobile tympanic membrane conditions, and (3) the quantification of tympanometric data using non-standard and subjective scaling (arbitrary values) at a 220-Hz probe-tone frequency.

In summary, most of the earlier studies that failed to reveal any significant difference between healthy and otosclerotic ears used a standard low probe-tone frequency and single-component tympanometry with nonstandard scaling (arbitrary) of Y values. In contrast, studies that reveal significant differences between the two groups compared SI across several probe-tone frequencies and Y components and applied more standard (absolute) scaling of Y values. Further research is necessary to ascertain the optimum probe-tone frequency and Y component in measuring static Y with respect to distinguishing healthy from otosclerotic ears.

In this study, the effect of probe-tone frequency on SI was examined. One specific question was asked: Do healthy and otosclerotic ears differ in SI at frequencies above the standard 226-Hz probe-tone frequency and, if so, what is the range of probe-tone frequencies where such differences are observed and what probe frequency is the optimal for distinguishing healthy from otosclerotic ears? The advantages of the higher probe-tone frequencies over standard low probe-tone frequency in measuring SI have been documented with respect to distinguishing low-impedance pathologies such as ossicular discontinuity and atrophic tympanic membrane (Liden et al, 1974; Van Camp et al, 1980). However, this advantage has not been established for more commonly occurring high-impedance pathologies such as otosclerosis. It was hypothesized that SI obtained at higher probe-tone frequencies, specifically frequencies in the vicinity of F45° of the normal middle ear (frequencies between 600 and 800 Hz), are the most useful in identifying otosclerosis. This hypothesis was based on Shahnaz and Polka's (1997) finding that F45° is the best single tympanometric measure for distinguishing healthy from otosclerotic ears. The findings of the present study are of a particular interest in clinical practice because a simple measure of SI at a single optimum probe-tone frequency is more accessible and easier to interpret than F45°. In this study, we examined the effects of probe-tone frequency on total Y and B measures because otosclerosis is understood to increase stiffness of the middle ear (Van Camp et al, 1986b). Hence, we expected to find similar results with respect to effect of probe frequency for both Y and B. G is assumed to be frequency independent and is not implicated in current models of otosclerosis (Van Camp et al, 1986); hence, we did not include this component in our initial analysis.

## METHODS

### Subjects

Thirty-six normal-hearing adults and 36 patients with a diagnosis of otosclerosis served as subjects. All of the normal-hearing adults and 14 of the patients served as subjects in previous research conducted by Shahnaz and Polka (1997). No subjects in either group had a history of head trauma or otoscopic evidence of eardrum abnormality as assessed by an otolaryngologist. Subjects with tympanic membrane abnormalities were excluded because these more lateral

<sup>1</sup>The authors did not mention at what probe-tone frequency this predictive value was obtained.

disorders can obscure more significant medial pathologies such as otosclerosis (Feldman, 1974). The ears were cleaned at the time of otoscopic examination, if needed.

The normal-hearing subjects were McGill University students or employees at the Royal Victoria Hospital, Montreal, who were compensated for their participation. To be included in the normal group, subjects had to (1) present pure-tone audiometric thresholds lower than 15 dB HL (re: ANSI 1969) at octave frequencies between 250 and 8000 Hz and no air-bone gap between 250 and 4000 Hz and (2) report no history of middle ear disease. Normal subjects ranged in age from 20 to 43 years (mean age 22 years). Tympanometry was performed in both ears in normal subjects. Data from four ears were excluded owing to tympanic membrane abnormalities, leaving a total of 68 ears.

Thirty-six patients with a diagnosis of otosclerosis and who were scheduled for surgery were recruited from McGill Teaching Hospitals. The patient group comprised 25 women and 11 men ranging in age from 22 to 76 years (mean = 47.7 years). Fixation of the ossicular chain consistent with the diagnosis of otosclerosis was confirmed in all patients at the surgery. Tympanometry and audiometry were performed in both ears, but only results from the candidate ear for the surgery were analyzed (total of 36 ears).<sup>2</sup> Seven additional patients were recruited, but their data were excluded owing to tympanic membrane abnormalities.

Pure-tone audiometry revealed a primarily conductive hearing impairment (air-bone gap of > 10 dB and a normal bone-conduction threshold at four test frequencies) in 18 of the 36 patients. Twenty-eight patients presented with a mixed hearing loss; in four of these patients, the mixed loss was limited to the high-frequency region. The audiometric contour was generally rising with greater conductive component in the low-frequency region than in the high-frequency region for all patients. The Carhart notch was observed in 19 patients; Carhart notch was defined as having bone-conduction thresholds at both 1000 Hz and 4000 Hz that are at least 10 dB lower (better bone-conduction threshold) than the bone-conduction threshold at 2000 Hz.

<sup>2</sup>The second ear could not be included within the normal group either because the hearing loss was bilateral or the other ear had already undergone surgery.

## Instrumentation

Pure-tone audiometry was conducted using a Grason Stadler (GSI-16) audiometer calibrated according to ANSI standards (re: S3.6. 1969). The Virtual digital immittance instrument (model 310) equipped with an extended high-frequency option was used to perform tympanometry. Before each data collection, the Virtual system was calibrated using three standard cavities (0.5, 2.0, and 5.0 cm<sup>3</sup>) according to the operation manual provided by the manufacturer. With this device, Y tympanograms are automatically displayed, but a display of tympanometric data in rectangular or polar format is also readily accessible.

## Procedure

In all subjects, tympanometry was performed following the otoscopic examination and pure-tone audiometry. For the patients, all testing was performed 1 day before surgery.

The data reported in this study were collected as part of a larger study on multifrequency, multicomponent tympanometry. The data collection protocol, described in detail in Shahnaz and Polka (1997), involved several steps. First, a 226-Hz tympanogram was recorded. Next, tympanograms were obtained at higher probe-tone frequencies, first using the sweep frequency recording and then using the sweep pressure recording method.<sup>3</sup> Only the data obtained using sweep pressure recording were used in the present study because this is the typical recording method used in a clinical context.

For the sweep pressure tympanograms, the air pressure of the external ear canal was decreased continuously from +250 to -300 daPa (positive to negative) at a rate of 125 daPa/sec (fast pump speed), whereas the probe-tone frequency was held constant. This pressure direction was used because it results in fewer irregular tympanograms than the ascending direction of pressure change (Wilson et al, 1984; Margolis and Shanks, 1985). Sweep pressure

<sup>3</sup>Both recording methods were being compared in the larger study. The sweep frequencies were recorded first because it has been reported that consecutive sweep pressure recordings appear to change the mechanical properties of the middle ear system (Vanpeperstraete et al, 1979; Osguthorpe and Lam, 1981), therefore affecting the results of sweep frequency recording.

typanograms were recorded using multiple probe-tone frequencies ranging from 250 to 2000 Hz progressing from low to high frequencies.<sup>4</sup> Twenty typanograms were recorded, one at each of the same frequencies used in the sweep frequency recording. The right ear was tested first for all of the normal-hearing subjects.

The measures analyzed in this study were derived from numerical values that were stored in a text format by the Virtual system when each typanogram was run.<sup>5</sup> In this format, the data are saved as uncompensated polar values (Y magnitude and corresponding phase angles [ $\phi$ ]) as a function of air pressure. The rectangular components, B and G, were derived from these polar values at different probe-tone frequencies using appropriate formulas (Margolis and Hunter, 1999, p. 387). Then each rectangular component, B and G, was corrected for ear canal Y at +250 daPa (positive compensation) and -300 daPa (negative compensation). The pressure corresponding to the peak of the typanogram was determined from the 226-Hz Y typanogram; the same peak pressure was used for all probe-tone frequencies. The compensated rectangular values were then converted back to their corresponding polar values (compensated Y and  $\phi$ ) using appropriate formulas (Margolis and Hunter, 1999, p. 387).

SI values were obtained in this way at nine probe-tone frequencies (226, 355, 450, 560, 630, 710, 800, 900, and 1000 Hz). Both total Y and

B measures were derived using both positive compensation (Y+ and B+) and negative compensation (Y- and B-). This resulted in 36 measures of SI (4 at each probe-tone frequency) for each subject.

### Statistical Analysis

Both statistical group difference method and test performance analysis were used to analyze the data. Statistical group difference was used to narrow the range of probe-tone frequencies to be analyzed further using test performance indices and receiver operating characteristic (ROC) curve analysis, which provide a way to assess which measure or measures in a set provide the best index for separating the groups.

Test performance analysis provides several indices (sensitivity or hit rate, specificity or false alarm, and A'<sup>6</sup>) that can be compared across different tympanometric measures. However, one limitation of this analysis is that it can only compare measures with respect to a single decision criterion or cutoff value. Standard statistical criteria, for example, 95 percent confidence interval, are typically used to define such cutoff values. However, these cutoff values do not necessarily isolate the best decision thresholds to use because they are based only on the distribution of a given measure in a healthy group and ignoring the distribution of the same measure in a diseased group. Moreover, comparing the test performance among different tympanometric measures based on only a single cutoff value can be misleading because it does not take into account all possible decision criteria. To overcome these limitations, ROC curve analysis was used. ROC curve analysis provides an objective means to statistically compare the performance of different tympanometric measures and to determine the optimal decision criterion or cutoff value. However, it should be noted that, although a given measure may be statistically superior to another measure based on ROC curve analysis, the difference in test performance between two measures (hit rate, false

<sup>4</sup>The progression from low to high frequencies was used to be consistent with the progression of frequencies used in the sweep frequency recordings, which was fixed by the instrumentation.

<sup>5</sup>We chose to derive the immittance measures from these data rather than use the admittance values automatically produced by the Virtual system to ensure the mathematical accuracy of our measures, especially at the higher probe-tone frequencies. Being a vector quantity, admittance cannot be added or subtracted unless the phase angles of the admittance parameters are identical (Margolis and Shanks, 1985; Shanks et al, 1993). At low probe frequencies, there is little difference in phase angles across admittance values because the ear is dominated by the stiffness component. At higher probe frequencies, both stiffness and friction contribute to total admittance, and thus phase angles differ. Therefore, at high frequencies, only admittance vectors that are represented in rectangular format (susceptance and conductance) should be subtracted to compensate for ear canal volume (Shanks et al, 1993). In this study, static admittance was calculated from compensated susceptance as well as compensated conductance. Some investigators suggest that the soft tissue and cerumen in the ear canal can contribute to acoustic conductance and must be compensated for (Feldman, 1976; Van Camp et al, 1986). Therefore, both components were taken into consideration in calculating static admittance.

<sup>6</sup>A' is a way of measuring the test performance in which hit rate is adjusted by the rate of false positives. To achieve a high A' score, a test must have both a high hit rate and a low false alarm rate. A' varies from 0.5 for a useless test to 1.0 for a perfect test (for more discussion see Robinson and Watson, 1972). A' was calculated from the decimal form of HT and FA using the Robinson and Watson (1972) formula:

$$A' = 0.5 + \frac{(HT - FA) \times (1 + HT - FA)}{4HT \times (1 - FA)}$$

**Table 1** Descriptive Statistics for Healthy Ears on Static Immittance (mmho) for Admittance (Y) and Susceptance (B) Using Positive (+) and Negative (-) Compensation

Frequency (Hz)	Y+ (mmho)		B+ (mmho)		Y- (mmho)		B- (mmho)	
	Mean (SD)	90% Range	Mean (SD)	90% Range	Mean (SD)	90% Range	Mean (SD)	90% Range
226	0.65 (0.31)	0.32-1.28	0.59 (0.27)	0.30-1.11	0.74 (0.31)	0.39-1.26	0.69 (0.27)	0.39-1.15
355	1.60 (1.15)	0.62-3.50	1.23 (0.67)	0.54-2.90	1.70 (1.13)	0.70-3.55	1.41 (0.68)	0.65-3.02
450	2.10 (1.21)	0.77-4.88	1.33 (0.66)	0.49-2.32	2.21 (1.18)	0.91-4.92	1.62 (0.69)	0.79-2.62
560	2.75 (1.40)	0.95-5.33	1.10 (0.75)	-0.22-2.17	2.78 (1.34)	1.05-5.00	1.56 (0.62)	0.73-2.60
630	3.07 (1.54)	1.14-5.64	0.65 (1.03)	-1.69-1.88	3.03 (1.46)	1.25-5.20	1.19 (0.80)	-0.33-2.25
710	3.34 (1.50)	1.33-5.83	0.14 (1.33)	-2.94-1.49	3.20 (1.38)	1.51-5.59	0.81 (1.05)	-1.60-1.84
800	3.57 (1.44)	1.53-6.04	-0.34 (1.72)	-3.84-1.30	3.00 (2.61)	1.19-5.75	0.63 (1.25)	-1.17-2.10
900	3.81 (1.45)	1.82-6.76	-1.30 (1.65)	-4.40-0.73	3.40 (1.35)	1.70-6.16	-0.30 (1.30)	-3.31-1.20
1000	3.97 (1.52)	1.75-6.78	-1.95 (1.83)	-5.71-0.21	3.47 (1.24)	1.55-5.87	-0.85(1.38)	-4.08-0.85

Results are shown for nine different probe-tone frequencies for healthy ears (N = 68).

alarm, and A') at the optimum cutoff value might not be clinically meaningful. The area under the ROC curve (AUC) and the 95 percent confidence interval for this area are reported here. The AUC can be interpreted as follows: an AUC of 0.81, for example, means that a randomly selected person from the positive group has a test value larger than that for a randomly chosen person from the negative group 81 percent of the time (Zweig and Campbell, 1993). When the variable under study cannot distinguish between the two groups, that is, where there is no difference between the two distributions, the AUC is 0.5. When there is a perfect separation of the values of the two groups, that is, there is no overlapping of the distributions, the AUC is 1 (i.e., the ROC curve reaches the upper left corner of the plot). The 95 percent confidence interval for the AUC can be used to test the hypothesis that the theoretical area is 0.5, that is, at a chance level. If the confidence interval does not include the 0.5 value, this is evidence that the test can be used to better distinguish between the two groups (Hanley and McNeil, 1982; Zweig and Campbell, 1993).

AUC can also be used to compare the performance of two different measures or the same measure at two different occasions. An objective approach is to test the statistical significance of the difference between the two AUC values, as suggested by Hanley and McNeil (1982). It should be noted that this comparison does not rely on the selection of a particular decision threshold.

## RESULTS

**D**escriptive statistics for SI measures in both healthy and otosclerotic ears are provided

in Tables 1 and 2. Mean SI values for Y+, Y-, B+, and B- measures are plotted at each probe-tone frequency for healthy and otosclerotic ears in Figures 1 and 2, respectively. As can be seen in these figures, mean Y+ and Y- values are higher for healthy ears than otosclerotic ears across all probe-tone frequencies, with the largest differences evident between 630 and 800 Hz. In contrast, B+ and B- values are not consistently higher for healthy ears than otosclerotic ears across probe frequencies.

Data analysis was done in two stages as described above. The first analysis stage was a statistical evaluation of group differences between healthy and otosclerotic ears. A mixed-model analysis of variance (ANOVA) was conducted for data obtained at each of the nine probe-tone frequencies. In each ANOVA, group (healthy vs otosclerotic ears) was a between-subject factor and estimate (Y+, Y-, B+, B-) was a within-subject factor. The main effect of group was significant at only two probe-tone frequencies, 630 Hz ( $F = 5.50$ ,  $df = 1, 102$ ,  $p = .02$ ,  $(\eta^2 = 0.20)$ ) and 710 Hz ( $F = 6.30$ ,  $df = 1, 102$ ,  $p = .01$ ,  $(\eta^2 = 0.10)$ ). There was no group by estimate interaction in any of these ANOVA, indicating that overall group effects were evident for all four estimates of SI. The main effect of estimate was also significant at all probe-tone frequencies ( $p < .05$ ), indicating that different methods of estimating SI yield different values. The simple effect of estimate collapsed across group was significant for both Y+ versus Y- and B+ versus B- contrasts (except at 800 Hz for Y+ vs Y- contrast); however, the effect started reversing its direction from Y- > Y+ to Y- < Y+ around 710 Hz.

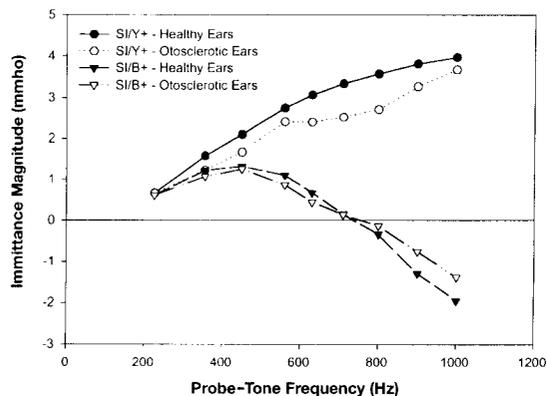
The second stage of our analysis focused on the eight measures that revealed statistical

**Table 2** Descriptive Statistics for Otosclerotic Ears on Static Immittance (mmho) for Admittance (Y) and Susceptance (B) Using Positive (+) and Negative (-) Compensation

Frequency (Hz)	Y+ (mmho)		B+ (mmho)		Y- (mmho)		B- (mmho)	
	Mean (SD)	90% Range	Mean (SD)	90% Range	Mean (SD)	90% Range	Mean (SD)	90% Range
226	0.64 (0.53)	0.09-1.82	0.59 (0.49)	0.09-1.64	0.71 (0.55)	0.13-1.89	0.67 (0.52)	0.13-1.74
355	1.24 (1.27)	0.19-4.09	1.07 (1.13)	0.16-3.19	1.33 (1.30)	0.23-4.21	1.21 (1.18)	0.22-3.42
450	1.69 (1.99)	0.23-6.32	1.26 (1.44)	0.21-3.61	1.85 (2.07)	0.32-6.42	1.50 (1.54)	0.31-3.98
560	2.41 (3.21)	0.26-10.35	0.85 (1.04)	-1.04-2.61	2.58 (3.16)	0.37-10.22	1.22 (1.44)	-0.34-3.38
630	2.40 (2.86)	0.34-9.63	0.42 (1.66)	-3.51-1.66	2.59 (2.73)	0.44-9.35	0.88 (1.60)	-2.75-2.87
710	2.52 (2.41)	0.37-8.71	0.13 (2.13)	-5.21-1.74	2.84 (1.97)	0.78-6.65	0.55 (1.88)	-4.08-2.51
800	2.71 (2.19)	0.50-6.98	-0.14 (2.09)	-5.17-1.71	2.84 (1.97)	0.78-6.65	0.55 (1.88)	-4.08-2.51
900	3.27 (2.55)	0.53-8.96	-0.76 (2.49)	-5.40-1.32	3.24 (2.21)	0.87-8.57	0.01 (2.14)	-4.14-2.04
1000	3.67 (2.83)	0.62-9.12	-1.39 (3.11)	-7.62-1.26	3.47 (2.31)	0.99-8.33	-0.44 (2.60)	-4.64-2.25

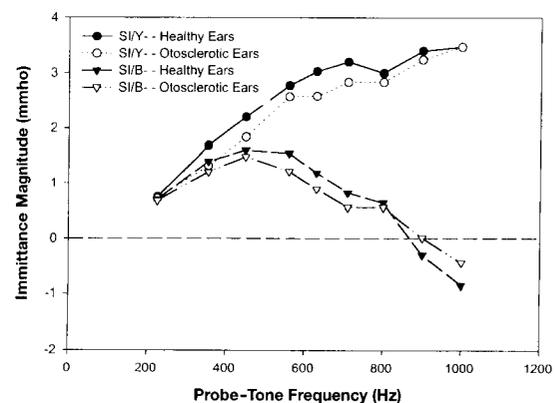
Results are shown for nine different probe-tone frequencies for otosclerotic ears (N = 36).

group differences in stage one and thus included Y+, Y-, B+, and B- measures obtained at 630 Hz and 710 Hz. Although it did not prove to be useful for distinguishing otosclerotic ears from healthy ears, a 226-Hz probe-tone frequency was also included in this analysis for a baseline comparison of a standard low probe-tone frequency to higher probe-tone frequencies. Test performance and ROC plot analyses were conducted for each of these measures. The ROC plots for SI measures conducted using Y+ at 226-Hz, 630-Hz, and 710-Hz probe-tone frequencies are shown in Figure 3. Table 3 shows the test performance indices derived from this analysis including sensitivity (hit rate), specificity (false alarm), A', and ROC plot information, including AUC and the lower limit defining the 90 percent confidence interval for the AUC (lower CI); the suggested (optimal) cutoff value for each variable is also listed.

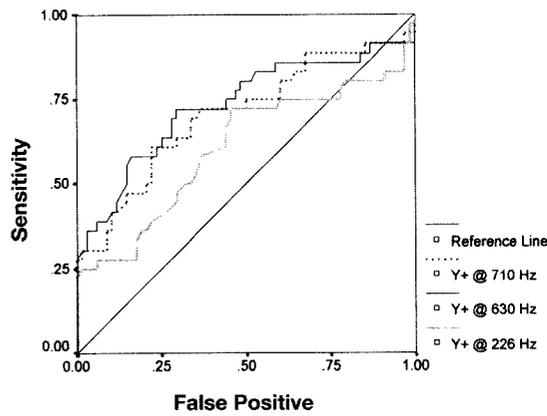


**Figure 1** Comparison of mean static immittance (SI) for positively compensated admittance (Y+) and susceptance (B+) in the healthy ears and otosclerotic ears.

The AUC (as described above in the statistics section) was analyzed to isolate the best index or indices for distinguishing healthy from otosclerotic ears among the 630-Hz and 710-Hz measures listed in Table 3. First, the AUC were analyzed to determine which AUC were significantly greater than 0.5 and thus provide a better than chance level separation of the two groups (healthy and otosclerotic ears). This analysis (using  $p < .01$ ) revealed that for both 630-Hz and 710-Hz measures, AUC were significantly above 0.5 (chance) for the Y+ but not for the Y-, B+, or B- measures. Next, AUC differences (also described above) were analyzed to determine whether there were significant differences between Y+ and Y- measures with respect to the ability to separate the healthy from the otosclerotic ears. This analysis (using  $p < .01$ ) also showed that Y+ measures were statistically superior to Y- at both 630 Hz



**Figure 2** Comparison of mean static immittance (SI) for negatively compensated admittance (Y-) and susceptance (B-) in the healthy ears and otosclerotic ears.



**Figure 3** Receiver operating characteristic (ROC) curve analysis for positively compensated static admittance (Y+) obtained at different probe-tone frequencies.

and 710 Hz and that Y+ measures obtained using a 630-Hz probe were significantly superior to measures obtained using a 710-Hz probe-tone frequency. Taken together, these results indicate that SI measured using Y+ at 630 Hz is the best index for distinguishing normal from otosclerotic ears. The distribution of this variable is plotted for healthy and otosclerotic ears in Figure 4, which displays Y+ values obtained at 630 Hz using a dual dot plot (a form of scatter plot), with a horizontal line indicating the cutoff point with the best separation (minimal false-negative and false-positive results) between the two groups. Data for Y+ values obtained using a standard 226-Hz probe are also plotted for comparison.

A third set of analyses was conducted given the unexpected finding that Y measures were clearly superior to B measures with respect to distinguishing otosclerotic from healthy ears. As mentioned in the introduction, otosclerosis has been consistently described as increasing the stiffness of the middle ear. Accordingly, the effect of this disease process should be comparable when looking at a measure of total Y (which includes stiffness and resistance components) or B (the stiffness component). Thus, the divergence of results for Y and B measures of immittance observed here suggests that otosclerosis also alters the resistance of the middle ear. Therefore, we also examined the G component of immittance obtained using 630-Hz and 710-Hz probe-tone frequencies. Test performance and ROC curve analyses revealed that AUC computed for G+ using 630- and 710-Hz probe tones were significantly ( $p < .01$ ) greater than 0.5 (chance). We also found that AUC were significantly higher for G than for B (for both negative and positive values), but AUC for G were not significantly lower than AUC observed for Y measures (positive and negative) at 630 Hz. These results indicate that otosclerosis predominantly alters resistance of the middle ear system.

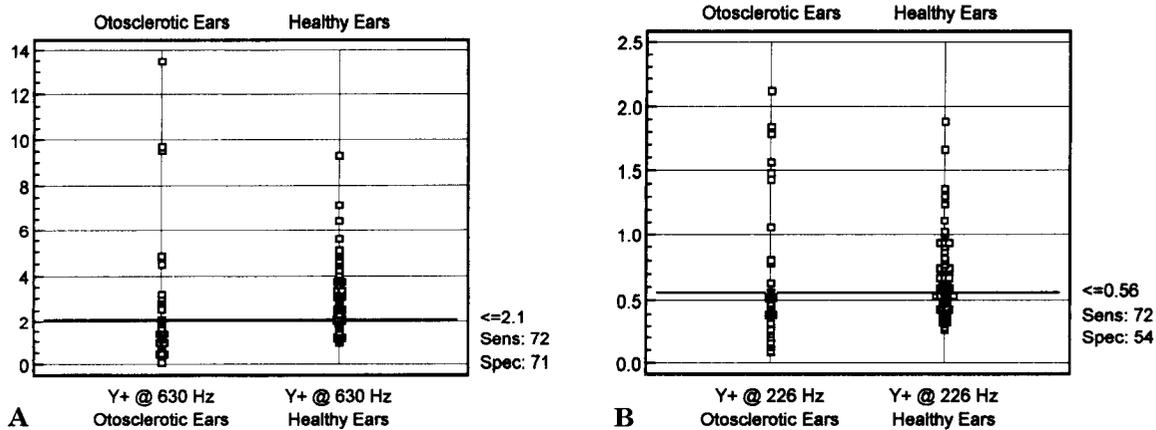
### DISCUSSION

Overall, as predicted, the results of this study confirm that SI measured at higher probe-tone frequencies is superior to a standard low probe tone in detecting otosclerotic ears. This

**Table 3** Test Performance Analysis, Hit Rate (HR or Sensitivity), False Alarm (FA or Specificity), and A' for Static Immittance (SI) Obtained Using Admittance (Y) and Susceptance (B) with Positive and Negative Compensation (Y+, B+, Y-, and B-) at Three Probe-Tone Frequencies and Receiver Operating Characteristic Plot Information

	Probe-Tone Frequency (Hz)	Suggested Cutoff (mmho)	HR (%)	FA (%)	A'	AUC	Lower CI
Y+	226	≤ 0.56	74	46	0.71	0.61	0.51
	630	≤ 2.10	72	29	0.80	0.73	0.64
	710	≤ 2.10	78	39	0.78	0.71	0.61
B+	226	≤ 0.45	53	71	0.70	0.60	0.50
	630	≤ 0.90	56	53	0.58	0.52	0.42
	710	≤ 0.90	42	71	0.62	0.57	0.47
Y-	226	≤ 0.63	64	63	0.71	0.62	0.52
	630	≤ 1.80	56	82	0.79	0.68	0.58
	710	≤ 1.90	50	82	0.76	0.66	0.56
B-	226	≤ 0.37	31	96	0.79	0.62	0.52
	630	≤ 0.90	36	75	0.61	0.54	0.44
	710	≤ 1.40	36	75	0.61	0.57	0.46

AUC = area under the curve; CI = confidence interval.



**Figure 4** A, The distribution of positively compensated admittance (Y+) at 630 Hz in healthy and otosclerotic ears. Horizontal line indicates the cutoff point with the best separation (minimal false-negative and false-positive results) between the two groups. B, The distribution of positively compensated admittance (Y+) at 226 Hz in healthy and otosclerotic ears. Horizontal line indicates the cutoff point with the best separation (minimal false-negative and false-positive results) between the two groups.

general finding is consistent with several earlier reports of studies in which multiple probe-tone frequencies and immittance components were applied in measuring SI and found it to be useful in differentiating healthy ears from otosclerotic ears (Burke and Nilges, 1970; Djupesland and Kvernold, 1973; Jacobson and Mahoney, 1977). Through systematic and objective comparisons of relevant probe-tone frequencies using both group statistics, test performance at the optimum cutoff, and ROC curve analysis, the present study indicates that 630 Hz is the optimal probe-tone frequency for measuring SI with respect to distinguishing healthy ears from otosclerotic ears. This frequency is very close to the average value of  $F45^\circ$  in the normal human middle ear (500–700 Hz depending on which measure is used), which proved to be the best single variable in distinguishing healthy ears from otosclerotic ears as reported by Shahnaz and Polka (1997). Although many commercially available immittance audiometric systems do not provide 630 Hz, some provide a 678-Hz probe tone, which should provide equivalent results.

The findings of this study also indicate that, when distinguishing healthy ears from otosclerotic ears using measures obtained with a 630-Hz probe tone, Y is superior to B and, surprisingly, G is also superior to B at this probe frequency (the difference is more pronounced at 710 Hz). These findings suggest that otosclerosis predominantly affects the G element of the middle ear at higher probe frequencies. As mentioned above, this finding is clearly inconsistent with the standard descriptions of otosclerosis as a pathology that

increases the stiffness of the middle ear. Thus, further research is needed to clarify the effects of otosclerosis on G and how these effects are expressed in tympanometry.

This study is not the first to show that both stiffness and resistance are affected by otosclerosis. This general finding was reported by Jacobson and Mahoney (1977). However, a more recent study by Muchnik and colleagues (1989) failed to find any differences between normal and otosclerotic ears for either B or G measures obtained using the same probe-tone frequencies (220 and 660 Hz) as the Jacobson and Mahoney (1977) study. There are two factors that may explain why the study of Muchnik and colleagues did not find differences between normal and otosclerotic ears. First, there may be a substantial error in their Y measures because they did not compensate for the effect of ear canal Y from the Y rectangular components, as was done here and in other studies (Shanks et al, 1993; Margolis and Hunter, 1999). Second, their results may be contaminated by other pathologies because they did not exclude patients with other middle ear abnormalities, such as atrophic monomeric tympanic membrane, as was done here and in the Jacobson and Mahoney (1977) study.

The present findings also suggest that SI measures derived using positive (+) compensation are generally better than negative (–) compensation for distinguishing healthy and otosclerotic ears. This recommendation is more relevant at higher probe-tone frequencies. The issue of the compensation has not been explored

in previous studies; however, better test–retest reliability was reported for static Y obtained using positive tail compensation (Margolis and Goycoolea, 1993).

Two additional variables that can also affect static Y, sex and age, were not addressed in the current study. Roup and colleagues (1998), in an attempt to control for subject age and sex, re-examined the Margolis and Heller (1987) normative tympanometric data obtained using standard low-frequency tympanometry. They have also established normative tympanometric values in another 102 young adults with normal hearing using standard low-frequency tympanometry. They found that male adults had significantly higher peak compensated static Y than female adults; however, the lower ends of the 90 percent range were similar for both males and females. Therefore, it is unlikely that the sex would have affected the results in the current study since only low peak compensated Y abnormalities were the focus of this study.

With regard to age effects, several studies reported greater variability among older adults (Wiley et al, 1996; Roup et al, 1998); however, the mean value of compensated Y and its 90 percent normal range were not statistically different for the studies of Roup and colleagues (1998; age range 20–30 years), Margolis and Heller (1987; age range 19–61 years), and Wiley and colleagues (1996; age range 48–92 years). This issue has not been investigated at higher probe-tone frequencies; therefore, in the present study, the greater variability observed in the patient group may be partly attributed to the age differences between the normal (age range 20–43 years) and the patient group (age range 22–76 years).

In summary, the advantage of higher probe-tone frequencies over a standard low probe-tone frequency in measuring static Y has been confirmed for detecting low-impedance pathologies such as ossicular discontinuity and atrophic tympanic membrane (Van Camp et al, 1980; Margolis and Shanks, 1985). The present findings establish the diagnostic utility of tympanometry performed using higher probe-tone frequencies for a high-impedance pathology (otosclerosis). The present study also indicates that a measure of total Y obtained using a 630-Hz probe tone and positive compensation is a better index for distinguishing healthy from otosclerotic ears than a tympanogram obtained using standard low probe-tone frequency. The results of this study also suggest that otosclerosis predominantly affects the friction element of

the middle ear, contrary to the widely accepted view of otosclerosis as a stiffness-based pathology. Further research is needed to clarify the role of G in both healthy and otosclerotic ears.

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