Multifrequency, Multicomponent Tympanometry in Normal and Otosclerotic Ears.

Navid Shahnaz
School of Communication Sciences and Disorders
McGill University, Montreal
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Abstract

Nine tympanometric measures were examined in 68 normal ears and 14 ears with surgically confirmed otosclerosis. Two parameters, static admittance and tympanometric width, were derived from standard low frequency tympanometry and two parameters, resonant frequency and frequency corresponding to admittance phase angle of 45° (F45°), were derived from multifrequency, multicomponent tympanometry. The results show the advantage of multifrequency, multicomponent tympanometry over standard low frequency tympanometry in differentiating otosclerotic ears from normal ears. In particular, for identifying high impedance pathologies, the present findings support the use of sweep frequency (SF) recording for measuring resonant frequency and frequency corresponding to admittance phase angle of 45° (F45°) and positive tail compensation for measuring resonant frequency. The relationship among the measures obtained in this study also revealed that two distinct signs are evident in the patient group; 1) an increase in the stiffness of the middle ear best shown by F45° measured using SF method, and 2) an increase in the sharpness of the tympanogram best shown by tympanometric width. The combination of F45° measured using SF method and tympanometric width separated normal from otosclerotic ears better than any single measure used in this study.

Sommaire

Neuf différentes mesures tympanométriques ont été faites sur 68 oreilles normales et 14 oreilles ayant de l'otosclérose (confirmée chirurgicalement). Deux valeurs (l'admittance statique et le facteur de qualité du tympanogramme) ont été déterminées à partir de tympanogrammes habituels (basse fréquence). Deux autres valeurs (la fréquence de résonance et la fréquence correspondant à une phase de 45° (F45°), ont été déterminées à partir de tympanogrammes multi-fréquences à composantes multiples. Les résultats montrent l'avantage d'utiliser la tympanométrie multi-fréquences à composantes multiples par rapport à la tympanométrie de basse fréquence pour la différenciation entre l'otosclérose et une oreille normale. Les présents résultats montrent en particulier que l'utilisation d'un balayage de fréquence (SF) et la compensation en pression positive (sources de la mesure de la fréquence de résonance et de la fréquence correspondant à une phase de 45°) permettent l'identification de pathologie présentant une grande impédance. La mise en relation des données obtenues lors de cette étude révèle deux indices permettant de distinguer entre nos deux groupes de sujets. 1) La mesure F45° par balayage de fréquence est la meilleure façon de voir l'augmentation de la rigidité au niveau de l'oreille moyenne. 2) Le facteur de qualité du tympanogramme est l'indice qui révèle le mieux l'augmentation de la finesse du pic du tympanogramme. La combinaison des mesures de F45° par balayage de fréquence et le facteur de qualité du tympanogramme permet de séparer l'otosclérose de l'oreille normale mieux que n'importe quelle autre mesure utilisée dans cette étude.

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Introduction

Tympanometry is a safe and quick method for assessing middle ear function. In this technique, a pliable probe is sealed in the outer ear through which a 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 can flow through the middle ear system, which is referred to as acoustic admittance. The admittance values are plotted as a function of the ear canal air pressure; this display is referred to as a tympanogram. Tympanometry performed at a standard low probe tone frequency (226 Hz) has proved to be useful in identifying many conditions that affect the middle ear system. However, most of the lesions that specifically affect the ossicular chain often cannot be identified using measures derived from standard tympanometry.

The appearance of multifrequency, multicomponent devices have made it possible to evaluate admittance subcomponents, conductance (determined by the friction in the system) and susceptance (determined by the stiffness and mass of the system), and to perform tympanometry across a wide range of probe tone frequencies. Research to date suggests that multifrequency, multicomponent tympanometry may have clear advantages over standard low frequency tympanometry in detecting lesions that affect the ossicular chain. However, the clinical utility of multifrequency, multicomponent tympanometry has not been clearly established. One potentially useful parameter that can be derived from multifrequency, multicomponent tympanometry is an estimate of the middle ear resonant frequency. There is considerable interest in assessing middle ear resonance because, in studies reporting group data, resonant frequency is often shifted higher or lower in ears with ossicular pathology in comparison with normal ears. However, previous studies have also suggested that the normal range of resonant frequency as measured by a tympanometry may be too large to make it a sensitive measure of those pathologies which increase the stiffness of the ossicular chain such as otosclerosis.

More recently, Shanks, Wilson, and Palmer (1987) have suggested another parameter that may distinguish normal ears and otosclerotic ears. From a plot of admittance subcomponents (conductance and susceptance) at different frequencies, they determined the frequency at which the conductance first becomes larger than susceptance. This value corresponds to a 45° phase angle when admittance is expressed in polar notation. Their preliminary data from one otosclerotic ear and ten young normal subjects suggests that this parameter may also have diagnostic value in differentiating normal ears from those with abnormal stiffness. Therefore, it will be informative to examine this parameter in a larger group of normal and otosclerotic ears and to compare its diagnostic value to that of resonant frequency.

The present project was directed at evaluating alternative tympanometric parameters with respect to distinguishing normal middle ears and ears with otosclerosis Two parameters derived from standard tympanometry, static admittance and tympanometric width, were compared with two parameters that can only be obtained using multifrequency, multicomponent tympanometry, middle ear resonant frequency and the frequency corresponding to an admittance phase angle of 45°. Previous studies have examined one or two of these variables in normal and otosclerotic ears or have only provided normative data. The present study contributes to our understanding of tympanometry as a tool for identifying otosclerosis by providing a systematic comparison of this set of variables in individuals with normal middle ear function and individuals with otosclerosis.

Literature Review

The following literature review is organized in four major sections. In the first section, some terms and basic principles underlying all immittance measurements will be defined. In the second section the measurement of immittance through tympanometry will be reviewed. The third section will begin with a description of otosclerosis which is followed by a review of studies concerned with the application of tympanometry in identifying otosclerosis. Consistent with the evolution of tympanometry, studies using standard low frequency tympanometry will be discussed first, followed by studies using multifrequency, multicomponent tympanometry. The fourth section will outline the goals of the present study.

Immittance Principles

Tympanometry is the measurement of the acoustic immittance of the ear as a function of ear canal air pressure (ANSI, S3.39-1987). Immittance is a generic term that encompasses impedance, admittance, and their components. Impedance (Z - in acoustic ohms) in the middle ear system is defined as the total opposition of this system to the flow of the acoustic energy. Admittance (Y - in acoustic mmhos) is the reciprocal of impedance and is the amount of acoustic energy that flows into the middle ear system. All currently available immittance instruments measure admittance. Therefore, in this study, admittance terminology will be used whenever possible, but not exclusively as most of the research conducted in the 1970s and early 1980s utilized impedance measures and terminology.

There are three variables that determine admittance: mass, compliance (the inverse of stiffness), and friction. The admittance offered by stiffness elements in the middle ear system is called compliant susceptance (also referred to as compliance) and is denoted by B_C (also stiffness reactance, negative reactance, or X_C in impedance terms). The admittance offered by mass elements in the middle ear system is called mass susceptance and is denoted by B_m (also mass reactance, positive reactance, or X_m in impedance terms). Total susceptance (or total reactance in impedance terms) is the algebraic sum of the mass and compliance elements as plotted along the Y axis in Figure 1. In Figure 1 (right), the compliance susceptance (B_c) is on the positive axis that begins at zero and extends upward indefinitely, whereas the mass susceptance (B_m) is on negative axis that begins at zero and extends downward indefinitely. If the total

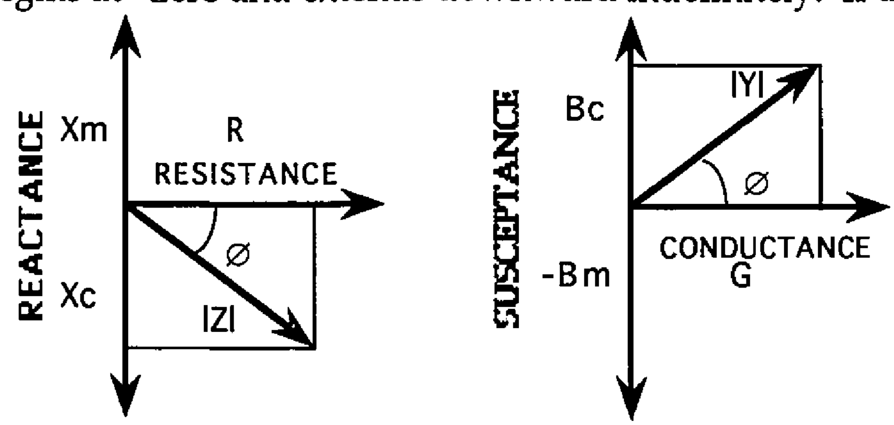

Figure 1. Left - The impedance vector [X_m: mass reactance; X_C: stiffness reactance; |Z|: absolute impedance magnitude; $Ø_Z$: impedance phase angle]. Right - The admittance vector [B_m: mass susceptance; B_C: stiffness susceptance; |Y|: absolute admittance magnitude; $Ø_Y$: admittance phase angle].

susceptance is positive a system is stiffness controlled; if this value is negative the system is mass controlled. As shown in Figure 1 (left) in impedance terms, the sign is reversed, therefore if total reactance is negative a system is stiffness controlled and if total reactance is positive a system is mass controlled.

The third variable determining the absorption or dissipation of acoustic energy is friction. This element is called conductance and is denoted by G (also resistance, or R in impedance system). Conductance is plotted on the X axis in Figure 1. The value of conductance is always positive.

The admittance of the system (|Y|) is a vector sum of conductance (G) and the total susceptance (B_t). Mathematically, admittance can be expressed in polar notation or in rectangular notation. In rectangular notation, admittance is expressed as the sum of its conductance (G) and susceptance (B_t) elements. Thus, acoustic admittance in rectangular notation can be expressed as:

$$Y = G + jB_t$$

Where j is mathematically equal to $\sqrt{-1}$ and indicates that conductance and susceptance can not be combined by simple addition because they are vectors that operate in different directions. The subscript *t* stands for total susceptance. In polar notation admittance is expressed by its absolute magnitude and phase angle. The angle formed by the admittance vector and the horizontal axis in Figure 1 (right) is denoted by the phase angle, Øy. Thus, acoustic admittance in polar notation can be expressed as:

$$|Y| \ \& \ \varnothing y$$

The polar and rectangular notations are mathematically related to one another. Table 1 provides conversion formulas that express these relationships.

Table 1. Definitions and conversion formulas for admittance.

Admittance_Y
$\lvert Y \rvert < \varnothing y$ (Polar notation)
$G + jB_t$ (Rectangular notation)
$G = \lvert Y \rvert \cos \varnothing y$
$B = \lvert Y \rvert \sin \varnothing y$
$\lvert Y \rvert = \sqrt{G^2} + B^2$
$\tan \varnothing y = B/G$
$\varnothing y = \arctan (B/G)$

To understand the application of multifrequency, multicomponent tympanometry, it is important to also consider how the relation between admittance components varies as a function of frequency in the normal adult middle ear system. Acoustic conductance (the frictional component) is independent of frequency, whereas compliance and mass susceptance are frequency dependent. Mass susceptance is directly proportional to frequency and compliance susceptance is inversely proportional to frequency. Therefore, as frequency increases, the total susceptance progresses from positive values (stiffness controlled) toward zero (resonance) to negative value (mass controlled). Resonance of the middle ear system is achieved when the compliant and mass susceptance are equal, i.e., total susceptance is equal to 0 mmhos. In humans, resonant frequency is typically measured using tympanometry and varies depending on the exact procedure used for its estimation. For example, the resonant frequency of the normal adult ear was reported to fall as low as 630 Hz and as high as 2000 Hz (Margolis & Goycoolea, 1993).

An example of the rotation of the admittance vector at different frequencies in a normal adult ear is shown in Figure 2. When the admittance vector lies between 0° and 90° (i.e., at frequencies below resonance) the system is stiffness controlled and when the admittance vector lies between 0° and -90° (i.e., at frequencies above resonance), the system is mass controlled. At low frequencies (226 Hz & 565 Hz in this example) susceptance is larger than conductance (B>G) and the admittance vector lies between 45° and 90°. As frequency increases susceptance (B) decreases and conductance (G) increases. Eventually susceptance becomes equal to conductance (B=G). This corresponds to a 45° phase angle. With further increases in frequency, conductance becomes larger than susceptance (B<G), i.e., at phase angles between 45° and 0° (791 & 904 Hz in this example). At or near resonance (1017 Hz in this example) total susceptance approaches zero (Bt = 0; when stiffness and mass susceptance are equal) and, thus conductance (caused by friction) is the only component contributing to the admittance of the system.

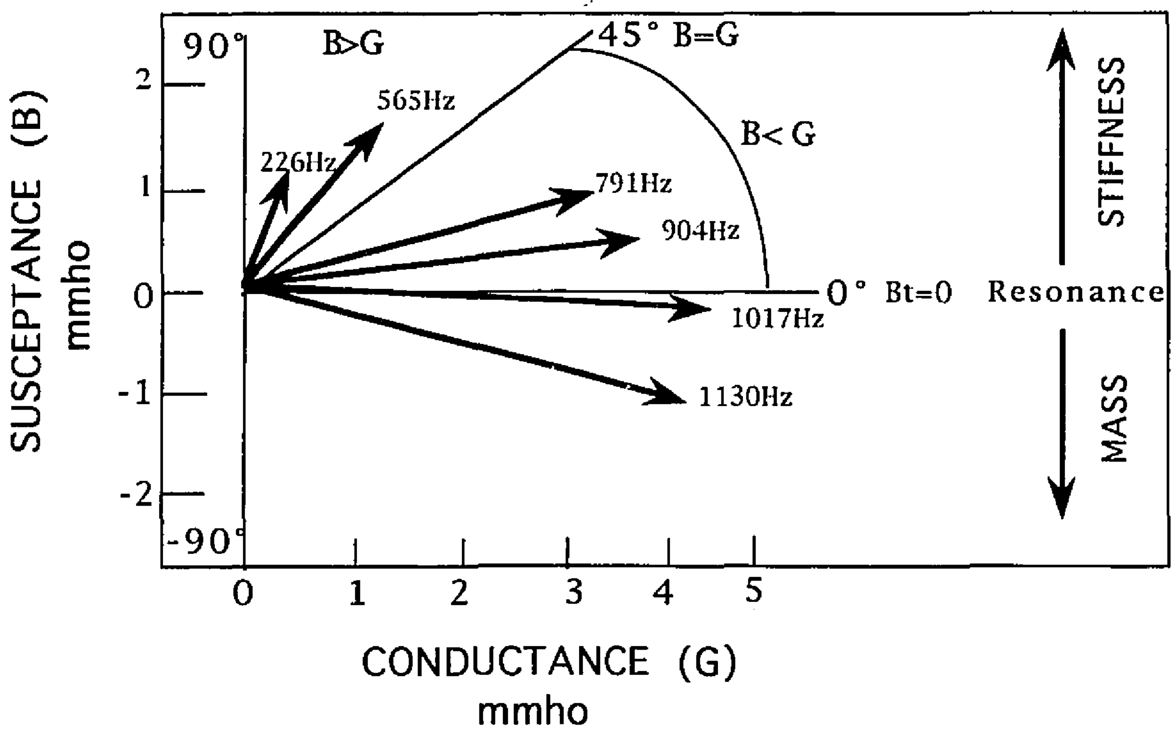

Figure 2. An example of admittance vector rotation as a function of frequency in a normal ear.

<u>Tympanometry</u>

This section begins with a description of procedures and basic principles underlying tympanometry. An overview of the clinical application of a standard tympanometry is then presented and is followed by a review of multifrequency, multicomponent tympanometry.

For clinical purposes, admittance of the middle ear is measured using tympanometry to gain information regarding middle ear function. Standard clinical tympanometry is performed using a low probe tone frequency, usually 220 or 226 Hz, and measures the admittance magnitude |Y| as a function of ear canal air pressure. The result is a graphic display called a tympanogram. As shown in Figure 2, at the low probe tone frequency used in standard tympanometry, the normal middle ear system is stiffness dominated and susceptance (the stiffness element) contributes more to overall admittance than conductance (the frictional element). A normal tympanogram recorded with a low probe tone frequency (226 Hz) is shown in Figure 4 (Page 15).

To record a tympanogram, a probe is inserted into the external ear canal. The probe has a pliable plastic tip which seals the probe in the external ear canal so that air pressure in the ear canal can be varied. The probe assembly is connected to an admittance meter. A schematic diagram of a typical probe assembly and admittance meter is shown in Figure 3. The probe assembly (Figure 3A) has three components: 1) a tube which is attached to an air pressure pump to vary the air pressure in the ear canal, 2) a miniature receiver which is attached to a signal generator to produce a probe tone and, 3) a miniature microphone to measure the reflected probe tone in the ear canal.

To produce a tympanogram a pure tone signal (or probe tone) is delivered through the probe to the ear while ear canal pressure is changed from negative to positive (or from positive to negative). The admittance meter keeps the probe tone in the ear canal at a constant level by means of an automatic gain control (AGC) circuit. The meter measures the electrical current needed to maintain a constant sound pressure level (SPL) in the ear canal which is directly proportional to admittance magnitude at the probe tip. Specifically, as admittance

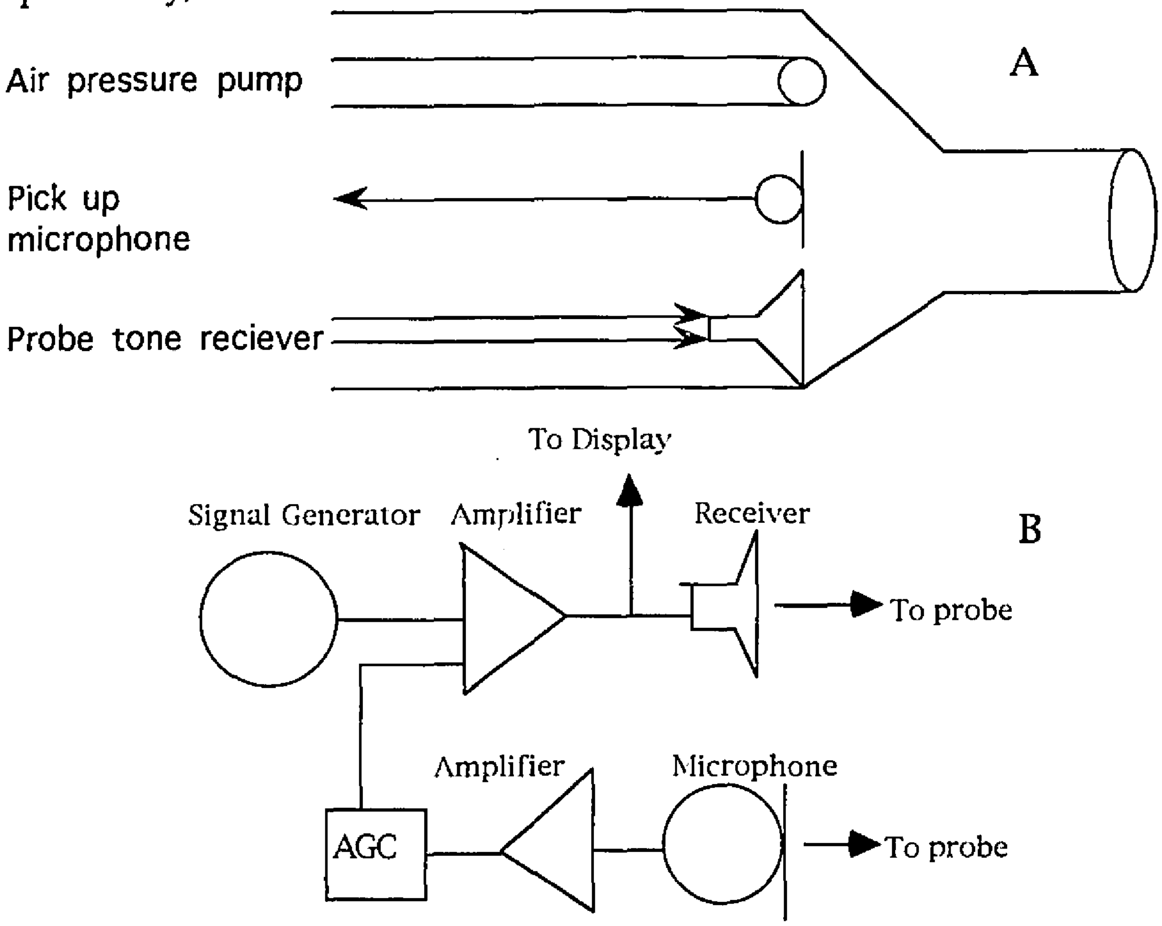

Figure 3. Block diagram of a probe assembly (A - top) and an admittance meter (B - bottom). (AGC = The automatic gain control).[1]

of the middle ear increases, the SPL in the canal will begin to decrease and therefore an increase in electrical current to the probe receiver will occur to maintain the constant SPL. Likewise, as the admittance of the middle ear decreases, the SPL in the canal will begin to rise and therefore a decrease in the electrical current to the probe receiver will occur to maintain a constant sound pressure level in the external ear canal. This change in the electrical current (in

[1] Adapted from Margolis & Shanks (1991).

response to changes in the SPL measured in the ear canal) is directly proportional to admittance magnitude at the tip of the probe. As shown in the tympanogram displayed in Figure 4, the acoustic admittance of the normal middle ear reaches a maximal near ambient pressure and decreases as ear canal pressure becomes more negative or more positive.

Since the probe tip of the admittance measurement system is remote from the surface of the tympanic membrane, admittance measured at the probe tip jointly reflects the admittance of the external auditory canal and the admittance of the middle ear. The dimensions of the external auditory canal vary depending on the depth of insertion of the probe tip as well as individual differences in ear canal size. This produces substantial variation in the admittance due to the external ear and thus to the overall measurement of admittance at the plane of the probe tip. Therefore, to derive a measure of middle ear admittance it is necessary to subtract the admittance due to the external ear canal from the overall admittance measure.

Fortunately, measuring admittance under changes in air pressure provides a way to derive an estimate of the admittance due to ear canal volume. This is accomplished through placing the ear drum under sufficient tension by a high positive or negative pressure to drive the impedance of middle ear toward infinity. The admittance measured at the probe tip under these extreme pressures provides a reasonable estimate of the ear canal admittance alone (also called ear canal volume). This volume estimate (e.g., at -296Ya in Figure 4) is then subtracted from the peak value which jointly reflects the admittance of the external auditory canal and the middle ear to arrive at a value that reflects only the admittance of the tympanic membrane and middle ear. This measure is shown as Peak Ytm in Figure 4; in this example the admittance at an extreme negative pressure is used to correct or compensate for ear canal volume. According to ANSI, (1987) the resulting value is properly referred to as the peak compensated static acoustic admittance. In current clinical practice this compensated measure is commonly called the static admittance or static compliance. When admittance has been compensated for ear canal volume, the resulting value may also be referred to as a measurement at plane of the tympanic membrane.

The compensated static admittance is typically higher when extreme negative (rather than extreme positive) pressure is used to estimate ear canal volume (Shanks & Lilly, 1981). This variation is due to an inherent asymmetry in the tympanogram such that the volume estimate at extreme negative pressure is typically lower compared to the volume estimate at extreme positive pressure (Margolis & Shanks, 1985). This asymmetry is caused by the reduced contribution of conductance, i.e., increased resistance at extreme negative pressures. It should be noted that a range of ear canal pressures may be used to estimate ear canal volume and that somewhat lower canal volume estimates (and hence higher compensated static admittance) may be observed as the ear canal pressure used to correct the volume is increased.

Clinical application of standard tympanometry. Static admittance and ear canal volume are used routinely in interpreting standard low frequency tympanograms. Two additional measures, peak pressure, and tympanometric width are also routinely derived for clinical application. Peak pressure refers to the position of the tympanometric peak on the pressure axis (Pme in Figure 4) and is measured in dekapascal (daPa). This measure provides an estimate of the pressure within the middle ear space. Tympanometric width (also referred to as tympanometric gradient), refers to the width of tympanogram (in daPa) measured at one half the compensated static admittance as illustrated in Figure 5 (DeJonge, 1986; Koebsell & Margolis, 1986). This measure provides an index of the shape of the tympanogram in the vicinity of the peak; it quantifies the relative sharpness (steepness) or roundness of the peak. A large tympanometric width is measured when the tympanogram is rounded and a small tympanometric width results when the tympanogram has a sharp peak. Different classification systems based on the static admittance, peak pressure, gradient, and/or shape of tympanograms have been devised for describing standard low frequency tympanograms (Feldman, 1976; Jerger 1970 & 1972; Liden, 1969; Paradise, Smith, & Bluestone, 1976).

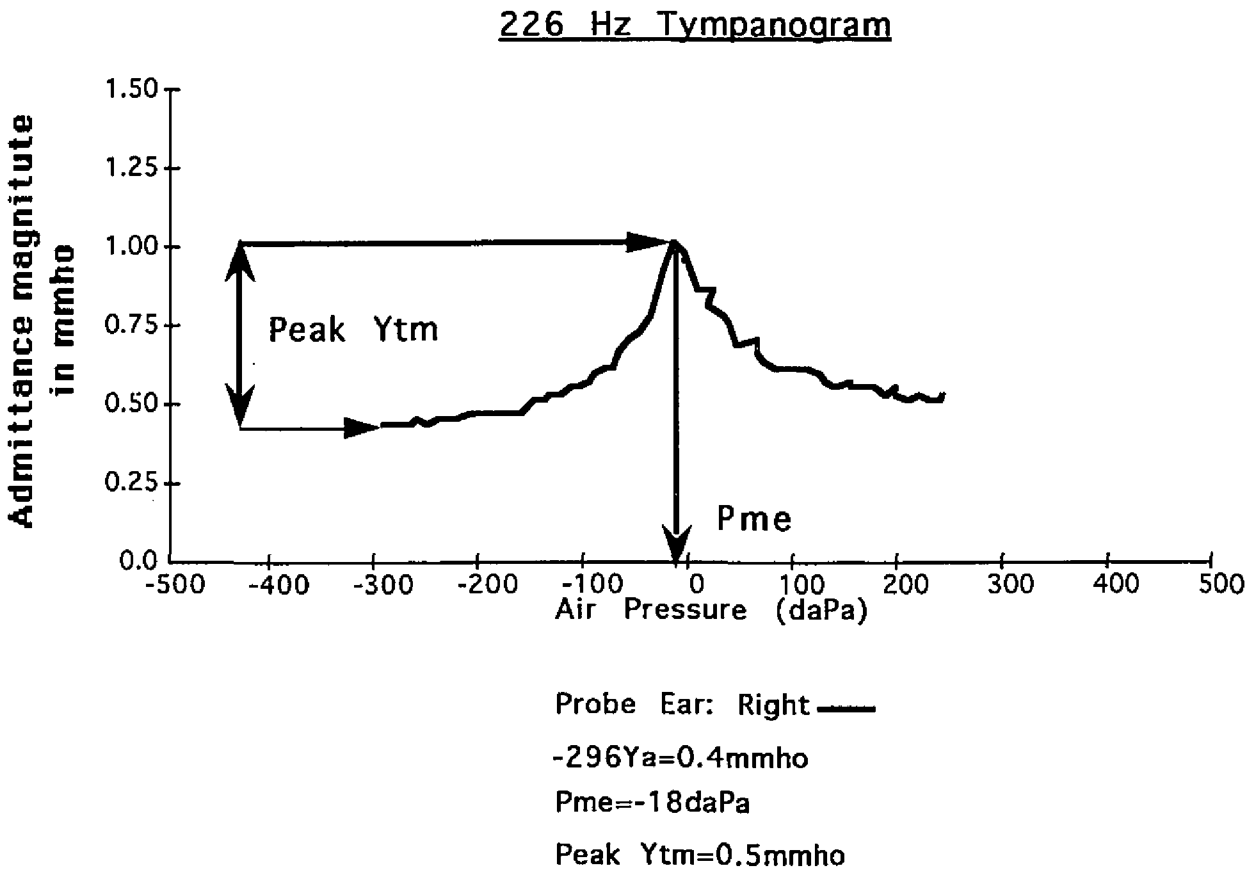

Figure 4. A normal 226 Hz admittance tympanogram. [Pme: middle ear pressure; Ytm: Peak compensated static admittance; -296Ya: pressure value used to compensate for ear canal volume].

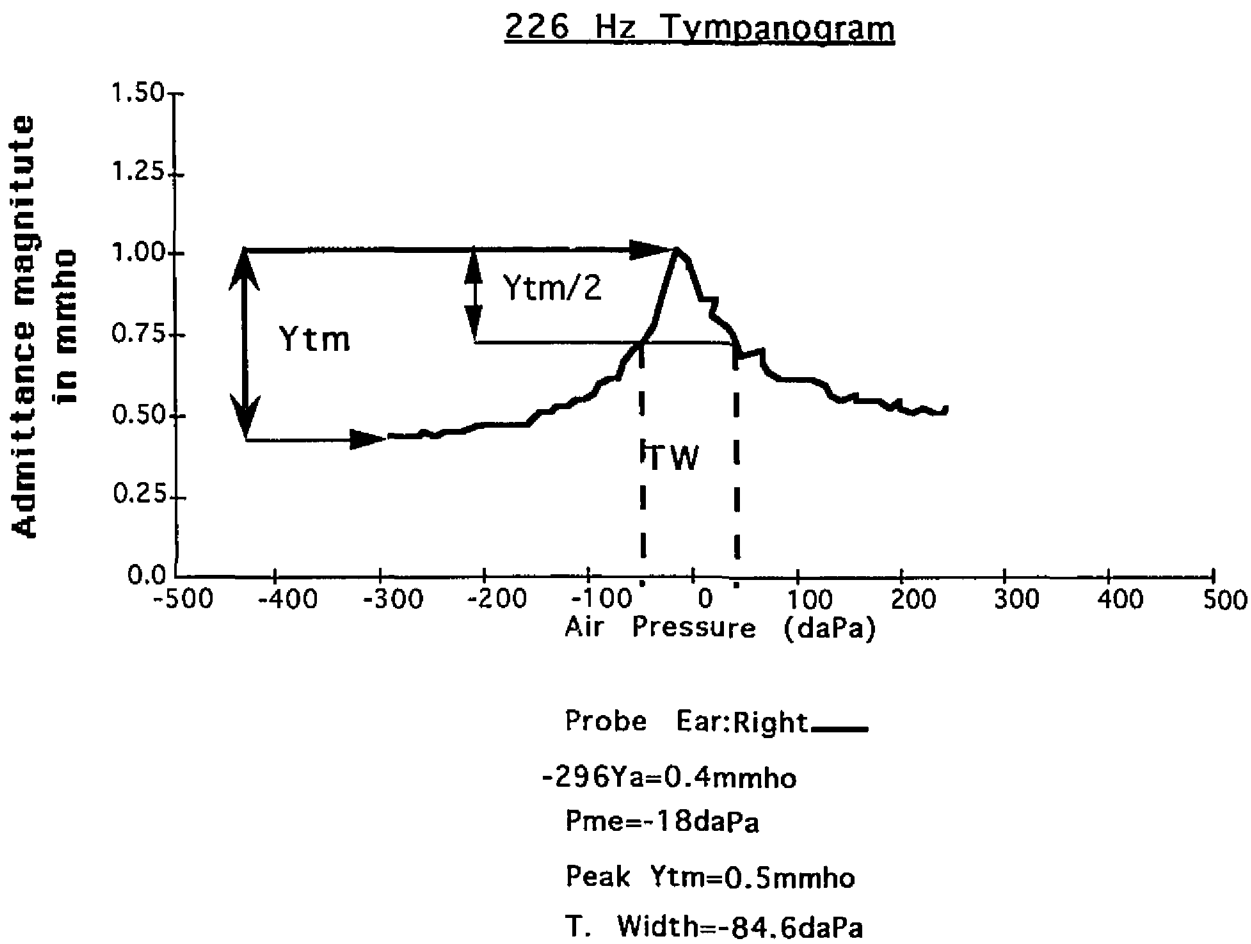

Figure 5. Calculation of tympanometric width (TW) in daPa from peak compensated admittance (Ytm). [Pme: middle ear pressure; Ytm: Peak compensated static admittance; -296Ya: pressure value used to compensate for ear canal volume; T. Width: Tympanometric width].

Since the pioneering work of Terkildsen and his colleagues around 1959, 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). Estimating the volume of air medial to the probe tip also contributes to the interpretation of abnormal tympanograms (Lilly & Shanks, 1981; Lindeman & Holmquist, 1982). However, of relevance to the present study, standard tympanometry often fails to distinguish normal middle ears from ears with lesions that affect the ossicular chain, such as otosclerosis, ossicular discontinuity, or congenital fixation of one or more ossicles (Colletti,1975, 1976; Lilly, 1984). That is, the traditional single component, low frequency probe tone tympanogram often does not yield a distinctive pattern for these pathologies. The typical pattern observed in these pathologies is normal Type A (Jerger classification system) tympanogram. That is, static compliance is typically within normal limits, though it may be abnormally low or abnormally high in some patients. Standard tympanometry may fail to reveal these pathologies because they involve structures that are medial to the tympanic membrane. The status of the tympanic membrane will dominate the tympanogram and therefore can overshadow conditions affecting more medial structures. Alternatively, the effect of ossicular pathologies on tympanometry is not yet well understood.

Multifrequency, multicomponent tympanometry. The 220 or 226 Hz probe tone frequency used in standard tympanometry was selected primarily for ease of calibration not because it necessarily provides the most clinically useful information. With the appearance of commercially available computer based tympanometry instruments, it is possible to record multiple tympanograms at different frequencies. It is also possible to record separate tympanograms for the admittance rectangular components, susceptance and conductance, at different frequencies. Accordingly, investigators have been examining the utility of multifrequency, multicomponent tympanometry for detection of lesions that affect the ossicular chain (Funasaka & Kumakawa, 1988; Hunter & Margolis, 1992; Lilly, 1984; Valvik, Johnsen, & Laukli, 1994).

As shown above, in normal ears, a low probe tone frequency tympanogram has a single peak. In contrast, tympanograms recorded at higher frequencies often have multiple peaks. Vanhuyse, Creten, & Van Camp (1975) examined tympanometric patterns at various probe tone frequencies and developed a model which predicts the shape of susceptance (B) and conductance (G) tympanograms, as the probe tone frequency increases in normal ears and in various pathologies. This model can be explained with reference to the relationship between reactance and resistance tympanograms as probe tone frequency increases. The Vanhuyse model categorizes the tympanograms based on the number of the peaks or extrema on the susceptance (B) tympanogram and the conductance (G) tympanogram and predicts four tympanometric patterns. The patterns are denoted by the number of extrema on the

B and G tympanograms. For example, the 1B1G pattern (Figure 6A) has one peak on the susceptance tympanogram and one peak on the conductance tympanogram. The 1B1G pattern occurs when the middle ear is stiffness dominated and the absolute value of reactance is greater than resistance at all ear canal air pressures, i.e., when the admittance phase angle is between 90° and 45°. In normal ears, the standard low frequency tympanometry yields a 1B1G pattern.

As probe tone frequency increases more complex patterns occur. The next pattern observed is 3B1G (Figure 6B), which has three extrema on the susceptance (B) tympanogram (two peaks on the side of a notch in the middle) and has a single peak on the conductance (G) tympanogram. The admittance tympanogram will also have one peak. When this pattern is observed, the ear is either stiffness dominated or at resonance, i.e., the admittance phase angle is between 45° and 0°. In this pattern reactance is still larger than resistance at extreme pressures, however, this relationship is reversed near the peak pressure. The central notch on the susceptance tympanogram occurs at the pressure corresponding to the peak value on the reactance tympanogram.

As probe tone frequency increases further, the 3B3G (Figure 6C) pattern emerges in which the susceptance and the conductance tympanograms each have three peaks. The admittance tympanogram will also have three peaks, i.e., it will have a notch. When this pattern is observed, the ear is either at resonance or is mass dominated, i.e., the admittance phase angle is between 0° and -45°.

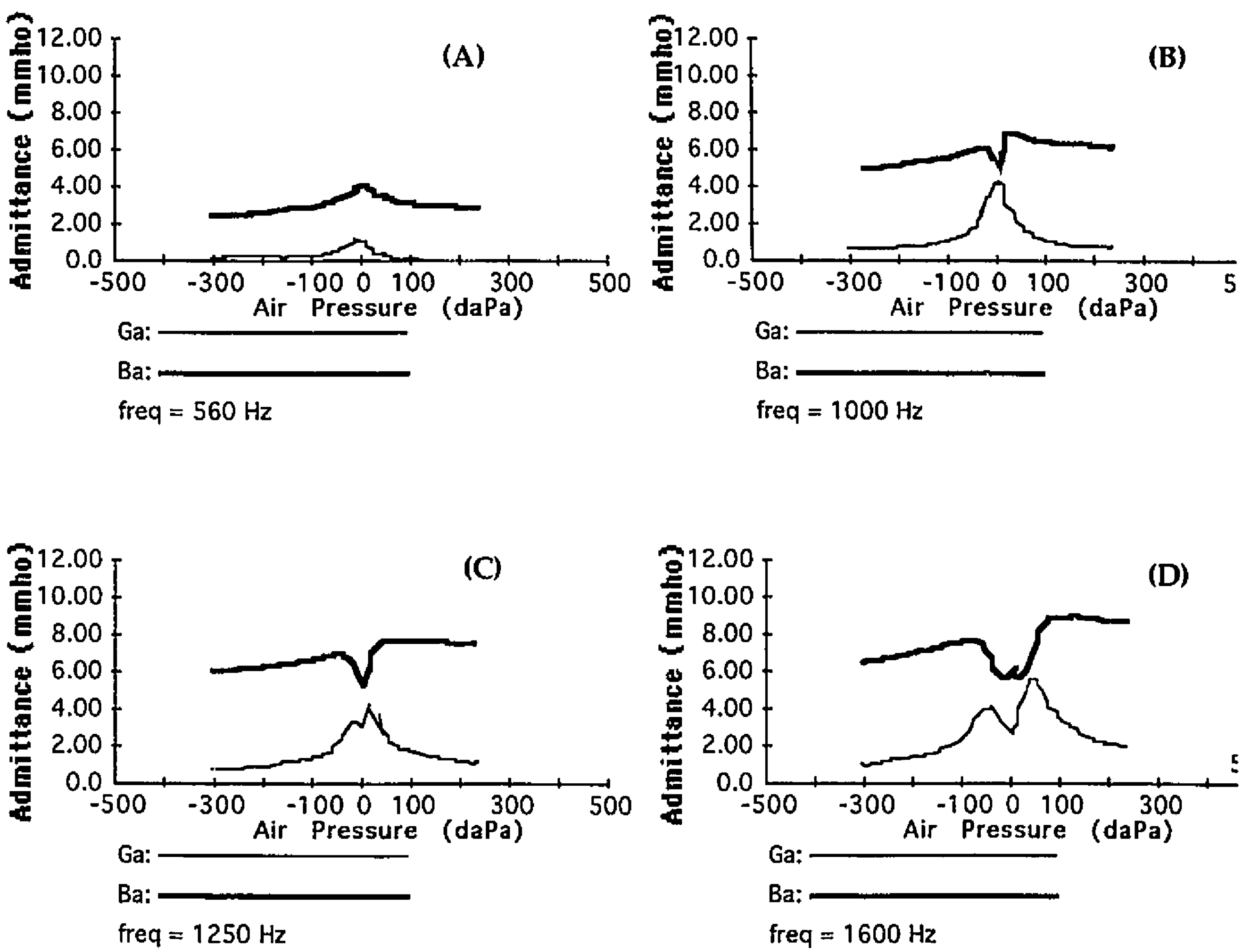

Figure 6. The Vanhuyse et al. (1975) model showing four patterns for susceptance (B_a) and conductance (G_a) tympanograms, 1B1G (A); 3B1G (B); 3B3G (C); and 5B3G (D).

This in turn results in a deep notch on the susceptance tympanogram. The middle ear is stiffness controlled when the central notch on the susceptance tympanogram is above either the positive or the negative tail, depending on which extreme is chosen to estimate ear canal volume. The middle ear is at resonance when the central notch on B tympanogram is equal to either the positive or the negative tail as this indicates that susceptance is zero. The system is mass controlled when the central notch falls below either the positive or the negative tail as this indicates that susceptance is negative.

In 5B3G (Figure 6D) the susceptance tympanogram has five peaks and the conductance tympanogram has three peaks. The admittance tympanogram will also have three peaks. In this pattern the ear is mass dominated and admittance phase angle is between -45° and -90°.

This sequence of patterns is found as frequency is increased in both normal and abnormal middle ears. However, the frequency at which each pattern occurs may be shifted higher or lower compared to normals. For example, in stiffening pathology such as otosclerosis in which resonant frequency is shifted upward, each of the various patterns can be expected to occur at higher frequencies compared to normals.

The Vanhuyse model shows how resonant frequency can be estimated from multifrequency, multicomponent tympanometry by examining susceptance tympanograms obtained at different probe tone frequencies. Recall that, in polar notation, the resonant frequency of the middle ear corresponds to a zero degree phase angle. Thus, resonant frequency can also be determined from phase angle data which are derivable from multifrequency, multicomponent tympanometry with some clinical instruments that are currently available. Determining the resonant frequency may have diagnostic value in that mass loading pathologies (such as ossicular discontinuity) shift the resonance to a lower frequency and other pathologies with abnormal stiffness (such as otosclerosis) shift the resonance to a higher frequency (Shanks & Shelton, 1991).

Besides resonant frequency, the frequency corresponding to other susceptance and conductance values or other phase angles can be obtained using multifrequency, multicomponent tympanometry. For example, as will be discussed further in the next section, there has been a recent interest in the frequency corresponding to 45° phase angle (where susceptance and conductance are approximately equal) as a parameter for distinguishing normal ears and ears with ossicular chain pathology. Overall, there is much yet to be explored with respect to the clinical application of multifrequency, multicomponent tympanometry.

Tympanometry and Otosclerosis

Otosclerosis is a focal disease of the otic capsule. It usually affects the anterior portion of the stapedial footplate. The bone is excessively resorped in this area and an abnormally soft and spongy bone tissue is created around the stapes, impairing stapedial mobility and producing a progressive conductive hearing loss which can develop into a mixed loss if left untreated. In most cases the onset of hearing loss is between 15 and 45 years of age (Booth, 1978). The disease is two times more common in females than males and is bilateral in most cases (Booth, 1978). The etiology of otosclerosis is obscure. Proposed theories implicate genetic, metabolic, vascular and infectious disturbances. Otosclerosis typically increases the stiffness of the middle ear system. Therefore, it is classified as a high-impedance (low-admittance) pathology. In advanced stages, otosclerosis can drive the input impedance of the cochlea to a very high value, effectively disconnecting the cochlea from the middle ear system.

In the 1970's several studies examined the clinical value of static admittance and tympanometric gradient in diagnosis of otosclerosis using impedance technology. Recall that these two variables are commonly derived in standard low frequency tympanometry. Jerger, Anthony, Jerger, & Mauldin (1974) analyzed the results of impedance audiometry in 454 patients with conductive hearing loss, sixty of whom were diagnosed with otosclerosis. Tympanometry findings reported on 95 ears in this patient group showed that 95 percent of the otosclerotic ears had a normal type A tympanogram. They also reported that the overlap in the range of static compliance (the older term for static admittance) values between normal and otosclerotic ears severely limits the use of this measurement. To illustrate the extent of this overlap, the 10th, 50th, and 90th percentiles of static compliance were compared in the otosclerotic group and the normal group. While the median (50th percentile) static compliance was lower in otosclerotic 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. This general finding was in agreement with earlier findings reported by Alberti and Kristensen (1970) and Jerger (1970) as well as Dempsey (1975).

Using the standard low frequency tympanometry several investigators have also reported a steeper tympanometric gradient in some subjects with confirmed otosclerosis in comparison with normal subjects (Dieroff, 1978; Ivey, 1975). Ivey (1975) examined the results of impedance audiometry in 28 ears with surgically confirmed otosclerosis. The results were compared with 18 otologically and audiologically confirmed normal ears. An average tympanogram was composed for each group from individual tympanometric data. From the group tympanogram for the otosclerotic ears, Ivey observed that at the peak of the tympanogram there was a rapid increase in acoustic impedance as ear canal air pressure was reduced. This sharp increase in impedance was manifest as a steeper peak in the average tympanogram of the otosclerotic ears compared to the average tympanogram for the normal ears. A later study by Dieroff (1978) also reported that some ears with otosclerosis had "steep" tympanometric curves. However, the criteria defining a "steep" tympanogram were not reported.

In subsequent studies, the steepness of tympanogram in the vicinity of the peak has been quantified as the measure of tympanometric width described earlier (see Figure 5). As well, examples of otosclerosis cases which display a reduced tympanometric width have been reported in the literature (Shanks, 1984) and several studies have provided normative data for adults on this variable (DeJonge,1986; Margolis & Goycoolea, 1993; Margolis & Heller, 1987). However, a systematic comparison of tympanometric width in normal ears and otosclerotic ears has not been conducted.

In the early 1970's researchers also began to explore the utility of multifrequency tympanometry to identify the stapes fixation which occurs in otosclerotic ears. These early studies using multifrequency tympanometry either utilized devices which measured impedance or converted admittance measures to impedance terms, as admittance technology was not in wide use at this time.

In 1973, Lilly reported impedance values in polar and in rectangular form at five discrete probe tone frequencies between 125 Hz and 750 Hz for twenty-four patients with surgically confirmed otosclerosis. These values were derived from raw data reported in an earlier study by Feldman (1971). Lilly found that, in normal ears, the median impedance magnitude (at the plane of tympanic membrane) increased by 2464 acoustic ohms as probe tone frequency increased from 125 Hz to 750 Hz. In contrast, in ears with stapes fixation the median impedance increased by 5489 acoustic ohms when probe tone frequency was increased from 125 Hz to 750 Hz. As well, for normal ears the change in probe frequency from 125 Hz to 750 Hz resulted in a 38.6° change in median phase angle (from -80.2° at 125 Hz to -41.6° at 750 Hz). In contrast, for the ears with stapes fixation the change in probe frequency resulted in only a 10.4° change in median phase angle (from -83.6° at 125 Hz to -73.2° at 750 Hz). These differences in impedance magnitude and phase angle are consistent with reported increases in stiffness associated with otosclerosis. Moreover, in this study the effects of stapes fixation on impedance values were more prominent when the data were expressed in polar form. It is also important to note that phase angle values were essentially the same at the low probe tone frequency (125 Hz), whereas, phase angle was more negative at 750 Hz in the ears with otosclerosis compared to the normal ears, indicating that the greater stiffness of the otosclerotic ear was more pronounced at this higher probe frequency. Analysis of the resistance and reactance components also confirmed that the group differences were due to changes in stiffness in that greater negative reactance was evident in the otosclerotic ears. Lilly also noted that resistance component increased with probe tone frequency in the otosclerotic ear, however, these values were well-within the values observed in the normal group.

Overall, from Lilly's findings it can be concluded that the resonant frequency is higher in the otosclerotic ear and therefore differential diagnosis should be facilitated by using a higher probe tone frequency which approaches the resonant frequency of the normal middle ear or by measuring resonant frequency itself.

Several subsequent studies are consistent with Lilly's findings (Van de Heyning, 1981; Van Camp and Vogeleer, 1986; Zwislocki, 1982). Zwislocki (1982) reported that at a probe tone frequency of about 700 Hz, reactance at the plane of tympanic membrane was negative (indicative a stiffness controlled system) in subjects with otosclerosis and was approximately twice as large (i.e., more negative and thus much stiffer) than in normal ears. In addition, resistance (R) at 700 Hz was essentially the same in otosclerotic and normal ears. This data was obtained using the Zwislocki acoustic bridge.

Van de Heyning (1981) measured the phase angle at the plane of tympanic membrane using an electroacoustic immittance instrument and found that otosclerosis produced a larger negative impedance phase angle at 660 Hz (Ø=-56°) in comparison with normals (Ø= -19°) indicating an increase in a stiffness of the middle ear transmission system in otosclerotic ears.

Van Camp and Vogeleer (1986) measured impedance rectangular components (reactance and resistance) using a 660 Hz probe tone in 29 subjects diagnosed with otosclerosis. In 30 normal subjects mean resistance and reactance values were 335 and -220 acoustic ohms, respectively with a mean phase angle of -26°. In otosclerotic ears mean resistance and reactance was 350 and -450 acoustic ohms, respectively with a mean phase angle of -51° which again indicates an increase in stiffness with a little change in resistance of the middle ear system.

Colletti (1975; 1976; 1977) was one of the first to develop a system capable of recording multiple-frequency tympanograms across a frequency range wide enough to observe immittance below and above resonance of the middle ear. Since his system plotted the impedance values, the resulting tympanograms were inverted compared to the admittance tympanograms shown earlier in the Figures 4 & 5. Colletti noticed that three distinct tympanometric patterns emerged as probe tone frequency was increased from 200 to 2000 Hz. The first pattern, recorded at low frequencies (<1000 Hz), was a V-shaped tympanogram (the inverse of an admittance pattern) which is consistent with a stiffness controlled middle ear. The second pattern, recorded at mid-frequencies (650-1400 Hz) and near the resonant frequency of the middle ear, was a W shaped or notched tympanogram. Colletti reported that impedance tympanogram will notch near the middle ear resonant frequency. Thus, the onset of the W pattern coincides with middle ear resonance which is consistent with the Vanhuyse model. The third pattern, recorded at high frequencies (>1400 Hz) where the middle ear is mass controlled, was inverted V shape tympanogram.

Colletti also recorded multifrequency impedance tympanograms in patients with different middle ear pathologies and noted that the transition from V to the notched pattern and to the inverted V pattern occurs at different frequencies for various middle ear conditions. He found that the transition to the W pattern (coinciding with middle ear resonance) was the easiest to identify. In patients with otosclerosis, the W pattern emerged between 850 and 1650 Hz (Mean of 1300 Hz), indicating an <u>increase</u> in a resonant frequency due to an increase in a stiffness of the middle ear transmission system. Conversely, in patients with ossicular discontinuity, the W pattern emerged between 500 & 900 Hz, indicating a <u>decrease</u> in resonant frequency due to an increase in the mass or a decrease in the stiffness of the middle ear transmission system[2]. When resonant frequency was estimated in this way, the

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[2] Ossicular discontinuity is a pathological condition that results in abnormally high acoustic admittance (low acoustic impedance). Such high-admittance pathologies often produce a decrease in the middle ear resonance frequency as

patients with otosclerosis showed considerable overlap with normals. However, in patients with ossicular discontinuity, the resonant frequency estimate had a narrower distribution with little overlap with the normal range. Very little overlap in this measure was observed between these two pathological groups. Therefore, in the presence of a conductive hearing loss, the Colletti procedure may be valuable in differentiating between stiffness and mass pathologies. His findings established a benchmark for subsequent work in the area.

In summary, early work using impedance technology showed that a group of subjects with otosclerotic ears will, on average demonstrate greater negative reactance (more stiffness controlled ears) and higher middle ear resonant frequency in comparison with a group of subjects with normal middle ears. Resistance appears not to be changed by otosclerosis. These findings clearly suggest that resonant frequency may have potential diagnostic value.

Recently researchers have begun to explore this potential using commercially available computer-based admittance devices. Currently in North America, two such systems are commercially available, the Grason-Stadler middle ear analyzer (GSI-33, Version 2) and the Virtual admittance system (model 310). With each system it is possible to measure the admittance subcomponents, susceptance and conductance, at different probe tone frequencies. However, each of these systems uses different procedures to derive phase angle and estimate the resonance frequency. Several studies examining

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a result of either an increase in the mass or a decrease in the stiffness of the middle ear system.

the clinical utility of resonant frequency have been reported using each of these newer admittance systems.

The estimation of resonant frequency in the GSI-33 is based on a procedure developed by Funasaka, Funai, & Kumakawa (1984). In their original paper, Funasaka et al. (1984) recorded the sound pressure level (in dB SPL)[3] and its phase angle at -200 daPa and at peak pressure while the probe tone frequency was swept from 220 to 2000 Hz (or 2500 Hz if necessary). The difference between SPL (and its phase angle) at -200 daPa and peak pressure (referred to as ΔSPL) was computed at each probe tone frequency. This ΔSPL is essentially a compensated admittance measure. The ΔSPL was then plotted as a function of frequency (in Hz). The frequency at which ΔSPL is closest to 0 dB corresponds to the resonant frequency of the middle ear system. Phase angle was also measured at -200 daPa and at peak pressure at each probe tone frequency. The frequency at which ΔØ reaches a maximum value also indirectly corresponds to resonant frequency of the middle ear system. Using this procedure the mean resonant frequency measured in 50 normal ears was 1500 Hz whereas a resonant frequency of 850 Hz was measured for one

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[3] Sound pressure level (SPL) in the external ear canal depends on several factors. However, most of these factors remain constant during tympanometry, and SPL depends primarily on the acoustic admittance at the tympanic membrane. At low probe tone frequency, the SPL at -200daPa is greater than the SPL at the peak pressure and therefore, ΔSPL (i.e. SPL at -200 - SPL at peak pressure) is negative. As the probe tone frequency increases the SPL at the peak pressure increases and eventually becomes equal to SPL at -200daPa, i.e. ΔSPL becomes zero. This point corresponds to the resonance frequency of the middle ear system (Lilly, 1984).

subject with ossicular discontinuity and a resonant frequency of 2250 Hz was measured in one subject with otosclerosis.

In a follow up study, Funasaka and Kumakawa (1988) used the same procedure to compute resonant frequency in fifty normal ears and 40 patients with ossicular disorders. When normal resonant frequency was defined using a 95% confidence interval around the mean of the normal group, 10 out of 12 cases of ossicular discontinuity were correctly diagnosed (i.e., showed an abnormally low resonant frequency) and 5 out of 6 cases of malleus and/ or incus fixation were correctly diagnosed (i.e., showed an abnormally high resonant frequency). However, only 12 out of 22 ears with otosclerosis were correctly diagnosed (i.e., showed an abnormally high resonant frequency). Thus, this method of estimating resonant frequency revealed distinct differences between normal ears and ears with ossicular discontinuity and ears with fixation of the malleus or incus, but was less successful in distinguishing normal and otosclerotic ears. However, their procedure should be useful in differentiating between ossicular discontinuity and otosclerosis, since there was very little overlap between these two groups.

The procedure developed by Funasaka et al. (1984) has been incorporated into the design of the GSI middle ear analyzer. However, with GSI-33 the user can choose to measure the admittance or its rectangular components (B and G) and admittance phase angle at extreme ear canal pressure (positive or negative depending on the user preferences) and at peak pressure (which is automatically derived by running a 226 Hz "Y" tympanogram) while the probe tone frequency is swept from 250 - 2000 Hz in 50 Hz steps.

These component values (ΔY, ΔB, or ΔG) and phase angle values (Δ∅) are compensated for canal volume by computing the difference between their value at extreme pressure and their value at peak pressure. The compensated values are plotted as function of probe tone frequency (250-2000 Hz) to determine resonant frequency.

Recently, Valvik et al. (1994) measured the resonant frequency for 100 subjects with normal hearing and in several groups of subjects with different middle ear pathologies using the GSI 33 (Version 2). Resonant frequency was measured by calculating ΔB as a function of probe tone frequency as described above and finding the frequency at which ΔB has a value of zero. Mean resonant frequency for a group of normal ears was 1049 Hz with a markedly wide range of 350 Hz to 1750 Hz. A wide range of resonance frequencies was also found preoperatively in 38 ears with otosclerosis, with a mean of 1238 Hz (SD of 209). Thus, the mean resonant frequency was significantly higher in the otosclerotic ears than in normal ears, but there was a considerable overlap between the two groups. They also recorded the resonant frequency in 5 otosclerotic ears after surgery. The mean resonant frequency in this group ranged from 150-650 Hz (mean of 460 Hz). As expected, stapes surgery reduced the resonant frequency, indicating a reduction in stiffness and/or an increase in mass of the middle ear transmission system.

Using the Virtual system (model 310), Margolis and Goycoolea (1993) gathered normative data from 56 normal ears to establish criteria for interpreting abnormal tympanometric measures. Using standard 226 Hz tympanogram, they measured static admittance, tympanometric width and tympanometric peak pressure. Using multifrequency, multicomponent tympanometry, eight different estimates of the resonant frequency were also derived.

Different resonance estimates were obtained from multifrequency tympanograms using two different recording methods, sweep frequency (SF) and sweep pressure (SP). With the SP method, ear canal air pressure is continuously changed while probe tone frequency is held constant. This is the traditional way of recording a tympanogram. Therefore, to obtain multifrequency information, multiple SP recordings at different probe tone frequencies are needed. With the SF method, ear canal air pressure is altered in discrete pressure intervals. At each successive pressure setting, a series of probe tones which increase from low to high frequency is presented. In this way, tympanometric data is obtained at multiple frequencies with a single positive to negative (or negative to positive) pressure change. When tympanometry is performed at many probe tone frequencies the SF recording method is more efficient than the SP recording method. However, the SP recording method is preferred over SF recording method when tympanometry is performed at two or three probe tone frequencies (e.g., 226 Hz and 660 Hz) or when tympanometry is performed on infants and young children who are less able to sit quietly for very long.

In the Margolis and Goycoolea study, both SF and SP methods were used to record susceptance and conductance tympanograms with 20 probe tone frequencies between 250 and 2000 Hz (1/6 octave step intervals). Using these data, resonant frequency estimates were derived in four ways. Resonant frequency was derived by finding the lowest frequency at which the notch value on the susceptance tympanogram reached 1) the positive tail (+200 daPa), 2) the negative tail (-500 daPa), or 3) crossed a hypothetical line connecting the positive and negative tails. An estimate of resonant frequency was also derived by finding the lowest frequency at which the admittance tympanogram notched. Each of these four methods of resonant frequency estimation was applied to data obtained using the two recording methods, sweep frequency and sweep pressure, resulting in 8 different estimates of a resonant frequency.

Margolis and Goycoolea found two patterns in their normative data. First, resonant frequency was consistently lower when derived from the sweep pressure recordings rather than the sweep frequency recordings. These differences are likely due to the faster rate of pressure change used in the sweep pressure recording method. Compensated susceptance has been shown to be higher (Shanks & Wilson, 1986) and the notch on the susceptance tympanogram to be deeper (Creten & Van Camp, 1975) when a faster rate of air pressure change is used. This effect produces a lower estimate of resonant frequency for faster rates of pressure change. A low estimate of resonant frequency with SP recording method may also have been observed because this method requires greater tympanometric runs than does the SF method. The acoustic admittance has been shown to be higher with multiple consecutive tympanometric runs which may result in earlier notch on the susceptance tympanogram and therefore, produce a lower estimate of resonant frequency (Osguthorpe & Lam, 1981; Vanpeperstraete, Creten, & Van Camp, 1979; Wilson, Shanks, & Kaplan, 1984).

A second finding reported by Margolis and Goycoolea was that the resonant frequency estimates were higher when negative tail (rather than positive tail) compensation was used. As mentioned earlier (pp. 13) this effect is due to the asymmetry in the tympanogram at extreme positive and negative pressures (Margolis & Smith, 1977) and its effect on compensation for ear canal volume.

In the examining the distribution of the various resonant frequency estimates as well as data on test retest reliability, Margolis and Goycoolea drew two conclusions concerning the clinical application of resonant frequency. First, Margolis and Goycoolea concluded that compensation at +200 daPa for ear canal volume is preferred for estimation of the resonant frequency because this compensation method produced lower intersubject variability and better test-retest reliability compared to other compensation methods. Second, they suggested that the sweep pressure recording is preferred for detecting pathologies that will produce an abnormally high resonant frequency such as otosclerosis whereas sweep frequency is preferred for identifying pathologies that will produce an abnormally low resonant frequency. This is because the upper limit of resonant frequency derived from sweep frequency recording extends to the maximum available probe tone frequency (2000 Hz) of The Virtual System. Thus, they concluded that ceiling effects are likely to limit the ability to measure abnormally high resonant frequencies using the sweep frequency procedure. Resonant frequency derived from sweep pressure recordings tends to produces relatively low resonant frequency values, suggesting that this method may be less sensitive to pathologies that lower resonant frequency.

Overall, these normative data published by Margolis and Goycoolea will contribute to more widespread use of multifrequency tympanometry in clinical practice by providing norms for resonant frequency and by suggesting specific clinical methods for deriving resonant frequency for different clinical application. However, comparable data must also be obtained from pathological groups to develop the most effective diagnostic criteria.

Another promising approach in the application of multifrequency, multicomponent tympanometry is provided by the work of Shanks et al. (1987)[4]. They measured compensated static susceptance and conductance at probe tone frequencies between approximately 226-1800 Hz. From this data, the lowest frequency at which conductance first becomes larger than susceptance was determined for 10 young, normal hearing subjects. This frequency corresponds to admittance phase angle of 45° and was on average 565 Hz for the normal subjects. Data was obtained from one patient with otosclerosis, and showed that the frequency corresponding to 45° phase angle was much higher (904 Hz). Interestingly, in this patient the resonant frequency was not markedly different from the normals. These preliminary findings suggest that the frequency corresponding to 45° phase angle may be a better index than resonant frequency with respect to distinguishing normal and otosclerotic ears. However, a larger sample of normal and

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[4] This study was reported at one of the American Speech-language and Hearing Association (ASHA) conference and further details are not available.

otosclerotic ears must be examined to confirm this pattern and to determine the extent to which normal and otosclerotic ears may overlap in this parameter. The frequency corresponding to 45° phase angle can be obtained with some newer clinical admittance devices (for example Virtual system 310 and GSI 33, version 2).

Goals of Present Study

The goals of this study were to improve the diagnostic utility of tympanometry with respect to distinguishing normal and otosclerotic ears and to contribute to the standardization of multifrequency tympanometry so as to further establish its potential utility in clinical diagnosis. These goals were achieved by examining a set of tympanometric parameters in ears with normal middle ear function and in otosclerotic ears. Normative data obtained in this study provide a basis for interpreting multifrequency tympanometric data obtained using the Virtual 310.

The specific parameters examined in this study included two parameters derived from standard low frequency tympanometry (static admittance and tympanometric width) and two parameters that can only be derived from multifrequency, multicomponent tympanometry (resonant frequency and frequency corresponding to admittance phase angle of 45°). All four of these parameters were examined in individuals with normal middle ear function and in individuals with otosclerosis. Previous studies have examined one or two of these parameters in otosclerotic and normal ears or have only provided normative data. Through a systematic within-subject comparison of these four tympanometric parameters in subjects with normal middle ear and subjects with otosclerosis the relation between these variables can be assessed and the relative contribution of each parameter to the diagnostic problem can be established. Furthermore, ways in which these tympanometric variables may be combined to improve diagnosis can be considered.

To achieve the goals of this study, resonant frequency was estimated through multifrequency tympanometry in several ways. To date, normative studies indicate that different methods for estimation of the resonant frequency result in different mean values and different ranges of resonant frequency (Margolis and Goycoolea, 1993). Likewise, each method may have certain advantages and disadvantages with respect to specific diagnostic problems and with specific patient populations. Therefore, it may be useful to measure resonant frequency in different ways for different clinical applications. For this reason, in the present study, resonant frequency was derived in five different ways; using two different recording methods and two different compensation methods, as well as using an automated screening procedure built into the Virtual 310. The frequency corresponding to 45° phase angle was also derived using two different recording methods. With these data, we can address the extent to which different methods for estimation of each parameter affect its diagnostic utility with respect to identifying otosclerotic ears as well as other ossicular chain pathologies.

Methods

Subjects

Thirty-six normal hearing adults and twelve patients diagnosed with otosclerosis served as subjects. No subjects in either group had a history of head trauma or otoscopic evidence of eardrum abnormality (assessed by a resident otolaryngologist). The exclusion of those subjects with tympanic membrane abnormalities was based on the fact that these more lateral pathologies can obscure more significant medial pathologies such as otosclerosis (Feldman, 1974). If cerumen was present, the ears were cleaned at the time of otoscopic examination by a resident otolaryngologist (before tympanometry).

The normal hearing subjects were McGill students or employees at the Royal Victoria Hospital who were compensated for their participation. Subjects had to meet two additional criteria to be considered normal. First, at the time of testing they had to present pure tone audiometric thresholds lower than 15 dBHL (re: ANSI 1969) and no air-bone gap at octave frequencies between 250-8000 Hz. Second, they had to report no history of middle ear disease. Normal subjects ranged in age from 20-43 years old (mean age = 22 years). Tympanometry was performed in both ears in normal subjects. Data from four ears were excluded due to tympanic membrane abnormalities leaving a total of 68 ears.

Fourteen patients diagnosed with otosclerosis and scheduled for surgery were recruited from McGill Teaching Hospitals (13 from the Royal Victoria Hospital; one from the Jewish General Hospital). The patient group was composed of nine females and five males ranging in age from 29 to 69 years (mean age = 48 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 before the surgery, however, only results from the candidate ear for the surgery were analyzed (total of 14 ears)[5] . Three additional patients were recruited but their data was excluded due to tympanic membrane abnormalities.

Pure tone audiometry revealed a primarily conductive hearing impairment in ten of the fourteen patients. Four patients presented with a mixed hearing loss which was limited to the high frequency region in two subjects. The audiometric contour was generally rising with greater conductive component in the low frequency region than high frequency region for all patients. The Carhart notch was observed in seven patients. Individual audiograms are provided in the Appendix.

<u>Instrumentation</u>

Pure tone audiometry was conducted using a Grason Stadler (GSI-16) audiometer. The system was calibrated according to ANSI standards (re: S3.6. 1969). A computer controlled aural acoustic immittance system (Virtual, model 310; Macintosh IIsi) equipped with the extended high-frequency option (EHF) was used in this study. This system performs many functions besides multifrequency multicomponent tympanometry and may also be used in a single

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[5] The second ear could not be included within the normal group because the hearing loss was either bilateral or the other ear had already undergone surgery.

probe tone, single component mode to conduct standard tympanometry. Before each data collection, the Virtual system was calibrated in three standard cavities (0.5, 2.0, and 5.0 cm^3) according to the operation manual provided by the manufacturer.

With the Virtual system the multifrequency function includes three sets of pre-selected frequency ranges, 250-1000 Hz, 500-2000 Hz, and 1000-2000 Hz that are covered in 1/6 octave increments. A complete frequency sweep may take 60-90 seconds, depending on the frequency and pressure ranges that an examiner selects. Tympanograms are displayed as admittance magnitude but tympanometric data can be analyzed and displayed in rectangular or polar plots. Previous tympanogram examples shown in Figures 4 and 5 were obtained using a single probe tone. Figure 7 shows the multifrequency tympanometric display generated using the sweep frequency recording method.

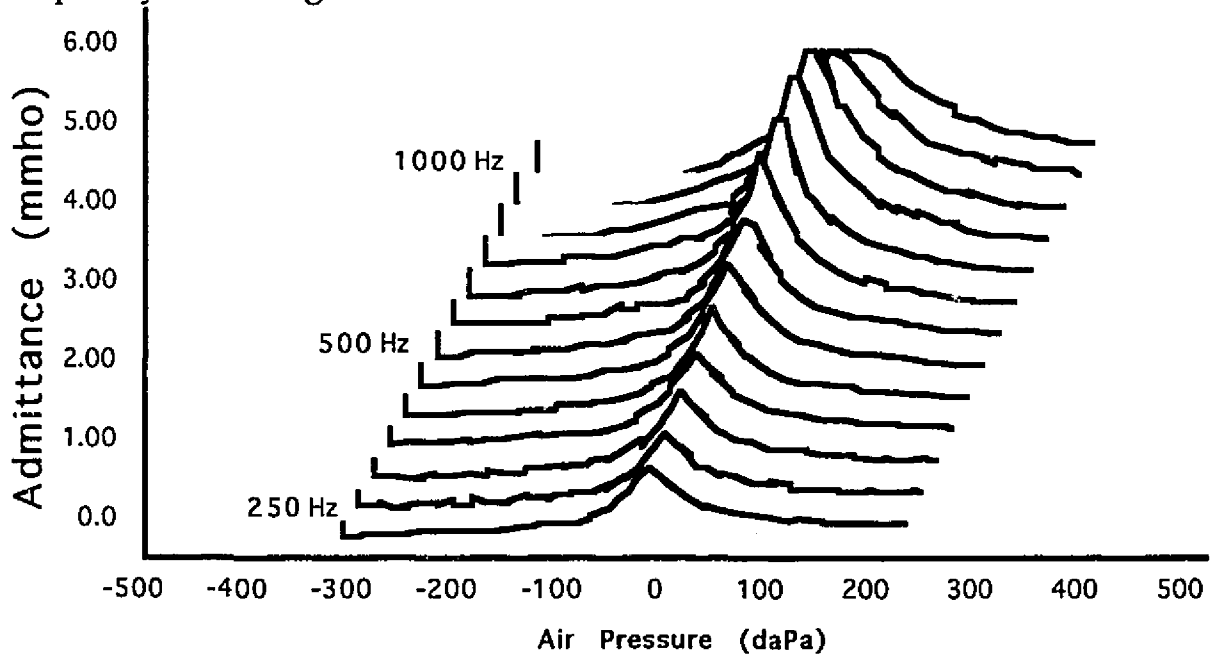


Figure 7. Multifrequency tympanograms (sweep frequency) from a normal adult.

Procedures

An otoscopic examination was conducted in all subjects by a resident otolaryngologist and the ears were cleaned if needed. Next, pure tone audiometry followed by tympanometry was performed in all subjects. For the patients, all testing was performed one day before surgery.

To begin immittance testing, a 226 Hz tympanogram was recorded. Next, tympanograms were obtained at higher probe tone frequencies, first using a sweep frequency recording and then using a sweep pressure recording procedure. In the sweep frequency procedure, admittance magnitude was measured while air pressure in the external ear canal was decreased from +250 daPa to -300 daPa in discrete 14 daPa steps. At each step, the probe tone frequency swept through a series of probe tones progressing from low to high frequencies. Two sweep frequency tympanograms were recorded; one sweep through a series of probe tone frequencies between 250-1000 Hz and one sweep through a series of probe tones between 1000-2000 Hz. In each series, the frequency changed in one-sixth octave steps; a total of 20 probe tone frequencies was tested.

In the sweep pressure method, 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) while the probe tone frequency was held constant. This procedure was repeated for multiple probe tone frequencies ranging from 250-2000 Hz progressing from low to high frequencies. Twenty tympanograms were recorded one at each of the same frequencies used in the sweep frequency recording.

A descending pressure direction (positive to negative) was used for both sweep frequency and sweep pressure tympanograms because it results in fewer irregular tympanograms compared to the ascending direction of pressure change (Margolis et al, 1985; Wilson, Shanks, & Kaplan, 1984). The right ear was tested first for all the normal hearing subjects.

Results and Discussion

Nine tympanometric measures were examined. Three measures were automatically calculated by the immittance system when the initial 226 Hz tympanogram was recorded: static admittance, tympanometric width, and the screening for resonant frequency. Four additional estimates of resonant frequency were also derived from the sweep pressure recordings (SP) and from the sweep frequency recordings (SF); two estimates were derived from data obtained using each of the two recording methods, one estimate using positive tail compensation and one estimate using negative tail compensation. Two estimates of the frequency corresponding to 45° admittance phase angle were also derived; one estimate was derived from the sweep pressure recordings (SP) and a second estimate was derived from the sweep frequency recordings (SF).

Results and discussion of these nine measures is organized in three sections. In the first section, statistical analysis and discussion of the results are presented separately for the four tympanometric parameters. This section is concerned with comparing the data on each parameter to previous normative studies and to research evaluating group differences between normal and otosclerotic ears. The second section provides an analysis and discussion of the data for the nine measures from a test performance perspective. This approach provides a way to determine how well each measure might serve as a test for distinguishing normal and otosclerotic ears and to examine the relative performance of the nine measures. In the third and final section, patterns of test performance across the nine measures were examined in individual normal and patient subjects. With this analysis it is possible to evaluate the relationship between the various measures within individual normals and patients and therefore to consider ways in which these measures may be combined to facilitate the separation of normal and otosclerotic ears.

Statistical Analysis & Discussion

This section is divided into five subsections which provide results and discussion for data on 1) static admittance, 2) tympanometric width, 3) resonant frequency-screening mode, 4) derived estimates of resonant frequency, and 5) frequency corresponding to 45° phase angle. Each section begins with a description of important steps in deriving the measure from the tympanograms. Next, descriptive data on each measure for the normal group and the patient group are presented. For each measure, frequency distributions for the normal and the patient groups are plotted and a table reporting the mean and standard deviation for each group is displayed. For the normal group the values defining the 95% confidence interval around the mean, and the values defining the 90% range (i.e., values corresponding to 5th and 95th percentile) are also provided to facilitate comparison with previous normative studies. For each parameter, statistical analysis of group differences (patient vs. normal) and differences in recording and compensation methods (when appropriate) were conducted. The findings are discussed with respect to previous normative studies and to studies comparing otosclerotic and normal ears.

Static admittance. Static admittance was derived automatically by the immittance system using negative tail compensation, i.e., by subtracting ear canal volume estimated at the most negative pressure (-300 daPa) from the peak admittance value. The distributions of static admittance values in the normal group and in the otosclerotic group are shown in Figure 8. Table 2 provides a summary of descriptive statistics for each group.

As expected, these data reveal a lower mean static admittance and a larger standard deviation for the patients compared to the normals. However, a one-tail t-test comparing static admittance in the normals and patients was not statistically significant [$t(80) = 1.22$; $p = 0.11$].

Static admittance measures observed in our normal subjects are comparable to previous normative data reported by Margolis & Goycoolea (1993) and by Shanks & Wilson (1986). The mean static admittance of 0.85 mmho obtained in this study is exactly the same as the mean value reported by Shanks and Wilson (1986) who used a different admittance instrument and a slower rate of pressure change (50 daPa/sec compared to 125 daPa/sec used in this study). However, the 90% range observed in this study (0.4 to 1.6 mmho) was larger than the 90% range reported by Shanks and Wilson (0.56 to 1.36 mmho). Both the mean and 90% range measured for static compliance in this study are quite similar to the mean (0.88 mmho) and 90% range (0.4 to 1.7 mmho) reported by Margolis and Goycoolea (1993). Margolis and Goycoolea used the same admittance instrumentation but a faster rate of pressure change (250 daPa/sec).

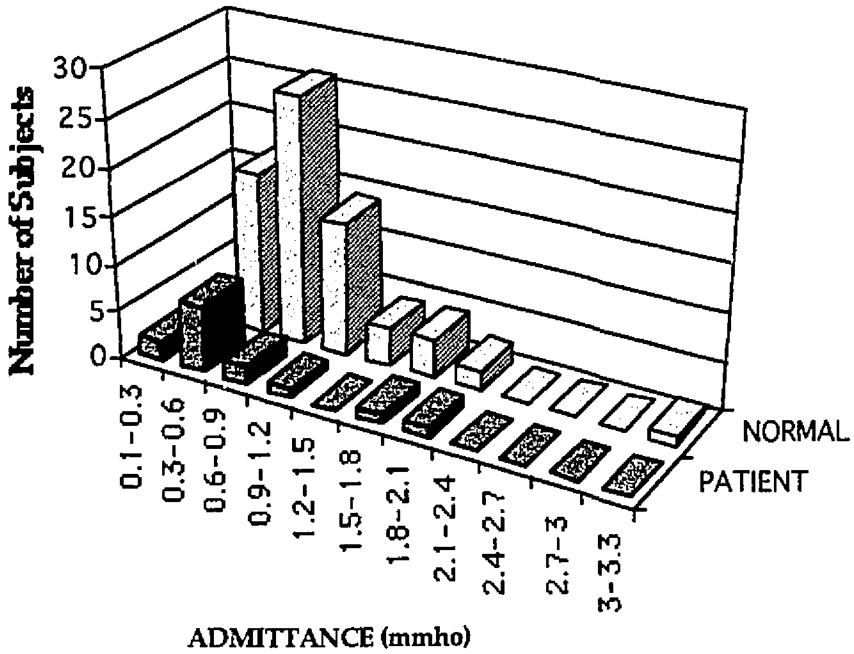


Figure 8. Distribution of static admittance for normal and otosclerotic ears.

	Normal n=68	Patient n=14
Mean	0.85	0.68
Standard Deviation	0.47	0.55
90% Range	0.4 - 1.6	
95% Confidence Interval	0.74 - 0.97	

Table 2. Descriptive statistics on static admittance (mmhos) for normal and otosclerotic ears.

With respect to group differences the mean static admittance in the patients tends to be lower than normals. However, the differences between normal and otosclerotic ears were not statistically significant as there was a significant overlap in the range of static admittance values observed in the normal and patient group. This result is consistent with previous research (Alberti & Kristensen, 1970; Dempsey, 1975; Jerger, 1970; and Jerger et al., 1974). Overall, the present findings suggest, as do previous studies, that static admittance has limited potential as a parameter for distinguishing normal and otosclerotic ears.

Tympanometric width. Tympanometric width (TW) in daPa was also automatically calculated by the immittance system. This value was derived by computing the width (in daPa) of the tympanogram at a point corresponding to one half of the static admittance determined using negative tail compensation (see Figure 5, page 16). The distributions of the tympanometric width values for otosclerotic and for normal ears are shown in Figure 9. The descriptive statistics for each group are shown in Table 3. As expected, these data reveal a lower mean tympanometric width and a larger standard deviation for the patients compared to the normals. However, a one-tail t-test comparing tympanometric width in the normals and patients was not statistically significant [$t(80)= 0.589$; $p = 0.28$].

Overall, the results of tympanometric width in our normal subjects are not comparable to three previous normative studies (DeJonge, 1986; Margolis & Goycoolea, 1993; Margolis & Heller, 1987). In each study, the differences observed are most likely attributed to different procedures and different admittance instrumentation used to derive TW. DeJonge (1986) reported an average TW value of 110 daPa and a 90% range of 60-160 daPa. In comparison, our mean value of 84 daPa was lower and our 90% range (48-134 daPa) was smaller. These differences are likely due to the use of different rates of pressure change (50 daPa/sec in the DeJonge study compare to 125 daPa/sec used in this study). Several studies have shown that a faster rate of pressure change results in higher static admittance (Koebsell and Margolis, 1985; Creten and Van Camp, 1974) which, in turn, will produce a narrower tympanometric width. The use of different admittance instruments may also contribute to the differences in TW across these two studies.

Margolis and Heller (1987) reported an average TW of 76.8 daPa and 90% range of 51-114 daPa. In comparison our mean value (84 daPa) was slightly higher and our 90% range (48-134 daPa) was wider. The possible sources of these discrepancies include the use of different compensation procedures (+200 daPa in Margolis and Heller and -300 daPa in this study) and different rates of pressure change (200 daPa/sec in Margolis and Heller and 125 daPa/sec in this study). Each of these factors may contribute to a smaller tympanometric value. As well, the use of different admittance instruments may contribute to the differences in TW across these two studies.

More recently Margolis and Goycoolea (1993) reported an average TW of 106 daPa and 90% range of 42-183 daPa. In comparison our mean value (84 daPa) was lower and our 90% range (48-134 daPa) was narrower. Across the two studies, there were differences in the rate of pressure change (250 daPa/sec in Margolis and Goycoolea and 125 daPa/sec in this study) as well as differences in the compensation procedures (200 daPa in Margolis and Goycoolea and -300 daPa in this study). However, neither of these factors can explain the differences in TW because these procedural differences should have resulted in systematically higher, rather than lower, TW results in the present study compared to Margolis and Goycoolea.

With respect to group differences the mean tympanometric width was smaller in the patient group than in the normal groups. However, the differences observed were not statistically significant as there was a significant overlap in the range of tympanometric width observed in the normal and patient group. Two previous studies (Dieroff, 1978; Ivey, 1975) have suggested that tympanometric width may be useful in distinguishing otosclerotic ears from normal ears. However, neither study provides a systematic comparison of TW in otosclerotic and normal ears. The present study which provides such a comparison does not support this hypothesis. Overall, our findings indicate that, by itself, TW is not a highly useful parameter for distinguishing otosclerotic ears and normal ears.

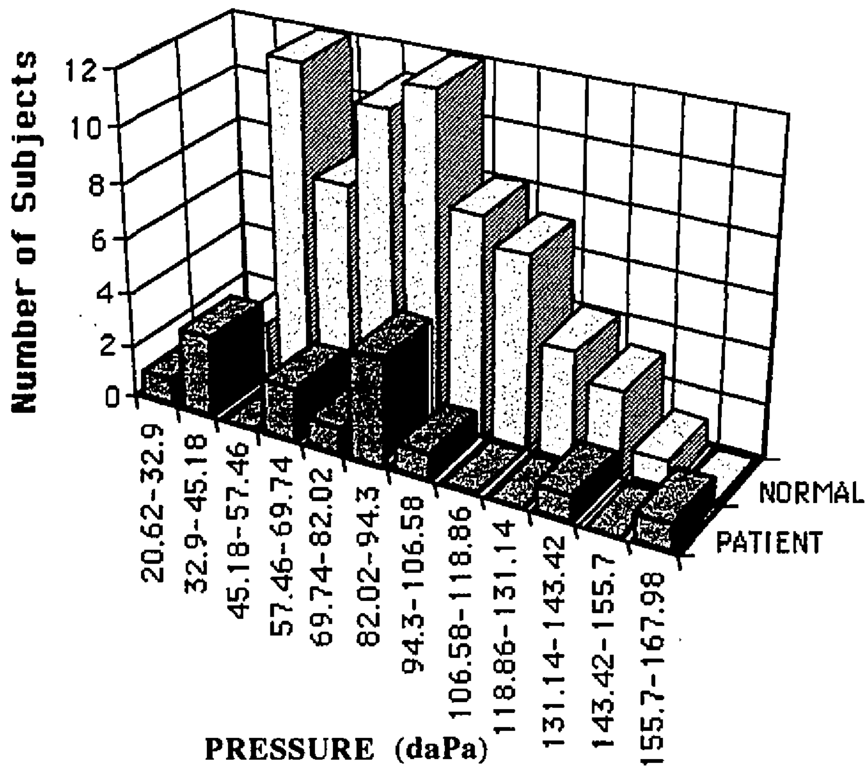


Figure 9. Distributions of tympanometric width for normal and otosclerotic ears

	Normal n=68	Patient n=14
Mean	84	79
Standard Deviation	27	38
90% Range	48 – 134	
95% Confidence Interval	78 – 91	

Table 3. Descriptive statistics of tympanometric width (daPa) for normal and otosclerotic ears.

Resonant frequency-Screening mode. When a standard 226 Hz tympanogram is recorded the Virtual system automatically performs a "screening" for the resonant frequency. The following series of computations is automatically performed by the system to derive this resonance estimate. First the probe tone is swept from 500-2000 Hz while the pressure is held constant at the peak pressure obtained from the 226 Hz tympanogram and the polar components, admittance magnitude |Y| and phase angle |Ø|, are measured at the plane of the probe tip. The rectangular components, susceptance (B) and conductance(G), are then computed from those polar values. The ear canal volume is corrected by subtracting the susceptance at extreme ear canal air pressure (-300 daPa) from the peak value or center of the notch in W pattern tympanogram[6] . A compensated polar plot (Y_{tm} and $Ø_{tm}$) is then derived from compensated susceptance and conductance (see conversion formulas in Table 1). A plot of phase angle at the plane of the tympanic membrane as a function of probe tone frequency is then derived and is displayed at the upper right corner of the screen as shown in Figure 10. Finally, the resonant frequency, defined as a phase angle of 0° is automatically derived from this plot and appears on the screen (710 Hz in this example).

6 The ear canal volume is corrected only from susceptance (and not the admittance) because this correction can be made only on data measured in rectangular form (B and G) given that vector quantities such as impedance or admittance can not be added unless they have identical phase angles. This is especially important since the immittance phase angle is also changed (Lilly, 1973; Shanks, 1984).

Frequency distributions of the values obtained from this resonance screening for the normal group and the otosclerotic group are shown in Figure 11. Descriptive statistics corresponding to this measure are provided in Table 4. Contrary to our expectations, these data indicate a lower mean resonant frequency for the patients compared to the normals. A one-tail t-test comparing the normals and patients was not statistically significant [t (80) = 0.84; p = 0.2].

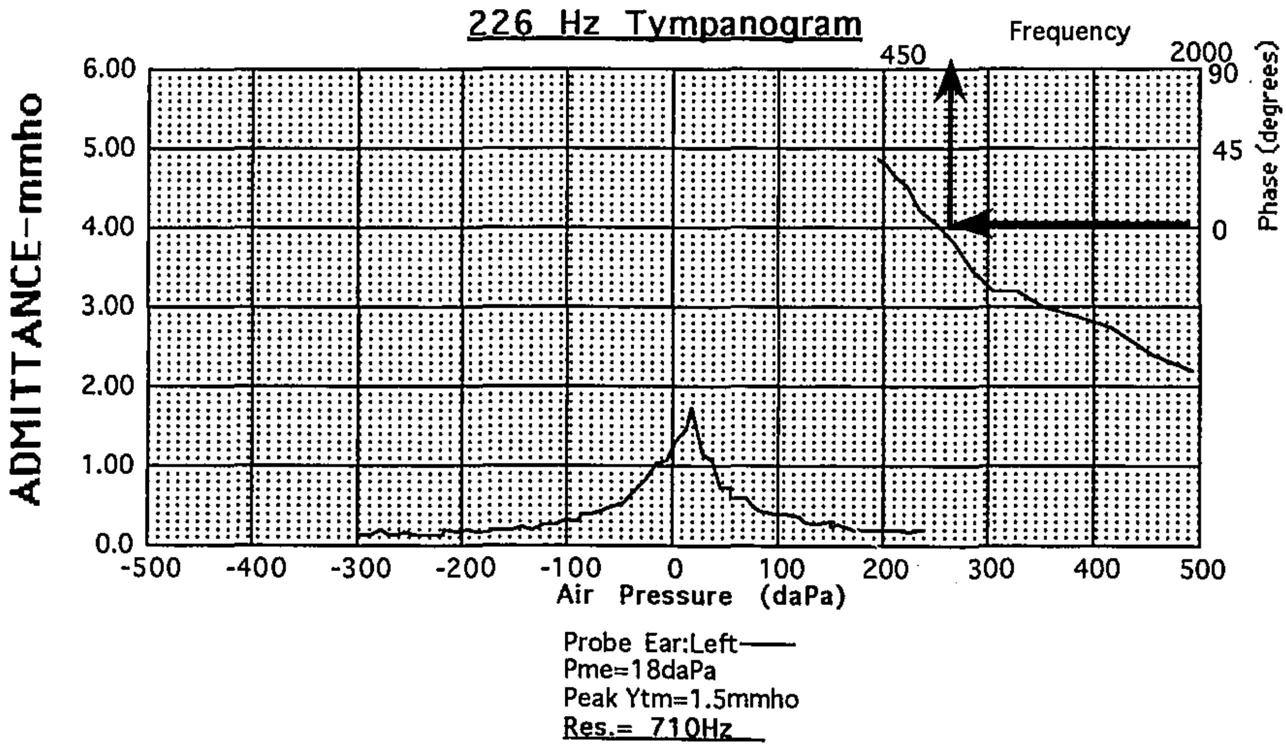


Figure 10. Illustration of data provided by resonance screening. The Øtm is plotted as a function of the probe tone frequency from 500-2000 Hz in the upper right corner of the display. Resonance is derived as the frequency corresponding to a phase angle of zero° on this function, (710 Hz in this example).

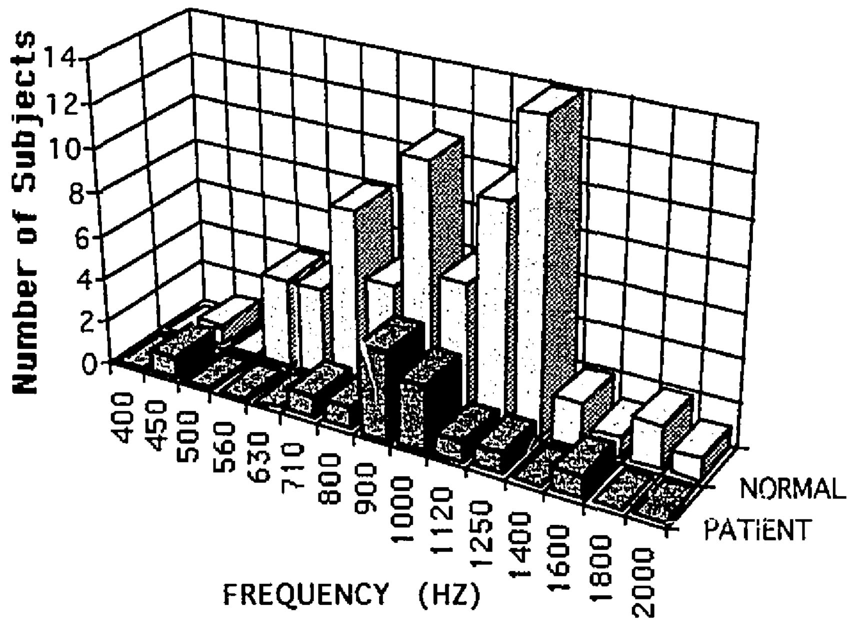
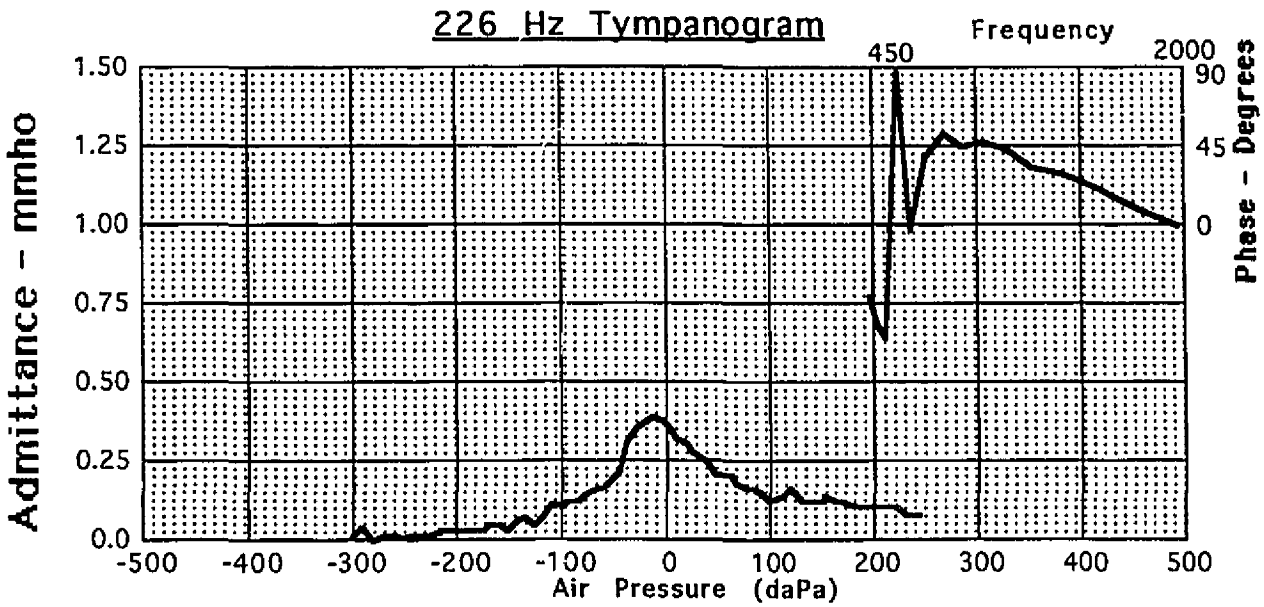


Figure 11. Distribution of resonant frequencies estimated by the screening mode for normal and otosclerotic ears.

	Normal n=68	Patient n=14
Mean	993	920
Standard Deviation	289	308
90% Range	630 - 1250	
95% Confidence Interval	923 - 1062	

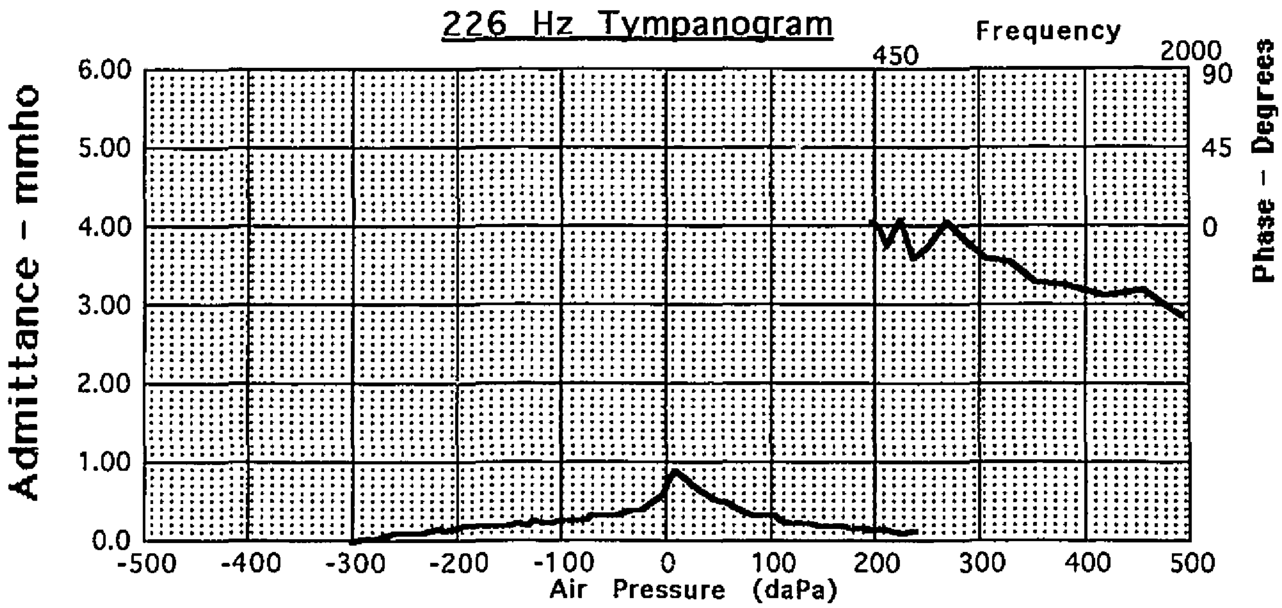
Table 4. Descriptive statistics for resonant frequency (Hz) estimated by the screening mode for normal and otosclerotic ears.

To our knowledge resonant frequency measures obtained using this automated screening function have not been examined in normal or in pathologic ears. Besides a wide overlap between the normal and otosclerotic ears, the mean value of the patient group was unexpectedly lower than the normal group. However, there are at least several reasons for believing that this screening function did not provide a valid measure of resonant frequency. Many of the subjects, for example, exhibited an abrupt spike in their phasor diagram (see upper right corner of Figure 12) which is most likely instrumentation artifacts. Recall that resonant frequency is defined as a phase angle of 0°. In this example the artificial spike, which crosses the 0° at 355 Hz, was erroneously labeled as the resonant frequency. Moreover, in some cases the relationship between the probe tone frequencies and the phase angle in the phasor plot was not consistent with the actual phase angle at those probe tone frequencies. For example, in Figure 13 the resonant frequency obtained automatically from the screening mode was 450 Hz. As shown in Figure 14, analysis of susceptance (B) and conductance(G) at this probe tone frequency revealed that the compensated G is smaller than B which is consistent with admittance phase angle below 45°. This discrepancy is probably due to a hardware or software error which produced a shift in the baseline of phase angle plot (see upper right corner of Figure 13).



Res.= 355 Hz

Figure 12. An example of artificial spike on a phasor plot.



Res.= 450 Hz

Figure 13. An example of shifted baseline in phasor plot.

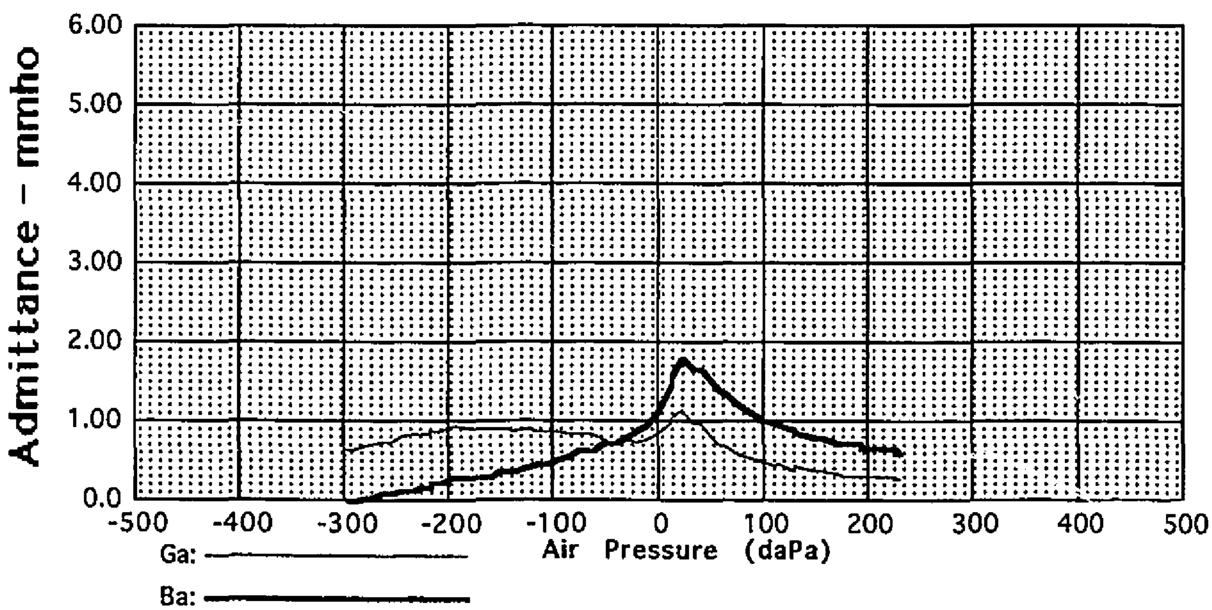


Figure 14. Admittance subcomponents at probe tone frequency of 450 Hz for the same subject as Figure 13.

In conclusion, the method employed in the automated screening mode for deriving resonant frequency with the Virtual system is conceptually sound. Unfortunately, there appear to be problems in the technological implementation of this approach that must be addressed before the clinical utility can be assessed. For this reason, clinical application of this automated screening for resonant frequency is not recommended at this time.

Derived estimates of resonant frequency. As we have discussed, the resonant frequency is the frequency at which mass and stiffness elements in the middle ear are zero or equal. Since the total susceptance is the algebraic sum of the mass and the stiffness elements in the middle ear, resonant frequency can be estimated from the susceptance tympanogram as the frequency at which compensated susceptance equals zero. This value can be determined by examining the susceptance tympanogram at multiple probe tone frequencies and finding the lowest frequency at which the notch value is equal or below the positive or negative tail, depending on the compensation method used. For example, in Figure 15 positive compensation was used. This Figure shows a susceptance tympanogram in which the central notch falls just below the positive tail of the tympanogram. Recall that tympanograms tend to be asymmetric at positive and negative ear canal air pressure (Margolis & Smith, 1977; Van Camp et al, 1986), therefore different results may be obtained if the compensation is performed at different pressure extremes. In this study, two compensation methods were used to derive the resonant frequency estimate: positive tail compensation (+250 daPa), and negative tail compensation (-300 daPa). These two compensation methods were applied to data obtained from each of the two different recording procedures, sweep frequency (SF) and sweep pressure (SP), resulting in four derived estimates of resonant frequency.

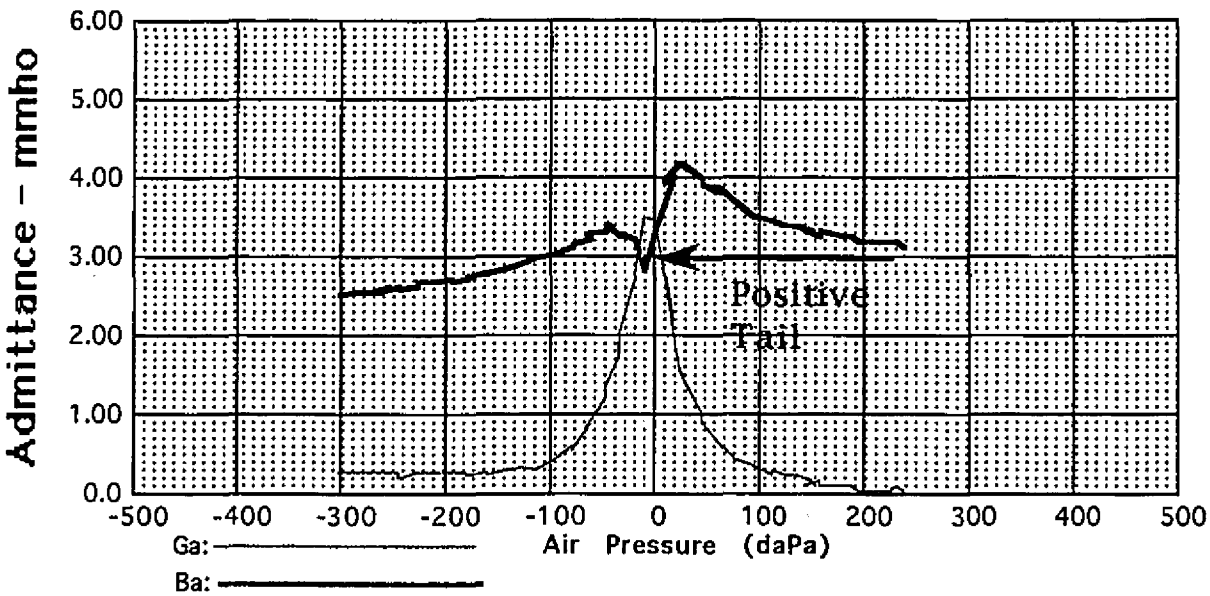


Figure 15. Illustration of a susceptance (B) tympanogram near the resonant frequency when positive tail compensation is used. Resonant frequency corresponds to the lowest frequency (900 Hz in this example) at which the central notch in the susceptance (B) tympanogram falls at or below the positive tail.

Distributions of the resonant frequency values in the normal group and the otosclerotic group derived using positive tail compensation are shown in Figure 16 for estimates obtained from the sweep frequency (SF) recordings and in Figure 17 for estimates derived from the sweep pressure (SP) recordings. Distributions of the resonant frequency values derived from negative tail compensation are shown in Figure 18 for estimates obtained from the SF recordings and in Figure 19 for estimates derived from the SP recordings. Descriptive statistics for the four estimates of resonant frequency are provided in Table 5.

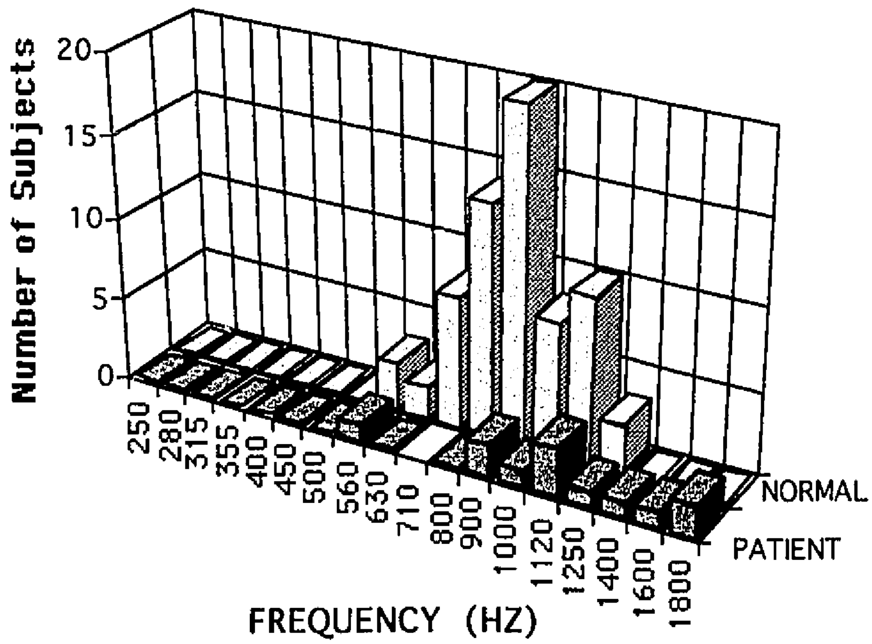


Figure 16. Distributions of resonant frequencies estimated using positive tail compensation from SF recordings for normal and otosclerotic ears.

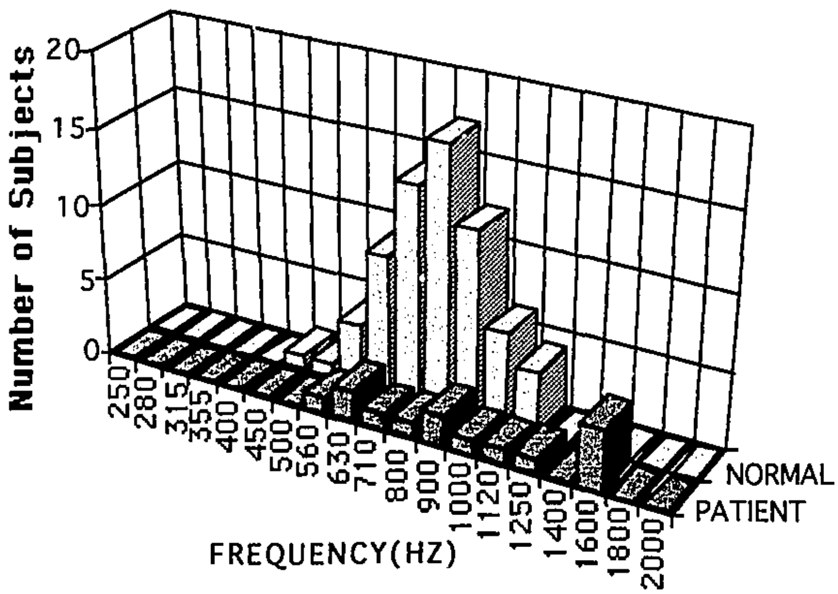


Figure 17. Distributions of resonant frequencies estimated using <u>positive</u> tail compensation from <u>SP</u> recording for normal and otosclerotic ears.

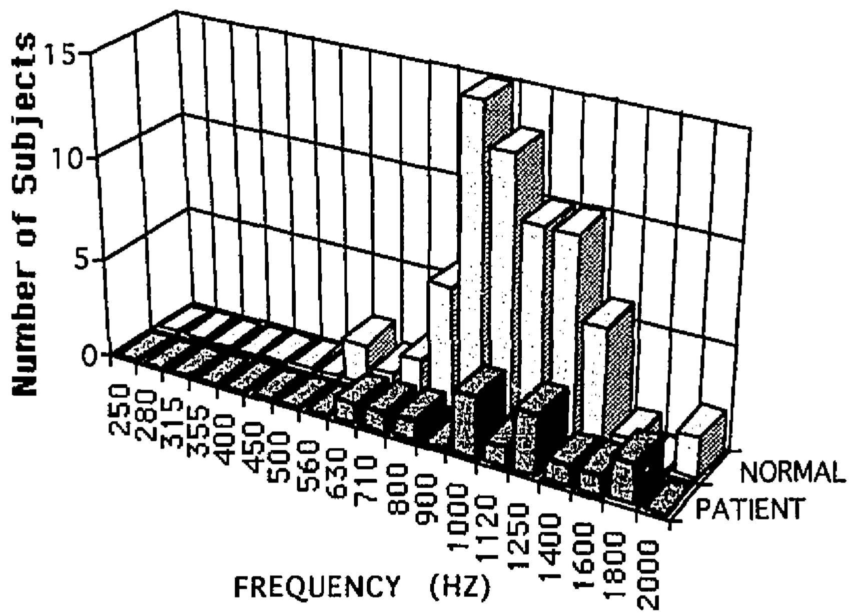


Figure 18. Distributions of resonant frequencies estimated using negative tail compensation from SF recording for normal and otosclerotic ears.

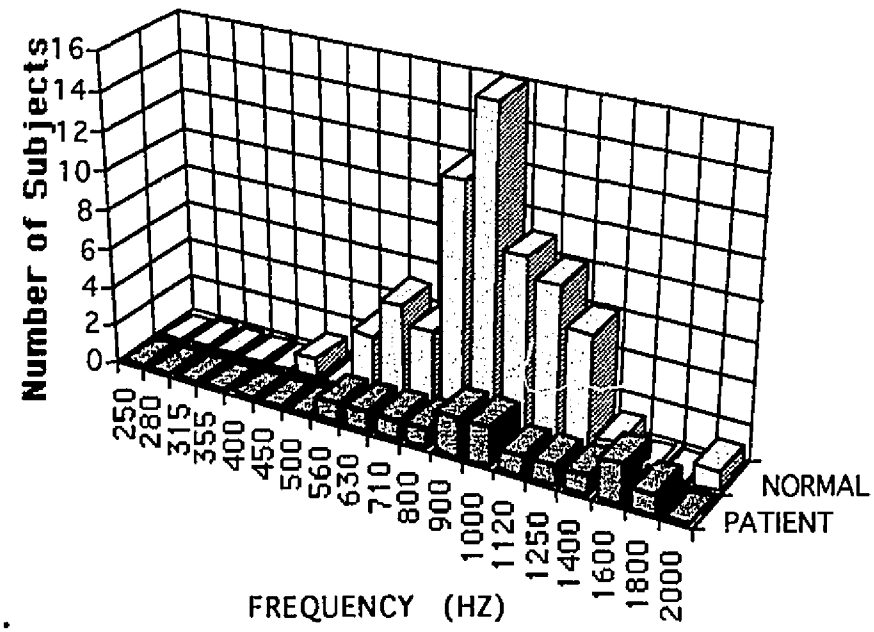


Figure 19. Distributions of resonant frequencies estimated using negative tail compensation from SP recording for normal and otosclerotic ears.

	Normal n=68		Normal n=68		Patient n=14		Patient n=14	
	SF+	SP+	SF-	SP-	SF+	SP+	SF-	SP-
Mean	894	789	1043	924	1142	1064	1186	1091
Standard Deviation	166	153	290	240	393	399	370	388
90% Range	630 – 1120	560 – 1000	710 – 1400	630 – 1250				
95% Confidence Interval	853 – 934	752 – 827	973 – 1113	865 – 982				

Table 5. Descriptive statistics of four derived estimates of resonant frequency (Hz) for normal and otosclerotic ears, SF+: sweep frequency method compensated by the positive tail; SP+: sweep pressure recording compensated by the negative tail; SF-: sweep frequency recording compensated by the negative tail; SP-: sweep pressure recording compensated by the negative tail.

As expected, these data clearly indicate a higher mean resonant frequency in the patients than in the normals regardless of the recording method (SF vs. SP) or compensation (positive versus negative) method used. As well, the standard deviation in the patient group was larger than the normal group for all four estimates of resonant frequency. Also as expected, in both normals and patients, the mean resonant frequency was higher for estimates derived from SF recordings compared to estimates derived from SP recordings. Moreover, as expected, in both normals and patients, mean resonant frequency was higher for estimates derived using negative tail compensation compared to those estimates derived using positive tail compensation.

To investigate these differences a mixed model ANOVA was conducted with Group (normal vs. patient) as a between-subject factor and Resonance Estimate as a within subject's factor (SF+, SF-, SP+, SP-). Table 6 provides the ANOVA summary table. The main effect of Group was significant [F (1,80) = 10, p = 0.0021] indicating that the patient group showed significantly higher resonant frequencies compared to the normal group. The main effect of Resonance Estimate was also significant [F (3,80) = 14.18, p = 0.00001] indicating that different methods for estimating the resonant frequency influenced the results. The interaction between Group and Resonance Estimates, plotted in Figure 20, was also marginally significant [F (3,80) = 2.374, p = 0.0709].

Source	df	SS	MS	*F*	*P*
Group	1	2021006	2021006	10	0.0021
Error	80	16023267	200291	-	-
Resonance Estimates	3	824565	274855	14.18	0.00001
Group X Resonance Estimates	3	138075	46025	2.374	0.0709
Error	240	4653140	19388	-	-

Table 6. Summary of ANOVA to test for differences between normals and patients with otosclerosis for four different estimates of resonant frequency.

To probe the Group by Resonance Estimate interaction, the simple effects analysis of Group and of Resonance Estimate were conducted. Simple effects of Group showed that patients had statistically higher resonant frequency values compared to normals for the SF+, SP+, and SP- measures [F (1,80) = 14.87, p = 0.0001 for SF+; F (1,80)= 19.23, p = 0.0001 for SP+; F (1,80) = 4.51, $p < 0.037$ for SP-]. However, for SF- there was no significant difference between normals and patients [F (1,80) = 2.58, p = 0.112]. The simple effects of Resonance Estimate revealed that the effect of Resonance Estimate was not significant in the patient group [F (3,240 = 2.13, p = 0.097], whereas this factor was highly significant in the normal group [F (3,240) = 38.11, p = 0.0001]. This, indicates that using different recording and compensation methods had a marked effect on the resonant frequency estimate in normals but little impact on resonant frequency estimation in the patient group. Subsequent Tukey comparisons in the normal group revealed that for each recording method resonance frequency was significantly higher ($p < 0.0001$) for negative compensation than for positive compensation method, i.e., SF->SF+ and SP->SP+. In addition, for each compensation method resonance frequency was significantly higher ($p < 0.0001$) for the SF recording method than for the SP recording method, i.e., SF+>SP+ and SF->SP-.

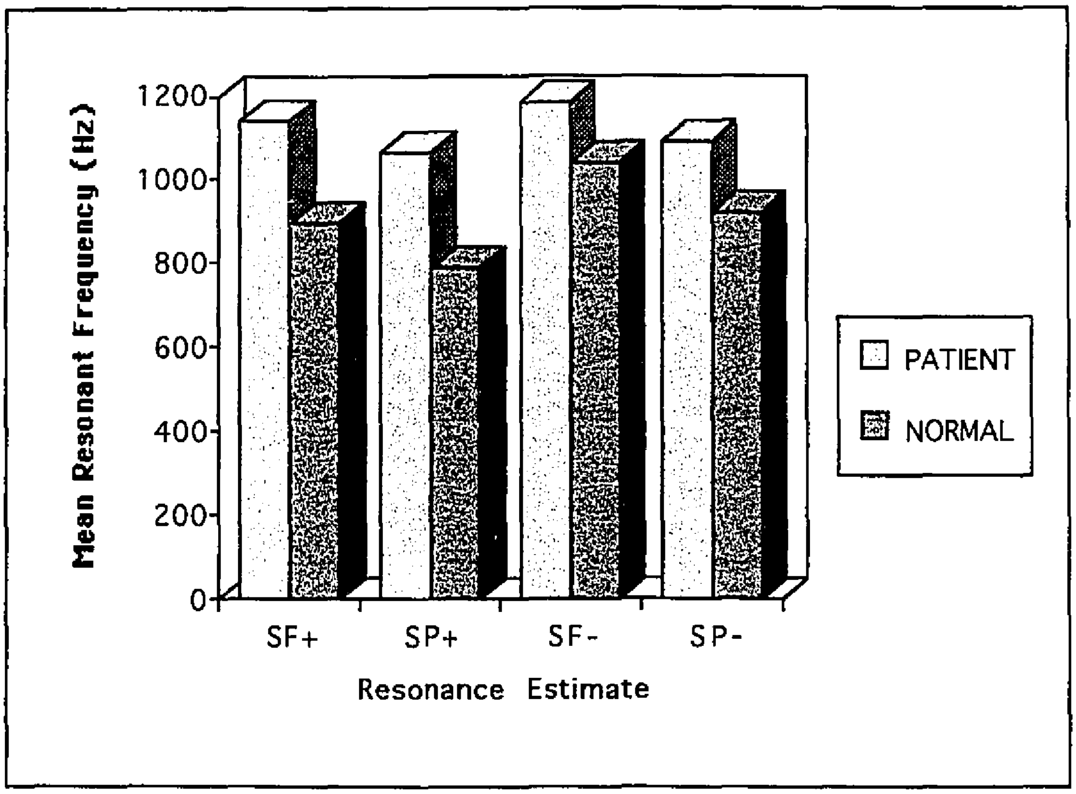


Figure 20. Mean resonant frequency estimated from different recording and compensation methods for normal and otosclerotic ears. SF+: Sweep frequency compensated by the positive tail; SF-: sweep frequency compensated by the negative tail; SP+: sweep pressure compensated by the positive tail; SP-: sweep pressure compensated by the negative tail.

We compared our four estimates of resonant frequency in our normal subjects to results reported in three previous studies of resonant frequency in normal middle ears (Funasaka et al., 1984; Margolis & Goycoolea, 1993; Valvik et al., 1994). Overall, the means observed in our study were lower than the results reported in these studies. Our mean values fall below the mean value of 1500 Hz reported by Funasaka et al. (1984) and our 95% confidence interval is narrower than the 95% confidence interval (720 to 1880 Hz) reported by these researchers. Likewise, our mean value for SF+ is also generally lower than the mean resonant frequency of 1049 Hz reported by Valvik et al. (1994) who used the GSI-33 (version 2) and a procedure similar to our SF+ measure. Overall, the differences observed between the present results and the findings reported by Funasaka et al. (1984) and by Valvik et al (1994) may be attributed to the use of different procedures or different admittance instruments to derive resonant frequency.

Margolis and Goycoolea (1993) employed the same immittance device and used similar, although not identical, methods to derive resonant frequency. As in the present study, they measured resonant frequency using SF and SP recording methods and using positive and negative tail compensation. However, they did not use the exact pressures values for compensation that have been employed in this study. Table 7 provides a summary of our results and the values reported by Margolis and Goycoolea to facilitate the comparison of findings across these two studies. The pressure values used for compensation in each study are also listed.

Table 7 shows that for each of the four measures of resonant frequency our mean value was lower than the mean value reported by Margolis and Goycoolea. As well, our standard deviation and 90% range for each resonance estimate was narrower than the value reported by these researchers. The discrepancy between the two studies is most pronounced with respect to the upper limit of the 90% range which is substantially lower in the present study for each estimate of resonant frequency. Despite these differences, in both studies SF- yielded the highest resonant frequency, SP+ yielded the lowest resonant frequency and values for SP- and SF+ fell in between. In addition, in both studies the four estimates show the same pattern of relative variability with SP+ and SF+ showing lower variability compared to SP- and SF-.

Margolis & Goycoolea (1993)	**SF+** (+200 daPa)	**SF-** (-500 daPa)	**SP+** (+200 daPa)	**SP-** (-500 daPa)
Mean	1135	1315	990	1132
Standard Deviation	306	377	290	337
90% Range	800 - 2000	710 - 2000	630 - 1400	710 - 2000
Current study	**SF+** (+250 daPa)	**SF-** (-300 daPa)	**SP+** (+250 daPa)	**SP-** (-300 daPa)
Mean	894	1043	789	924
Standard Deviation	166	290	153	240
90% Range	630 - 1120	710 - 1400	560 - 1000	630 - 1250

Table 7. Normative derived resonant frequency (Hz) data for two different studies. The numbers in parenthesis are the pressures at which compensation for ear canal volume was made.

With respect to SF- and SP- measures, differences in the pressures used for compensation likely contribute to the discrepancy in resonant frequency across the two studies. As shown in Table 7, a lower negative pressure was used in the present study in comparison to the -500 daPa used by Margolis and Goycoolea to compensate for ear canal volume. As discussed earlier (see page 13), compensation using a lower negative pressure value results in a higher estimate of middle ear admittance (Margolis & Smith, 1977; Moller, 1965; Shanks & Lilly, 1981) and, in turn, a lower frequency is reached before the notch in the susceptance tympanogram falls below the negative tail.

With respect to SF+ and SF- measures of resonant frequency, the reasons for the differences across these two studies are unclear. With these measures, the small difference in pressures used for compensation cannot explain the discrepancies. The effect (if any) of the higher positive pressure used for compensation in this study would be to increase, not decrease, the estimate of resonant frequency[7].

With respect to effects of recording method and compensation method, the present results replicate previous findings. Consistent with Margolis & Goycoolea (1993) we found significantly higher estimates of resonant frequency for the SF than for the SP recording method and significantly higher values for negative compensation than for positive compensation. Although the same trends were observed in the patient group, the differences were not statistically significant. The lack of statistical power due to the smaller sample size in the patient group may explain this result.

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[7] With respect to SF+ and SF- measures, it should also be noted that the lower rate of pressure change used in this study (125 daPa/sec) compared to the 250 daPa/sec rate used by Margolis and Goycoolea did not result in higher resonant frequency values in the present study, as might have been predicted. Apparently, the difference in these two rates is not sufficient to affect the estimation of resonant frequency.

The most reasonable explanation for obtaining a lower resonant frequency with the SP recording method is that faster rate of pressure change used in the SP recording method (compared to the SF method) results in a higher compensated susceptance value (Shanks & Wilson, 1986) and therefore a deeper notch in the susceptance tympanogram (Creten & Van Camp, 1974). Hence, the central notch on the susceptance tympanogram falls below the tail at a lower frequency. A lower resonant frequency may also be derived from the SP recording method because this method requires a larger number of tympanometric runs than does the SF method. It has been shown that consecutive tympanometric runs can result in a higher acoustic admittance which may produce a lower estimate of resonant frequency (Osguthorpe & Lam, 1981; Vanpeperstraete et al., 1979; Wilson et al., 1984).

The differences observed between the two compensation methods is explained by the asymmetry between negative and positive tympanometric pressures as discussed earlier (page 13). The susceptance tympanogram is usually lower at negative pressures compared to positive pressures (Margolis & Smith, 1977). Therefore, a higher frequency is reached before the central notch in the susceptance tympanogram falls below the negative tail.

With respect to group differences, our data clearly indicate a statistically higher mean resonant frequency in the otosclerotic ears compared to the normal ears, consistent with previous studies (Colletti, 1977; Funasaka et al 1984; Funasaka & Kumakawa, 1988; Valvik et al, 1993). As well, consistent with the aforementioned studies, there was considerable overlap in resonant frequency evident in our normal and patient groups. Group differences were apparent for all four estimates of resonant frequency, and were significant for every measure except for SF-. The failure of SF- procedure to yield a statistically significant difference between normal and patient groups is probably due to its high variability in the normal group.

As shown in Figure 20, among the four estimates of resonant frequency, the difference between the normal and otosclerotic ears appears to be larger for measures derived using positive tail compensation (SP+ and SF+) than for measures using negative compensation (SP- and SF-). In contrast, the difference between the normals and otosclerotic ears appears to be less affected by differences in recording method. Furthermore, as shown in Tables 5 and 7, there are much larger differences in intersubject variability in the normal group associated with compensation procedure (SF- vs. SF+ and SP- vs. SP+) than with recording method (SF- vs. SP- and SF+ vs. SF+). These observations suggest that the choice of compensation procedure will have a greater impact on the identification of otosclerosis on the basis of resonant frequency than will the choice of recording method.

Overall, three conclusions can be drawn from these data on resonant frequency. First, resonant frequency is superior to measures obtained using standard tympanometry in distinguishing normal from otosclerotic ears. Second, when using resonant frequency to identify otosclerosis, the choice of compensation method may be more important than the choice of recording method. Finally, when using resonant frequency to identify otosclerosis, the positive tail compensation will yield better results than the negative tail compensation.

Admittance Phase Angle of 45°. To determine the probe frequency corresponding to a 45° phase angle, the rectangular components, susceptance (B) and conductance (G), were derived from the data obtained in the SF and SP recordings. This derivation was accomplished through selecting "Cartesian Y" from the display menu of the Virtual 310 software. Then the susceptance tympanogram was compensated by selecting "compensated susceptance" from the display menu. Compensated susceptance uses a different calculation to estimate the ear canal volume. This method takes phase angle into account in its calculation. For this reason it tends to be a more accurate representation of actual ear canal volume. To determine the frequency corresponding to 45° phase angle, the frequency at which conductance first became equal or larger than compensated susceptance was determined (see Figure 21). This was accomplished through tracing susceptance and conductance tympanograms at different probe tone frequencies. This procedure was applied to tympanograms recorded using the sweep frequency and sweep pressure methods.

Distributions of the frequency corresponding to 45° phase angle for normal and otosclerotic ears are shown in Figure 22 for estimates derived from sweep frequency (SF) recordings and in Figure 23 for estimates derived from sweep pressure (SP) recordings. Descriptive statistics corresponding to this measure are provided in Table 8 for both SF and SP recordings.

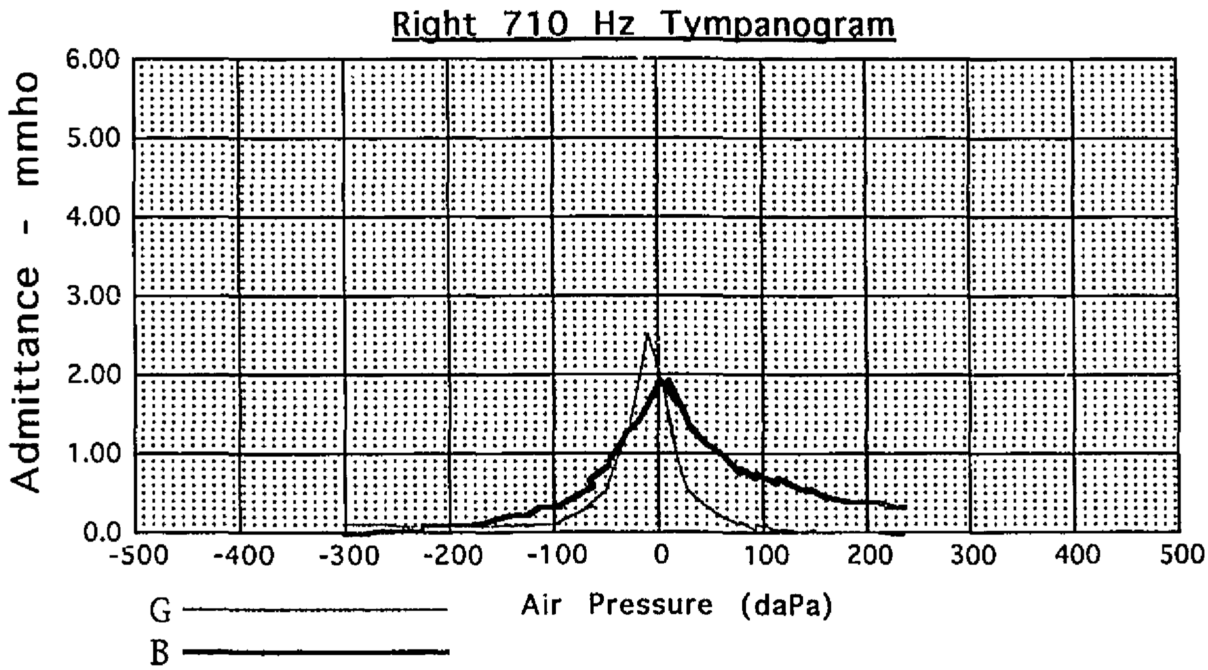

Figure 21. Illustration of the method used to estimate the admittance phase angle of 45°. In this example the frequency at which conductance(G) first became larger than susceptance(B) was 710 Hz.

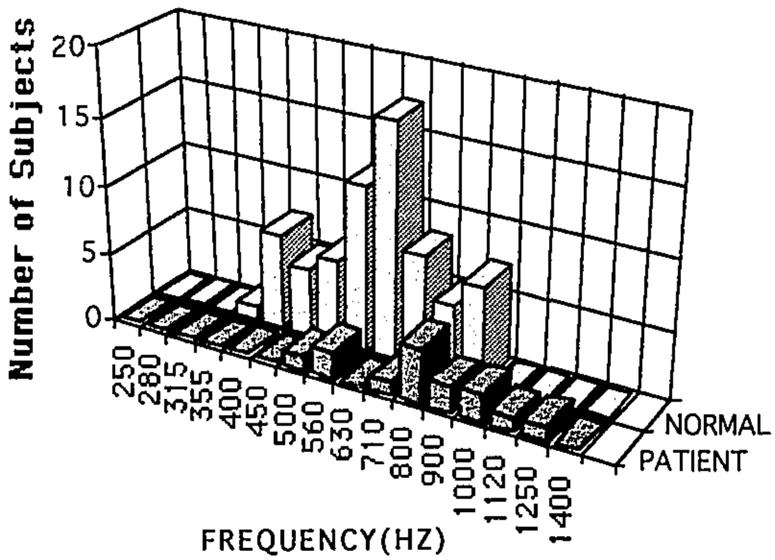

Figure 22. Distributions of frequency corresponding to admittance phase angle of 45° estimated using SF recordings for normal and otosclerotic ears.

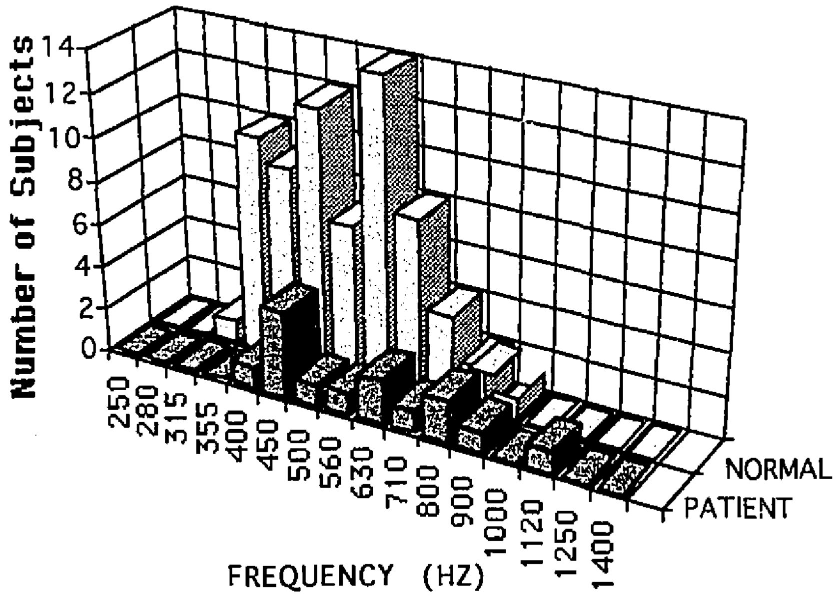

Figure 23. Distributions of frequency corresponding to admittance phase angle of 45° estimated using SP recordings for normal and otosclerotic ears.

	Normal n=68		Patient n=14	
	SF	SP	SF	SP
Mean	615	508	846	632
Standard Deviation	148	127	239	211
90% Range	400 I 870	355 I 686		
95% Confidence Interval	579 I 651	477 I 539		

Table 8. Descriptive statistics for frequency (Hz) corresponding to admittance phase angle of 45° using sweep frequency (SF) and sweep pressure (SP) recordings for normal and otosclerotic ears.

As expected, the frequency corresponding to 45° phase angle is higher in the patient group than in the normals regardless of the recording method (SF Vs SP) used. For both measures, the standard deviation was also larger in the patient group compare to the normal group. Also as expected, in both normals and patients the 45° phase occurred at a higher frequency when it was derived from a SF recording than when it was derived from a SP recording.

To investigate these differences a mixed model ANOVA was conducted with Group (normal vs. patient) as a between subject factor and the Recording Methods (SF vs. SP) as a within subject factor. Table 9 provides the ANOVA summary table. Both the main effects of Group [F (1,80) = 16.31, p = 0.0001] and Recording Method [F (1,80) = 183.6, p = 0.00001] were highly significant. The interaction between Group and Recording Method, plotted in Figure 24, was also highly significant (F (1,80) = 20.52, p = 0.0001).

To probe the interaction the simple effects of Group and of Recording Methods were analyzed. Simple effects of Recording Method revealed that a higher frequency corresponding to 45° phase angle was obtained from the SF recordings in the normal group [F (1,80) = 119.14.1, p = 0.0001] as well as in the patient group [F (1,80)= 98.54, p = 0.0001]. Simple effects of Group revealed that the frequency corresponding to admittance phase angle of 45° was statistically higher in the patients than normals for both the SF [F (1,80) = 22.58, p = 0.0001] and the SP recording method [F (1,80) = 8.63, p = 0.004). However, the interaction plotted in Figure 20

Source	df	SS	MS	*F*	*P*
Group	1	734160	734160	16.31	0.0001
Error	80	3599992	44999.9	-	-
Recording Method	1	598877	598877	183.6	0.00001
Group X Recording Method	1	66925	66925	20.52	0.00001
Error	80	260947	3262	-	-

Table 9. Summary of ANOVA results to test for differences in patients with otosclerosis for two different estimates of the admittance phase angle of 45°.

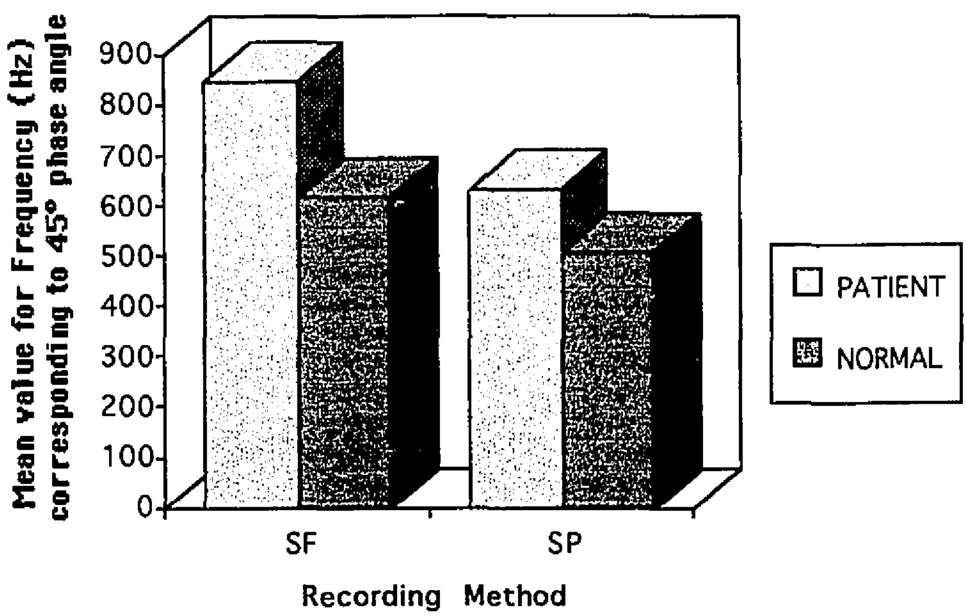

Figure 24. Mean values for frequency corresponding to 45° phase angle estimated from SF and SP recordings in normal subjects and patients with otosclerosis.

indicates that the group differences were larger when admittance phase angle of 45° was estimated from SF recordings compared to the estimate derived from SP recordings.

The results of frequency corresponding to admittance phase angle of 45° in our normal subjects are comparable with results of Shanks et al. (1987). To our knowledge, no other studies of this parameter have been published. Our mean value (615 Hz) for admittance phase angle of 45° using SF recording method is close to the mean value of 565 Hz reported by Shanks et al. (1987). The mean value of admittance phase angle of 45° was also higher for the SF recording method compare to SP recording method in both normal and patient groups. This difference can be explained as an effect of the faster rate of pressure change used in the SP recording method because increasing the rate of pressure change increases the peak susceptance, conductance, and admittance values (Creten & Van Camp, 1974; Koebsell & Margolis, 1985) which results in a lower value for admittance phase angle of 45°.

Analysis of group differences revealed that the group mean for the frequency corresponding to 45° phase angle was statistically higher in the patient group compared to the normal group. This finding confirms the preliminary finding reported by Shanks et al. (1987). The group difference was significant in data obtained using both SF and SP recording methods. However, the mean difference between the normals and otosclerotic ears was larger for the results obtained using the sweep frequency recording method compared to the sweep pressure recording method. Overall, these findings indicate that the frequency corresponding to phase angle of 45° is a useful parameter for distinguishing normals from otosclerotic ears. Moreover, on the basis of the present results, the SF recording method is recommended when frequency corresponding to 45° phase angle is used to identify otosclerosis or other high impedance pathologies .

Test Performance Analysis

In this section, all nine tympanometric measures were evaluated using several test performance measures. To evaluate test performance a range of values which define normal function must be specified. Some investigators (e.g., Funasaka et al., 1984; Funasaka & Kumakawa, 1988) have used the 95% confidence interval around the mean to define normal immittance values. In contrast, several investigators (Feldman, 1974; Shanks & Wilson, 1986; Wiley, Oviatt, & Block, 1987; Wilson, Shanks, & Kaplan, 1981; Zwislocki & Feldman, 1970) have used the 90% range, i.e., the range encompassing values between the 5th and the 95th percentile, to define normal immittance values. These investigators have pointed out that standard deviations or confidence intervals are less appropriate for defining the normal variation in such measures because immittance values are generally positively skewed. To avoid problems due to skewness, they chose to report the median and the values defining the 90% range. In the present study, Pearson's coefficient of skew (*sk*) was computed for each measure to assess skewness. This value was ≤ 0.5 for every measure except static admittance ($sk = 2.2$) which means that the distribution of each measure can be considered approximately symmetrical (Runyon, 1985). Thus, the use of 95% confidence interval was statistically appropriate for every measure examined in this study except static admittance. Test performance was evaluated using both criteria for normal function found in the current literature, i.e., 1) defined as values falling within the 95% confidence interval around the mean, and 2) defined as values falling within the 90% range.

Using each of these criteria for normal function, correct and incorrect classification of patients and normals was determined for each measure. Then using the classification data, several measures of test performance were computed and compared. Table 10 summarizes test performance results on 14 ears with otosclerosis and 68 normal ears based on the nine tympanometric measures used in this study. The percentage of the otosclerotic ears correctly identified (i.e., hit rate or sensitivity) and the percentage of the normals group incorrectly identified as a otosclerotic ear (i.e., false alarm rate or false positive) was calculated separately for each criteria. For tympanometric width and static admittance, cases were identified as otosclerotic when their value fell below the lower limit of the normal values. For the remaining measures cases were identified as an otosclerotic ear when their value on the measure exceeded the upper limit of normal values. A' was also calculated from the hit rate (HT) and false alarm rate (FA)[8]. A' is a way of measuring the test performance in which hit rate is adjusted by the

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[8] A' was calculated from the decimal form of HT & FA using Robinson Watson (1972) formula: $A' = 0.5 + \frac{(HT - FA) \times (1 + HT - FA)}{4HT \times (1 - FA)}$.

rate of false positives. To achieve a high A' score, a test must have both a high hit rate and a low false alarm. A' varies from 0.5 for a useless test to 1.0 for a perfect test (for more discussion see Robinson & Watson, 1972).

Test	95% Confid. Interval	%HT	%FA	A'	90% Range	%HT	%FA	A'
SC	0.74-0.97 mmhos	71	53	0.66	0.4-1.6 mmhos	21	6	0.72
TW	78-91 daPa	43	44	0.49	48-134 daPa	21	6	0.72
Fr.Scrn	923-1062 Hz	21	43	0.30	630-1250 Hz	7	7	0.50
Fr.SF+	853-934 Hz	64	31	0.75	630-1120 Hz	36	4	0.81
Fr.SF-	973-1113 Hz	57	34	0.69	710-1400 Hz	21	4	0.75
Fr.SP+	752-827 Hz	64	32	0.74	560-1000 Hz	43	6	0.81
Fr.SP-	865-982 Hz	57	37	0.67	630-1250 Hz	29	3	0.79
F45°-SF	579-651 Hz	79	29	0.84	400-870 Hz	50	7	0.83
F45°-SP	477-539 Hz	57	43	O.62	355-686 Hz	28	7	0.74

Table 10. Test Performance of nine tympanometric measures in differentiating normal and otosclerotic ears when normal is defined by the 95% confidence interval around the mean and by 90% range.

Abbreviations are as follows:

SC	Static compliance
TW:	Tympanometric width
Fr.:	Resonant frequency
Scrn.:	Automatic screening
F45°:	Frequency corresponding to 45°
SF:	Sweep frequency recording
SP:	Sweep pressure recording
+:	Positive tail compensation
-:	Negative tail compensation

As shown in Table 10, of the two criteria used in this study, 95% confidence interval provides greater sensitivity (i.e., higher HT) rate than does 90% range. With respect to distinguishing normal middle ear function from otosclerosis, a criterion that results in a higher sensitivity is desirable because tympanometry is typically interpreted together with other audiological measures (e.g., audiometry) which provide good specificity . For this reason, conclusions drawn in this study are based on the test performance results obtained using the 95% confidence interval to define normal function.

Table 10 shows that F45°-SF was the best single tympanometric measure for differentiating normal and otosclerotic ears. This measure had the highest HT rate and the lowest FA rate. Following F45°-SF, the four derived estimates of resonant frequency had better performance compared to the remaining measures. The FA rates were fairly comparable among the different derived estimates of resonant frequency, whereas the HT rates differed. In particular, better performance was obtained for derived estimates of resonant frequencies using positive tail compensation (SF+ and SP+) compared to those that were derived using negative tail compensation (SF- and SP-). On the other hand, test performance was quite similar for measures derived using different recording methods (SF+ vs. SP+ and SF- vs. SP-). The FA rate for F45°-SP was comparable to TW and Fr.Scrn. measures, however, its HT rate was better. Moreover, the HT rate for static admittance was higher than any other measures (except F45°-SF) but it had the poorest specificity compared to the other measures. TW and the resonant frequency obtained by the screening mode had the poorest performance compared to the other variables, although the TW had a better HT rate than Fr.Scrn measure.

From the relative performance of this set of measures it can be concluded that if parameters derived from multifrequency, multicomponent tympanometry are measured in a particular way they can be more useful than parameters derived from standard low frequency tympanometry with respect to distinguishing normals from otosclerotic ears. The present findings also show that F45° is a better parameter for distinguishing normal from otosclerosis than the resonant frequency, as suggested earlier by Shanks et al. (1987). The present findings also confirm that for derived estimates of resonant frequency different compensation methods have greater impact on the test performance than does different recording methods. The present findings put into question Margolis and Goycoolea's recommendation that the SF recording method not be used for assessment of high impedance pathologies. Their recommendation was based on the ceiling effect in resonant frequency measures using SF recording method for normal subjects. The present findings indicate that the choice of recording method makes little difference in the test performance. Therefore, choice of recording method may be made on the basis of practical issues .

Individual Patterns of Test Performance

In this section, patterns of test performance were examined in individual normal (Table 12) and patient subjects (Table 11) based on 95% confidence interval criteria . The positive sign (+) in these Tables indicates a correct diagnosis (HT) in the patient group and incorrect diagnosis as otosclerotic in the normals (FA). The negative sign (-) indicates incorrect identification as normal (false negative) in the patient group and correct identification as normals in the normal group (specificity).

Table 11 and 12 show that individual patterns were not stable across different tympanometric measures. Whether or not a normal is identified as an otosclerotic ear depends on particular tympanometric measures considered. Almost every normal was incorrectly identified as otosclerotic on at least one measure. In contrast, there were no patients who were not identified by at least one of the measures used in this study. This means that by combining one or more measures, a 100% HT rate can be achieved. Nine patients were correctly identified on six or more measures.

An interesting pattern emerged from Table 11. With respect to cases 1, 2, 6, and 13 in the patient group, most of the measures failed to correctly identify these cases as an otosclerotic ear. However, in each of these cases the tympanometric width (TW) correctly identified them as an otosclerotic ear. This pattern suggest that using F45°-SF (the best single tympanometric variable for discriminating normal and otosclerotic ears) and TW together may improve the ability to discriminate between ears with and without otosclerosis. However, combining these two measures in their current state resulted in a very poor specificity (only 25 normals correctly identified). In order to solve this problem a new cut off close to 5th percentile (47 daPa) was used for the TW. This new cut off again correctly identified cases 1, 2, 6, and 13 in the patient group and, on the basisis of TW, sixty-six ears (97%) in the normal group were correctly identified as normal by this new cut off. A combination of TW using this new cut off with F45°-SF such that normal is defined as negative on both TW and F45°-SF and otosclerosis is defined as positive on either TW or F45°-SF resulted in a HT rate of 100%, FA rate of 32%, and overall A' of 0.92. The test performance for this combination of measures exceeds the performance of any single measure.

The results of individual patterns of test performance indicate that two distinct signs of disease exist in the patient group: 1) an increase in the stiffness of the middle ear system reflected as an increase in resonant frequency and/or increase in the frequency corresponding to 45° phase angle, and 2) a sharper tympanogram manifested by an abnormally low tympanometric width. Most of the patients displayed one of these two signs; only two patients displayed both signs. Examination of the patients' audiograms did not reveal a clear relationship between individual test performance and various audiometric patterns, including frequency characteristics, type of hearing loss (mixed vs. conductive hearing loss), air-bone-gap patterns, and presence of Carhart notch.

Patient	SC	TW	Fr.Scn.	Fr.SF+	Fr.SF-	Fr.SP+	Fr.SP-	F45°-SF	F45°-SP
1	+	+	-	-	-	-	-	-	-
2	-	+	-	-	-	-	-	+	-
3	+	-	-	+	+	+	+	+	+
4	+	-	-	+	+	+	+	+	-
5	+	-	-	+	+	+	+	+	-
6	-	+	-	-	-	-	-	-	-
7	-	+	-	-	-	-	-	+	+
8	+	-	-	+	+	+	+	+	+
9	+	-	+	+	-	+	-	+	+
10	+	-	+	+	+	+	+	+	+
11	+	+	+	+	+	+	+	+	+
12	+	-	-	+	+	+	+	+	+
13	-	+	-	-	-	-	-	-	-
14	+	-	-	+	+	+	+	+	+
Total (+)	10	6	3	9	8	9	8	11	8

Table 11. Patterns of test performance of the nine tympanometric parameters in individual patient subjects based on 95% confidence interval criteria. The (+) sign indicates a correct diagnosis as an otosclerotic ear (HT). The negative sign (-) indicates incorrect identification as normal (false negative) in the patient group.

Row #	Normal	SC	TW	Fr.Scrn.	Fr.SF+	Fr.SF-	Fr.SP+	Fr.SP-	F45°-SF	F45°-SP
1	n=5	-	-	-	-	-	-	-	-	-
2	n=3	+	-	-	-	-	-	-	-	-
3	n=12	-	+	-	-	-	-	-	-	-
4	n=1	-	-	+	-	-	-	-	-	-
5	n=2	-	-	-	-	+	-	-	-	-
6	n=1	-	-	-	-	-	-	-	-	+
7	n=2	+	+	-	-	-	-	-	-	-
8	n=2	-	+	+	-	-	-	-	-	-
9	n=1	-	+	-	-	+	-	-	-	-
10	n=1	-	-	+	+	-	-	-	-	-
11	n=1	-	-	-	+	+	-	-	-	-
12	n=1	+	-	-	-	+	-	-	-	-
13	n=1	-	-	+	-	-	-	-	-	+
14	n=1	+	+	+	-	-	-	-	-	-
15	n=1	-	+	+	-	-	-	-	-	+
16	n=1	+	-	-	-	-	+	-	-	+
17	n=1	-	-	+	-	+	-	+	-	-
18	n=1	-	+	-	-	-	-	-	+	+
19	n=1	+	-	-	+	+	-	-	-	-
20	n=1	+	+	+	-	-	-	-	-	+
21	n=1	+	-	-	+	+	-	+	-	-
22	n=2	+	-	-	-	-	+	+	-	+
23	n=2	+	+	+	-	-	-	-	+	+
24	n=1	+	+	-	-	+	-	+	-	+
25	n=1	+	-	+	+	+	-	-	+	-
26	n=1	-	-	+	+	+	+	+	-	-
27	n=1	-	-	-	+	+	-	+	+	+
28	n=1	+	+	-	-	+	-	+	+	+
29	n=1	+	+	-	-	+	+	+	-	+
30	n=1	+	-	+	+	+	+	+	-	-
31	n=1	+	-	+	+	-	+	-	+	+
32	n=1	+	-	-	+	+	+	+	-	-
33	n=1	+	+	+	+	+	+	+	-	-
34	n=1	+	-	+	+	-	+	+	+	+
35	n=8	+	-	+	+	+	+	+	+	+
36	n=4	+	+	+	+	+	+	+	+	+
Total (+)	n=68	36	31	29	23	29	22	25	20	27

Table 12. Patterns of test performance of the nine tympanometric parameters in individual normal subjects based on 95% confidence interval criteria. The (+) sign indicates incorrect diagnosis as an otosclerotic ear (FA) in the normals. The negative sign (-) indicates correct identification as normals in the normal group (specificity).

General Discussion

In this study two goals were addressed. The first was to evaluate alternative measures for distinguishing normal ears from otosclerotic ears using both standard and multifrequency tympanometry. The second goal was to provide guidelines and normative data for interpreting multifrequency, multicomponent tympanometry obtained using the Virtual 310 computer-controlled immittance system. To address these goals, nine tympanometric measures were examined in 68 normal ears and 14 subjects with surgically confirmed otosclerosis. Two of them, static admittance and tympanometric width are derivable from single component standard 226 Hz tympanogram. The remaining seven measures were different estimates of resonant frequency and frequency corresponding to 45° phase angle that can be only obtained using multifrequency, multicomponent tympanometry.

Six general conclusions can be drawn from the present study. First, the results of this study support the advantage of multifrequency, multicomponent tympanometry over standard low frequency tympanometry in distinguishing normals and otosclerotic ears. To date, the advantage of higher probe tone frequencies over standard low frequency tympanometry has been confirmed in detecting low impedance pathologies (e.g., Colletti, 1976; Funasaka et al., 1984; Liden et al., 1977; Lilly, 1984; Van Camp et al., 1980; Zwislocki & Feldman, 1970) but was not been established with respect to commonly occurring high impedance pathologies such as otosclerosis (Van Camp et al., 1986). Through a systematic comparison of the relevant parameters obtained from standard tympanometry and multifrequency , multicomponent tympanometry, the present study also confirms the advantage of higher probe tone frequencies over standard low frequency tympanometry in detecting high impedance pathologies such as otosclerosis. The time that it takes to run and analyze a series of multifrequency tympanograms is longer than standard low frequency tympanometry. However, given that it appears to provide a better performance than standard tympanometry, the use of multifrequency, multicomponent tympanometry can be justified.

Second, the results of this study indicate that among different parameters obtained from multifrequency, multicomponent tympanometry, the frequency corresponding to admittance phase angle of 45° (F45°) is the best single measure to distinguish normals and otosclerotic ears (in fact, no single patient was found to be identified by resonant frequency and not by F45°). These findings indicate that an increase in the stiffness of the middle ear system as a result of otosclerosis can be best shown by F45°. This finding is consistent with the earlier findings reported by Shanks et al. (1987). Moreover, less testing time is required for F45° than for resonant frequency. Thus, F45° has a practical as well as a performance advantage over resonant frequency.

Third, the findings of the present study lead us to the recommendation of sweep frequency (SF) recording method for measuring F45° as well as resonant frequency. In measuring F45°, the SF recording method has a practical as well as performance advantage over the sweep pressure (SP) recording method in that it is faster and more efficient than SP recording method. In measuring resonant frequency, the SF recording method has no performance advantage but has a practical advantage over SP recording method.

Fourth, results of this study indicate that obtained estimates of resonance frequency using positive tail compensation have a better diagnostic value than obtained estimates using negative tail compensation regardless of the recording method used. Therefore, the positive tail compensation method is a preferred method for estimation of the resonant frequency in distinguishing normals from otosclerotic ears. This is consistent with the recommendation made by Margolis and Goycoolea (1993).

A fifth important conclusion that can be drawn from this finding is that two distinct signs exist in the patient group: 1) an increase in the stiffness of the middle ear, best shown by F45°-SF, and 2) an increase in the sharpness of the tympanogram, best shown by tympanometric width (TW). Patterns in individual test performance indicate that these parameters are to some extent negatively correlated in that most patients (11/14) were accurately identified by one sign but not the other. Therefore, combining these two measures, F45°-SF and TW, clearly improves our ability to separate normal ears from otosclerotic ears. Tympanometric width is often calculated automatically by most immittance systems when standard low frequency tympanometry is performed. Therefore, the total test time of measuring these two parameters is still within a reasonable time demand of most clinicians.

Finally, the results of this study indicate optimal decision criteria can be derived only when data on both normals and the relevant diseased population are available. Most of the previous studies recommended a 90% range to define normal function for immittance values (Feldman, 1974; Shanks & Wilson, 1986; Wiley et al., 1987; Wilson et al., 1981; Zwislocki & Feldman, 1970). This approach is formed as a way to achieve high specificity (95% of normal ears should be negative on the test). However, in these studies no data on otosclerotic ears were available on which to evaluate the sensitivity. The value of a given decision criterion cannot be determined without an understanding of the sensitivity of that criteria. In the test performance data gathered in this study it is clear that maximizing specificity does not maximize sensitivity and does not assure good overall performance. In fact, setting cutoffs based on the specificity, without consideration of sensitivity, could lead to poor overall test performance. Therefore, to optimize test performance, decision criteria must be based on properties of both the normals and the diseased population on which the test will be used. Moreover, given that the characteristics of different disease populations vary, different criteria may be needed to address different clinical decisions.

Three general limitations can be found in the present study. One limitation of this study was the relatively small sample size of the patient group. Therefore, caution should be taken in interpreting the present data as representative of all otosclerotic ears. There was higher intersubject variability in the otosclerotic group compared to the normal group. The range and standard deviation was wider in the otosclerotic ears.

A second limitation was the restricted choice of probe tone frequencies to measure resonant frequency and frequency corresponding to admittance phase angle of 45°. As it was discussed in the Method section, the probe tone frequencies ranged from 250 to 2000 Hz in 1/6 octave intervals. As the probe tone frequency is increased, the precision of each measure will be decreased because, in octave scales, as the probe tone frequency increases, the interval between adjacent frequencies will be also increased. Therefore, this particular limit is more prominent for resonant frequencies which occurs at relatively higher probe tone frequencies compared to F45°. Further investigation is needed to compile the normative data on a smaller frequency interval.

The third limitation is that only one compensation method (negative compensation) was evaluated in computing static admittance and tympanometric width. Several studies (Koebsell, Shanks, Cone-Wesson, & Wilson, 1988; Margolis & Shanks, 1991) have shown that the use of the negative tail compensation method in calculating TW produces greater variability in both normal ears and in ears with different middle ear disorders. Further investigation is needed to investigate the effect of compensation method on the test performance for static admittance and tympanometric width.

Three promising directions for future research have emerged from the findings of this study. First, the clinical utility of static admittance and tympanometric width using a single probe tone frequency near the frequency corresponding to admittance phase angle of 45° should be explored and compared to present results. Several clinical and laboratory studies have reported prominent differences between normal and otosclerotic ears (Burke and Nilges, 1970; Margolis, Osguthorpe, & Popelka, 1978; Zwislocki, 1963) when compensated static impedance or admittance components recorded using higher probe tone frequencies were compared. Moreover, a simple measure of static admittance and tympanometric width take less time compared to other multifrequency parameters. Currently, research is underway to explore the best single probe tone frequency near F45° for distinguishing normal and otosclerotic ears using static admittance and tympanometric width.

Second, further exploration of two distinct tympanometric signs observed in the patient group is also necessary. Although no relationship between these signs and audiometric patterns were evident, it will be interesting to investigate whether these distinct tympanometric signs are associated with different manifestation of the disease that are evident at surgery.

Finally, diagnostic utility of nine tympanometric measures was studied with respect to identifying one type of high impedance pathology. Further studies of this kind, investigating other middle ear pathologies are needed to advance the overall clinical application of tympanometry.

Summary

In this study, multifrequency, multicomponent tympanometry was found to be clinically useful in distinguishing normal and otosclerotic ears. The results of this study indicate that the frequency corresponding to admittance phase angle of 45° (F45°) is the best single criterion in distinguishing normal from otosclerotic ears.

Moreover, based on the relationship of all the measures used in this study, two distinct signs of otosclerosis were observed in the patient group; 1) an increase in the stiffness of the middle ear system, and 2) an increase in the sharpness of the tympanogram. These two signs are most clearly manifested by F45° and TW, respectively. Combining these two measures yields a marked improvement in the ability to distinguish normal and otosclerotic ears using tympanometric information. Overall, the present study demonstrates that a systematic comparison of multiple tympanometric measures in normal and diseased groups can advance our understanding of the nature of a specific middle ear pathology. Moreover, it also can refine clinical assessment procedures.

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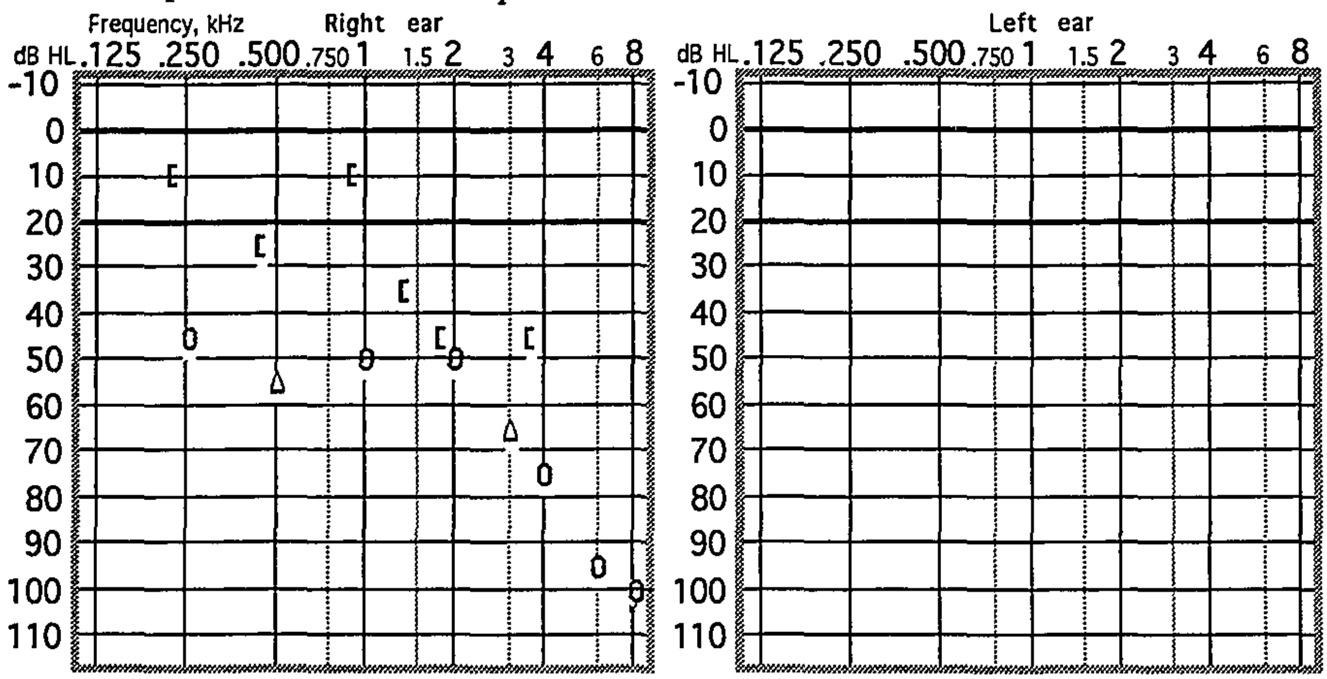
APPENDIX PATIENT 1

Individual audiograms for the patient group. The patient numbers correspond to the number presnted in Table 11.



Legend

		Unmasked	Masked
Air (phone)	Right	O	Δ
	Left	X	□
Air (insert)	Right	ⓞ	Δ
	Left	X	□
Bone	Right	<	[
	Left	>	]

SF	MCL	UCL	No Resp
S	M	U	↙ ↘

Pure Tone Average

.5,1,2 kHz	Right	Left
Three freq.	51	
Best two	50	

	SRT	SDT	MCL	UCL
Air: Right	75 dB		80 dB	
Left				
SF: Unaided				
Right Aided				
Left Aided				

Recognition (Percent at dB HL)

Right	84% 80 dB		
Left			
Bin			

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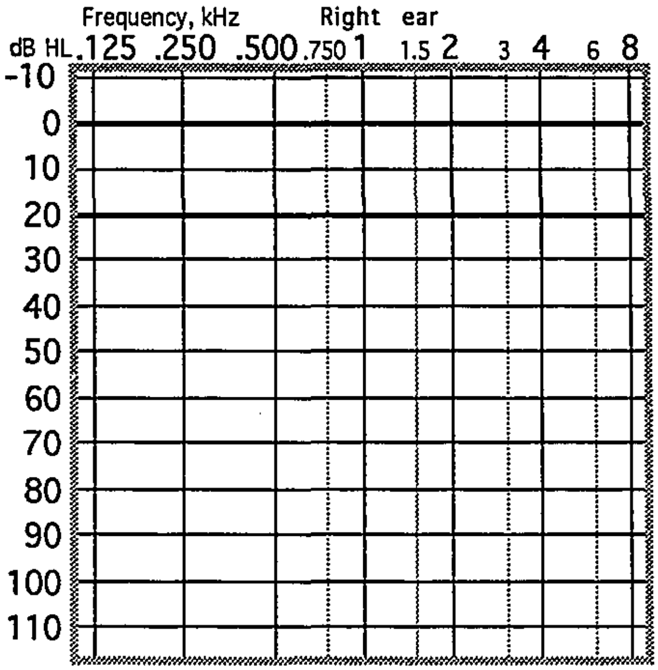
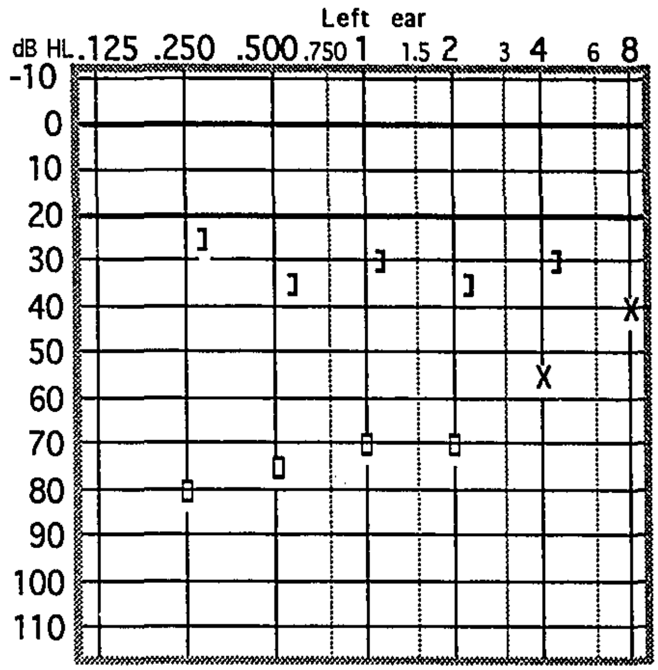
Name: PATIENT 2
Chart #: Age: 48
Wednesday, January 31, 1996 22:20
Tester: fggfgh
ANSI S3.6-1969 Virtual M320 #0210 Cal. 04/16/90





Legend		Unmasked	Masked
Air (phone)	Right	O	Δ
	Left	X	□
Air (insert)	Right	O	Δ
	Left	X	□
Bone	Right	<	[
	Left	>	]

SF	MCL	UCL	No Resp
S	M	U	↙ ↘

Pure Tone Average

.5,1,2 kHz	Right	Left
Three freq.		71
Best two		70

	SRT	SDT	MCL	UCL
Air: Right	65 dB		95 dB	
Left				
SF: Unaided				
Right Aided				
Left Aided				

Recognition (Percent at dB HL)

Right	92% 95 dB		
Left			
Bin			

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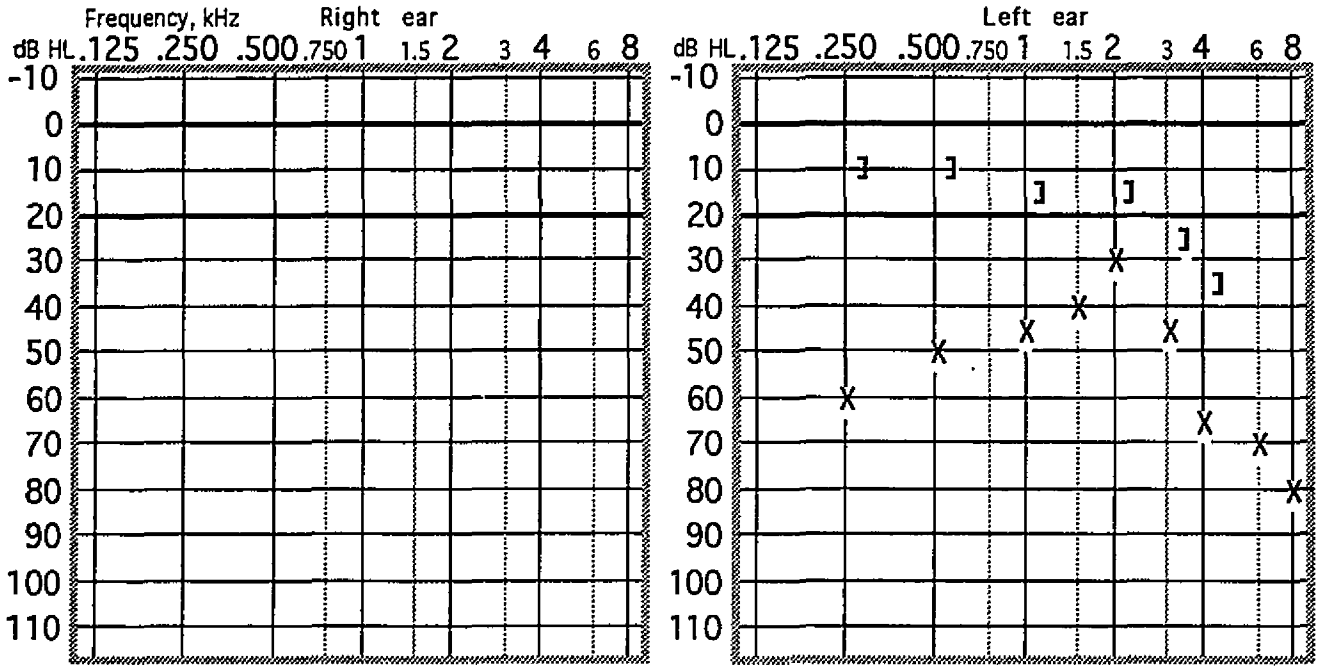
Name: PATIENT 3
Chart #: Age: 37
Wednesday, January 31, 1996 22:31
Tester: fggfgh
ANSI S3.6-1969 Virtual M320 #0210 Cal. 04/16/90



Legend	Unmasked	Masked
Air (phone) Right	O	Δ
Air (phone) Left	X	☐
Air (insert) Right	O	Δ
Air (insert) Left	X	☐
Bone Right	<	[
Bone Left	>	]

SF	MCL	UCL	No Resp
S	M	U	↙ ↘

Pure Tone Average

.5,1,2 kHz	Right	Left
Three freq.		41
Best two		37

	SRT	SDT	MCL	UCL
Air: Right	45 dB		80 dB	
Left				
SF: Unaided				
Right Aided				
Left Aided				

Recognition (Percent at dB HL)

Right	100 % 80 dB		
Left			
Bin			

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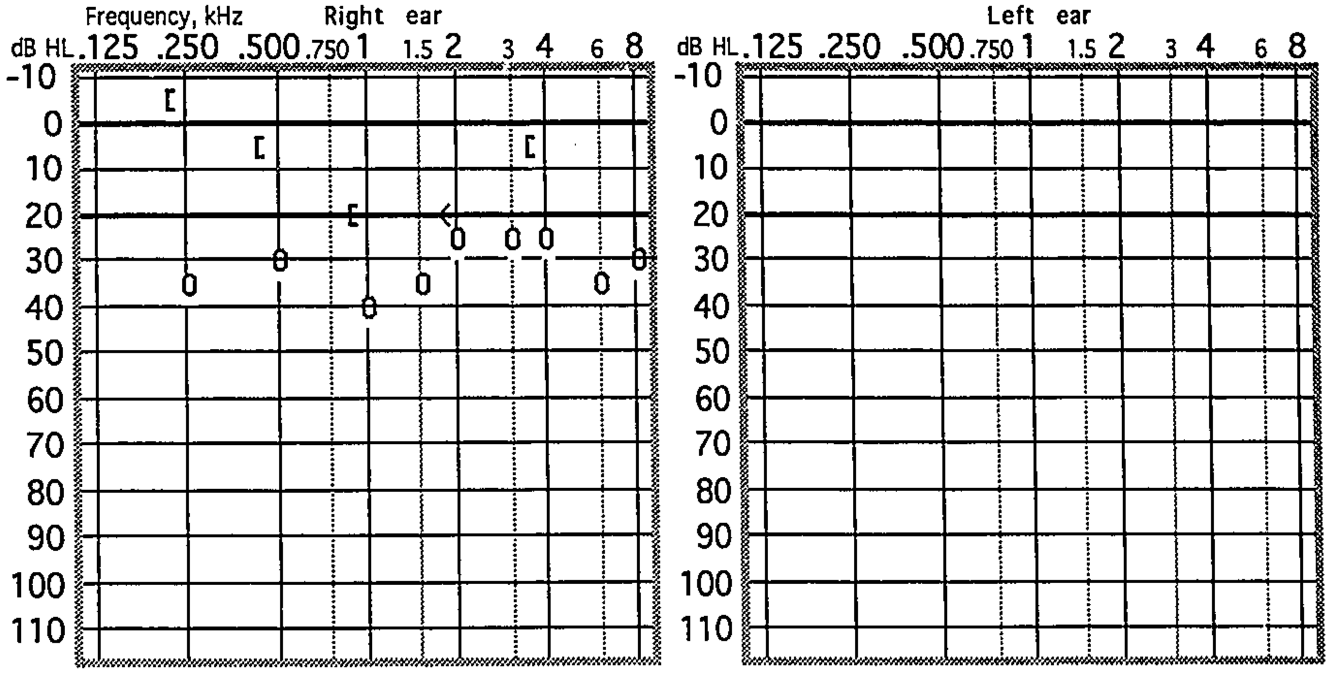
Name: PATIENT 4
Chart #: Age: 55
Wednesday, January 31, 1996 22:49
Tester: fggfgh
ANSI S3.6-1969 Virtual M320 #0210 Cal. 04/16/90



Pure Tone Average

.5,1,2 kHz	Right	Left
Three freq.	31	
Best two	27	

Legend

		Unmasked	Masked
Air (phone)	Right	O	Δ
	Left	X	▯
Air (insert)	Right	O	Δ
	Left	X	▯
Bone	Right	<	[
	Left	>	]

SF	MCL	UCL	No Resp
S	M	U	↙ ↘

	SRT	SDT	MCL	UCL
Air: Right	35 dB		65 dB	
Left				
SF: Unaided				
Right Aided				
Left Aided				

Recognition (Percent at dB HL)

Right	100 % 65 dB		
Left			
Bin			

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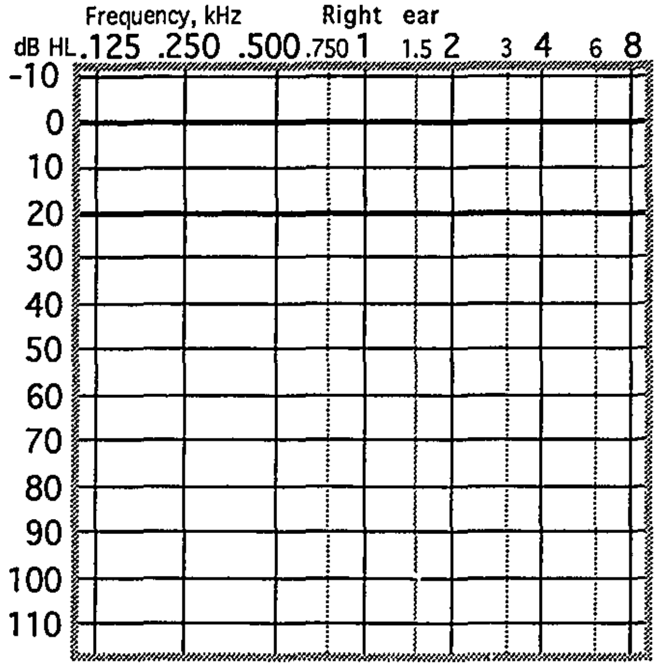
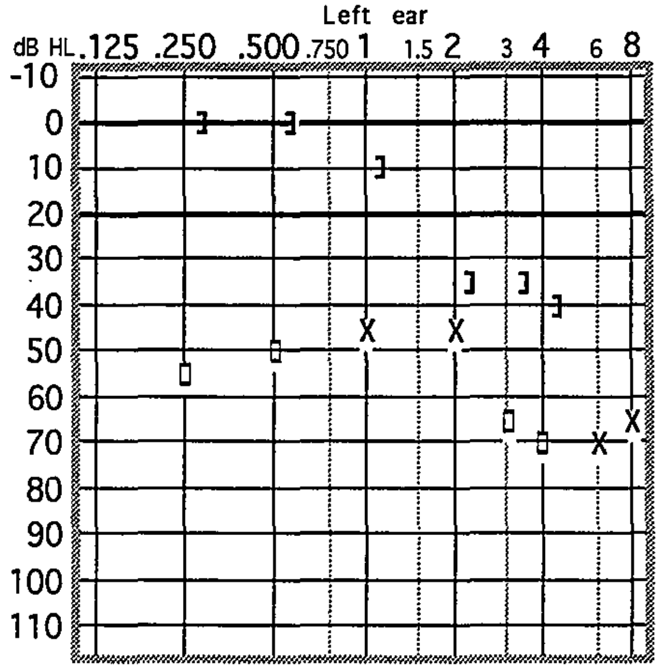
Name: PATIENT 5
Chart #: Age: 55
Wednesday, January 31, 1996 22:51
Tester: fggfgh
ANSI S3.6-1969 Virtual M320 #0210 Cal. 04/16/90





Legend		Unmasked	Masked
Air (phone)	Right	O	Δ
	Left	X	☐
Air (insert)	Right	O	Δ
	Left	X	☐
Bone	Right	<	[
	Left	>	]

SF	MCL	UCL	No Resp
S	M	U	↙ ↘

Pure Tone Average

.5,1,2 kHz	Right	Left
Three freq.		46
Best two		45

	SRT	SDT	MCL	UCL
Air: Right	50 dB		75 dB	
Left				
SF: Unaided				
Right Aided				
Left Aided				

Recognition (Percent at dB HL)

Right	88% 75 dB		
Left			
Bin			

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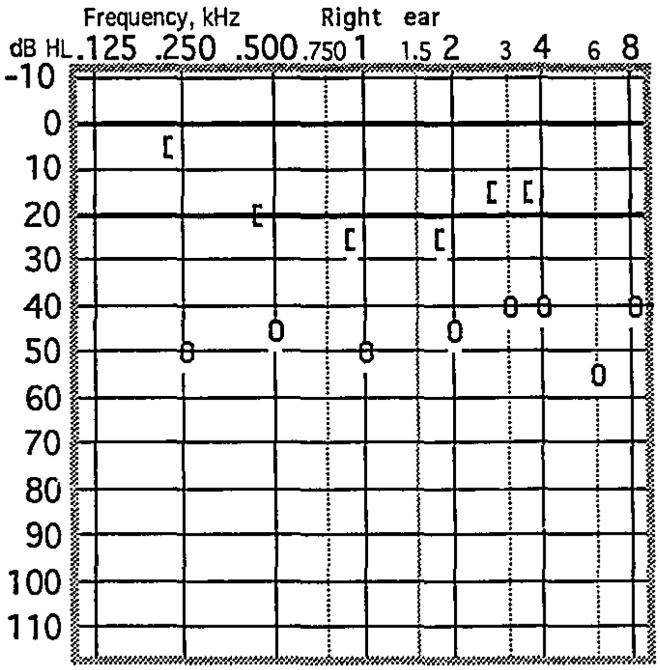
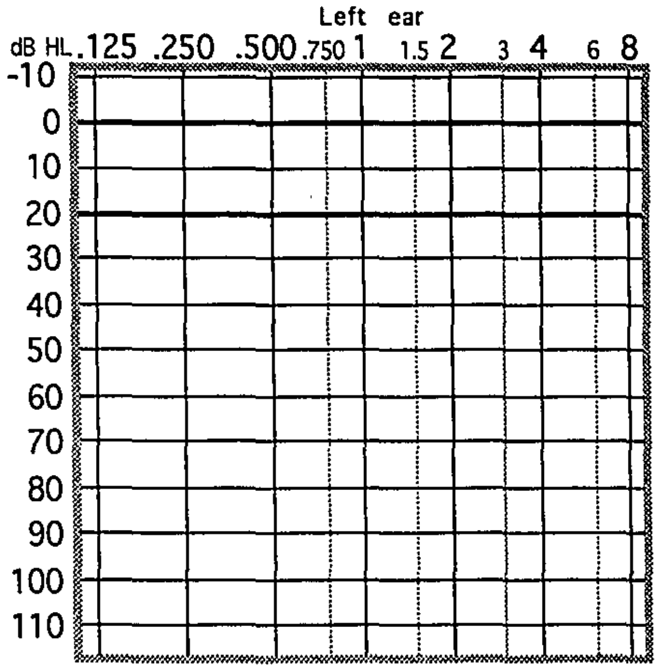
Name: PATIENT 6
Chart #: Age: 38
Wednesday, January 31, 1996 22:24
Tester: fggfgh
ANSI S3.6-1969 Virtual M320 #0210 Cal. 04/16/90





Legend

		Unmasked	Masked
Air (phone)	Right	O	Δ
	Left	X	□
Air (insert)	Right	O	Δ
	Left	X	□
Bone	Right	<	[
	Left	>	]

SF	MCL	UCL	No Resp
S	M	U	↙ ↘

Pure Tone Average

.5,1,2 kHz	Right	Left
Three freq.	46	
Best two	45	

	SRT	SDT	MCL	UCL
Air: Right	45 dB		80 dB	
Left				
SF: Unaided				
Right Aided				
Left Aided				

Recognition (Percent at dB HL)

Right	100% 80dB		
Left			
Bin			

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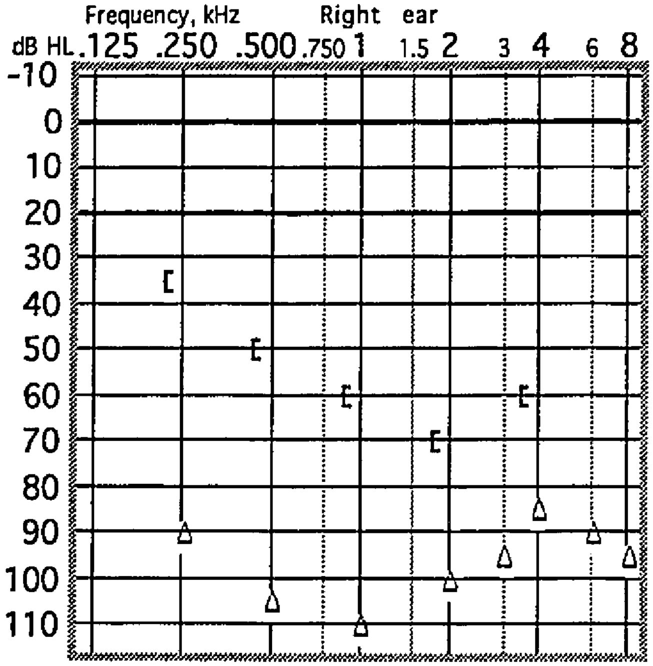
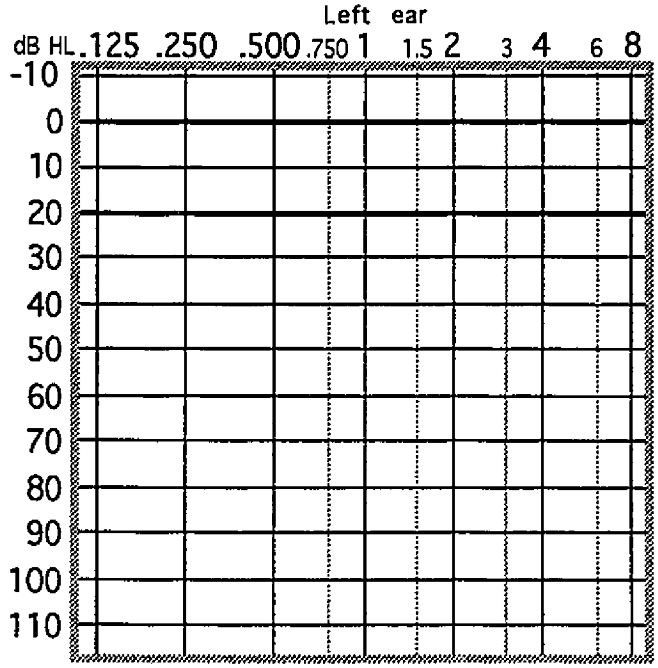
Name: PATIENT 7
Chart #: Age: 63
Wednesday, January 31, 1996 22:27
Tester: fggfgh
ANSI S3.6-1969 Virtual M320 #0210 Cal. 04/16/90





Legend

		Unmasked	Masked
Air (phone)	Right	O	Δ
	Left	X	▢
Air (insert)	Right	O	Δ
	Left	X	▢
Bone	Right	<	[
	Left	>	]

SF	MCL	UCL	No Resp
S	M	U	↙ ↘

Pure Tone Average

.5,1,2 kHz	Right	Left
Three freq.	105	
Best two	102	

	SRT	SDT	MCL	UCL
Air: Right	100 dB			
Left				
SF: Unaided				
Right Aided				
Left Aided				

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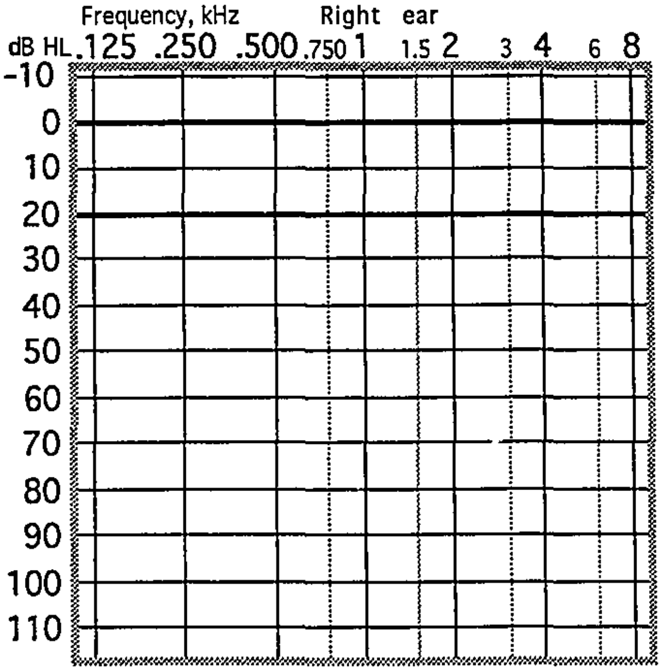
Name: PATIENT 8

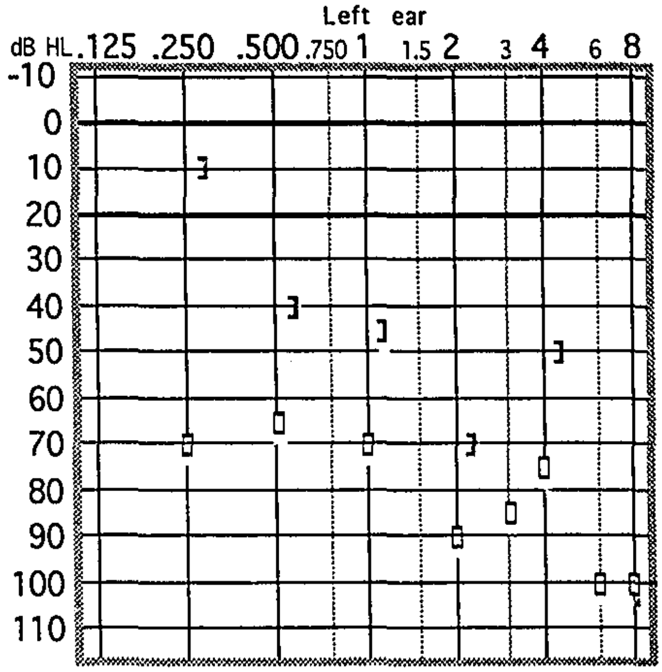
Chart #: Age:

Wednesday, January 31, 1996 22:54

Tester: fggfgh

ANSI S3.6-1969 Virtual M320 #0210 Cal. 04/16/90





Pure Tone Average

.5,1,2 kHz	Right	Left
Three freq.		75
Best two		67

Legend	Unmasked Masked	
Air (phone)	Right O Δ Left X □	
Air (insert)	Right O Δ Left X □	
Bone	Right < [Left >]	

SF	MCL	UCL	No Resp
S	M	U	↙ ↘

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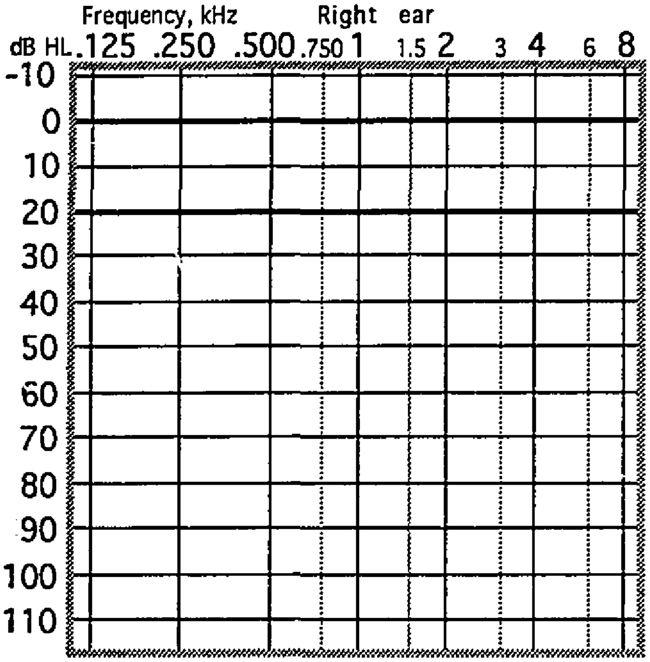
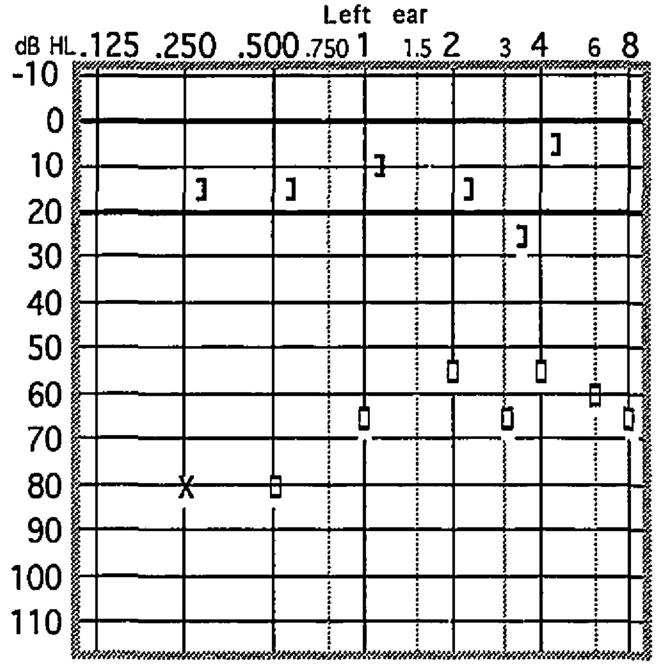
Name: PATIENT 9
Chart #: Age: 29
Wednesday, January 31, 1996 22:46
Tester: fggfgh
ANSI S3.6-1969 Virtual M320 #0210 Cal. 04/16/90





Pure Tone Average

.5,1,2 kHz	Right	Left
Three freq.		66
Best two		60

Legend		Unmasked	Masked
Air (phone)	Right	O	Δ
	Left	X	□
Air (insert)	Right	O	Δ
	Left	X	□
Bone	Right	<	[
	Left	>	]

SF	MCL	UCL	No Resp
S	M	U	↙ ↘

	SRT	SDT	MCL	UCL
Air: Right	60 dB		85 dB	
Left				
SF: Unaided				
Right Aided				
Left Aided				

Recognition (Percent at dB HL)

Right	92% 85 dB		
Left			
Bin			

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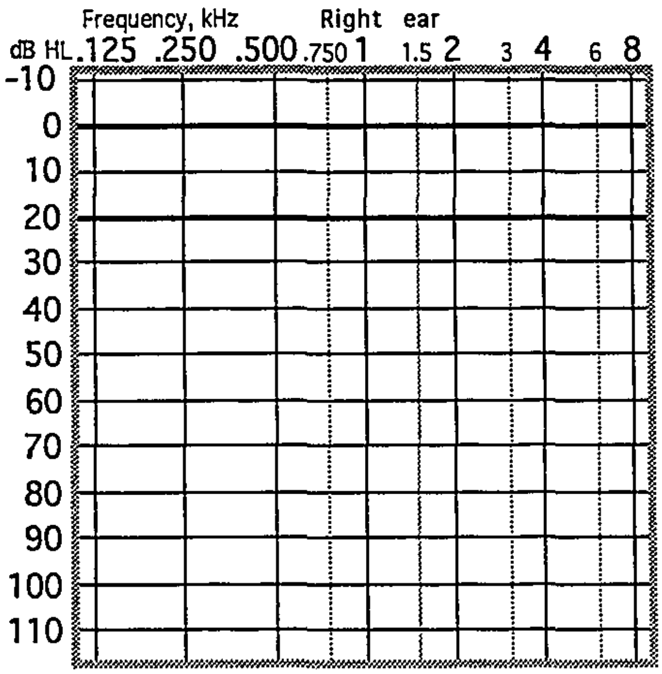
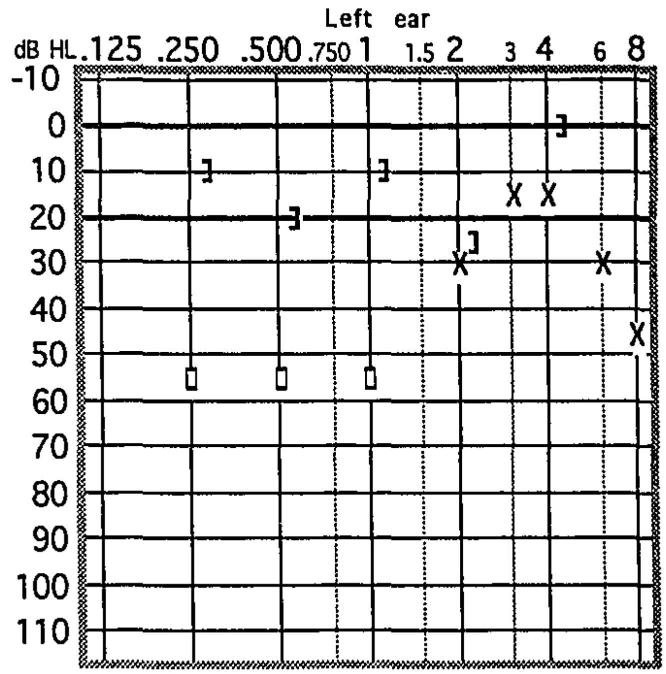
Name: PATIENT 10
Chart #: Age: 41
Wednesday, January 31, 1996 22:57
Tester: fggfgh
ANSI S3.6-1969 Virtual M320 #0210 Cal. 04/16/90





Legend		Unmasked	Masked
Air (phone)	Right	O	Δ
	Left	X	□
Air (insert)	Right		
	Left		
Bone	Right	<	[
	Left	>	]

SF	MCL	UCL	No Resp
S	M	U	

Pure Tone Average

.5,1,2 kHz	Right	Left
Three freq.		46
Best two		42

	SRT	SDT	MCL	UCL
Air: Right	35 dB			
Left				
SF: Unaided				
Right Aided				
Left Aided				

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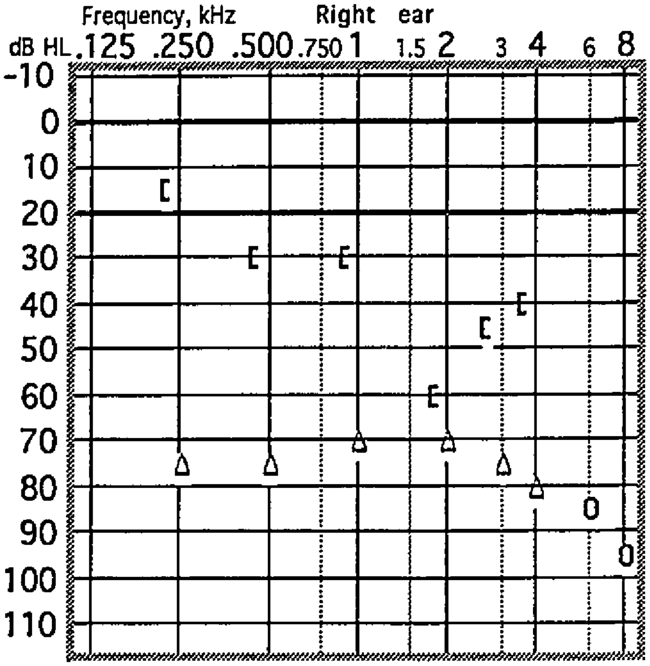
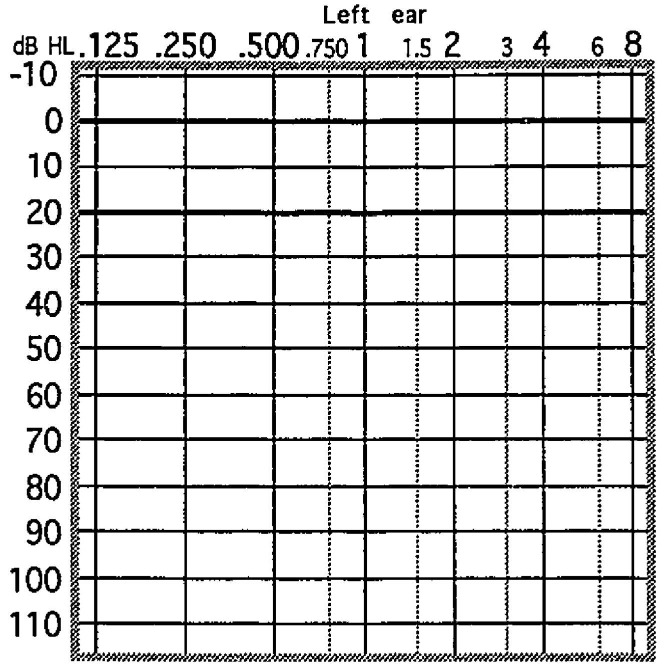
Name: PATIENT 11
Chart #: Age: 69
Wednesday, January 31, 1996 22:34
Tester: fggfgh
ANSI S3.6-1969 Virtual M320 #0210 Cal. 04/16/90





Pure Tone Average

.5,1,2 kHz	Right	Left
Three freq.	71	
Best two	70	

Legend		Unmasked	Masked
Air (phone)	Right	O	Δ
	Left	X	☐
Air (insert)	Right	O	Δ
	Left	X	☐
Bone	Right	<	[
	Left	>	]

SF	MCL	UCL	No Resp
S	M	U	↙ ↘

	SRT	SDT	MCL	UCL
Air: Right	70 dB		100 dB	
Left				
SF: Unaided				
Right Aided				
Left Aided				

Recognition (Percent at dB HL)

Right	96% 100 dB		
Left			
Bin			

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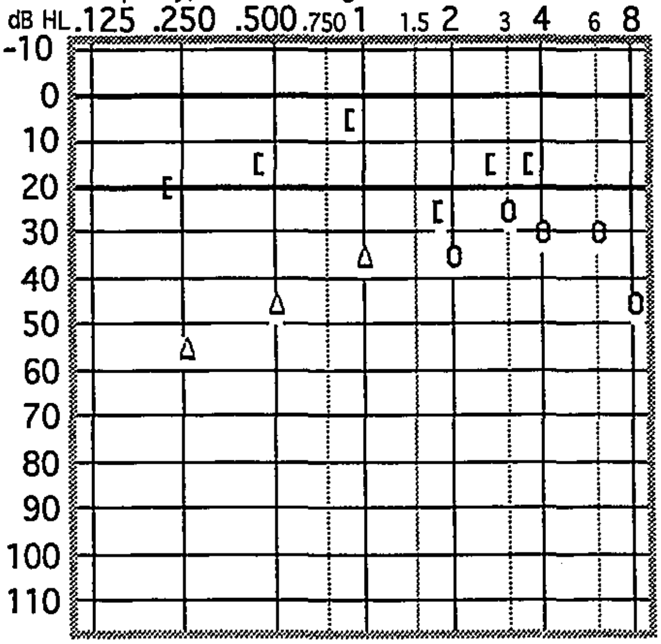
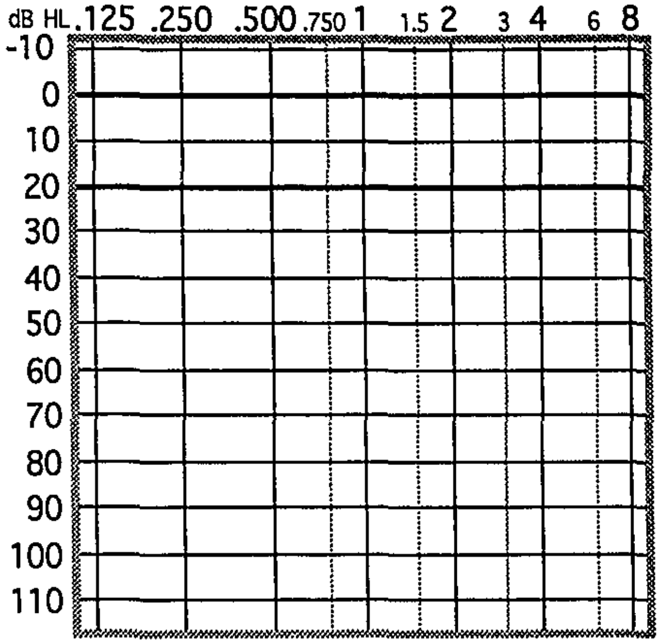
Name: PATIENT 12
Chart #: Age: 57
Wednesday, January 31, 1996 22:37
Tester: fggfgh
ANSI S3.6-1969 Virtual M320 #0210 Cal. 04/16/90





Legend

		Unmasked	Masked
Air (phone)	Right	O	Δ
	Left	X	□
Air (insert)	Right	O	Δ
	Left	X	□
Bone	Right	<	[
	Left	>	]

SF	MCL	UCL	No Resp
S	M	U	↙ ↘

Pure Tone Average

.5,1,2 kHz	Right	Left
Three freq.	38	
Best two	35	

	SRT	SDT	MCL	UCL
Air: Right	35 dB		75 dB	
Left				
SF: Unaided				
Right Aided				
Left Aided				

Recognition (Percent at dB HL)

Right	92% 75 dB		
Left			
Bin			

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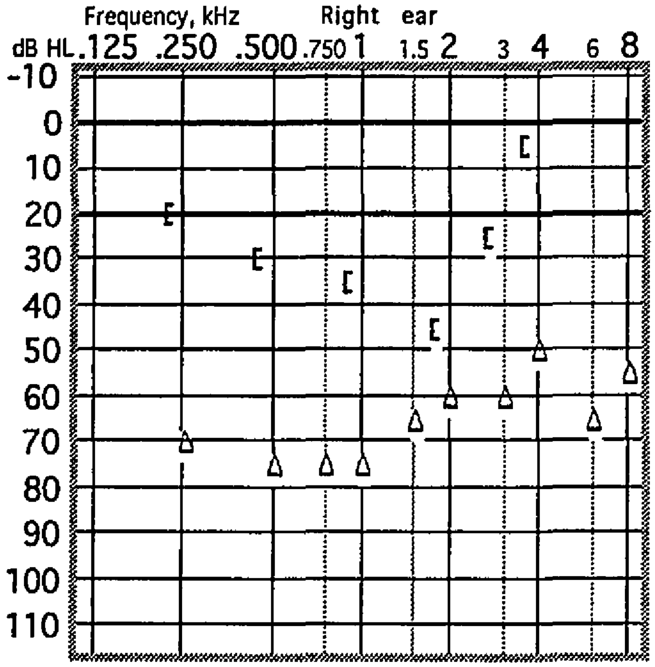
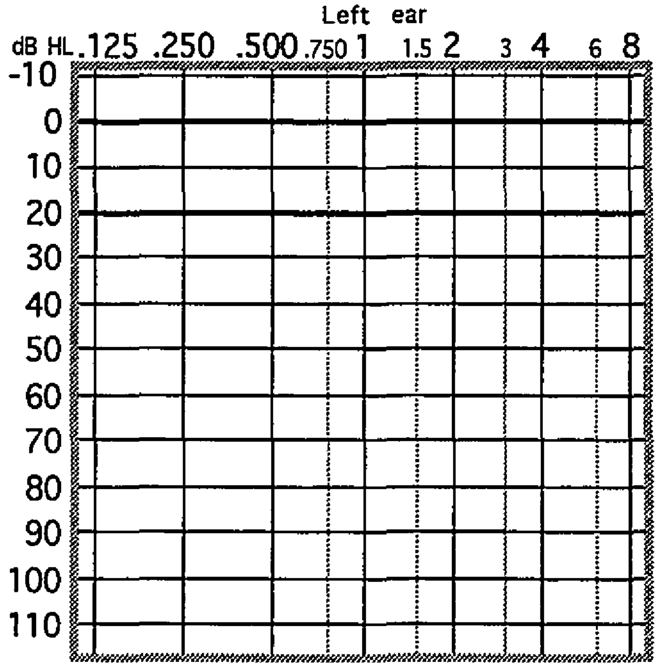
Name: PATIENT 13
Chart #: Age: 35
Wednesday, January 31, 1996 22:26
Tester: fggfgh
ANSI S3.6-1969 Virtual M320 #0210 Cal. 04/16/90





Pure Tone Average

.5,1,2 kHz	Right	Left
Three freq.	70	
Best two	67	

Legend

		Unmasked	Masked
Air (phone)	Right	O	Δ
	Left	X	□
Air (insert)	Right	O	Δ
	Left	X	□
Bone	Right	<	[
	Left	>	]

SF	MCL	UCL	No Resp
S	M	U	↙ ↘

	SRT	SDT	MCL	UCL
Air: Right	60 dB		95 dB	
Left				
SF: Unaided				
Right Aided				
Left Aided				

Recognition (Percent at dB HL)

Right	100% 95 dB		
Left			
Bin			

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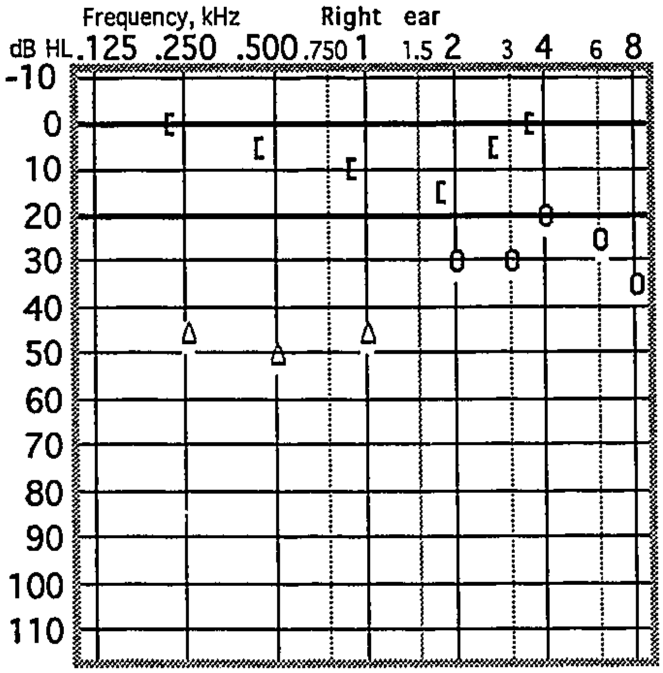
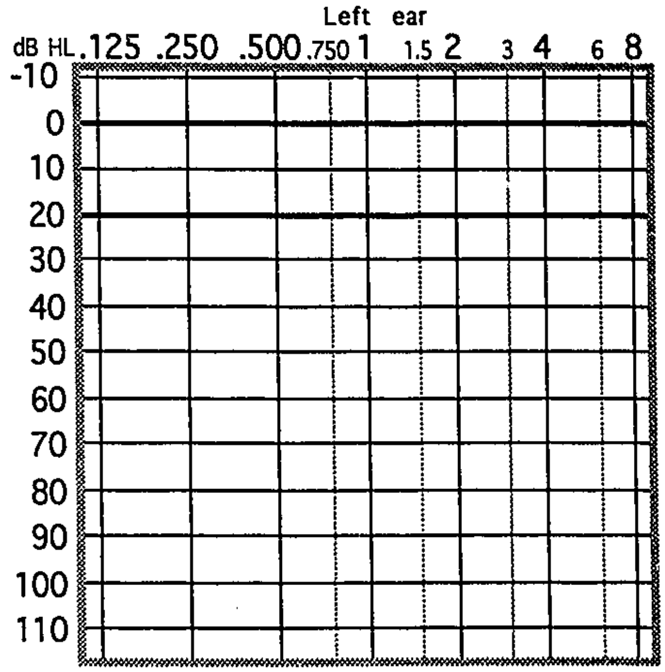
Name: PATIENT 14
Chart #: Age: 37
Wednesday, January 31, 1996 23:01
Tester: fggfgh
ANSI S3.6 -1969 Virtual M320 #0210 Cal. 04/16/90





Legend

		Unmasked	Masked
Air (phone)	Right	O	Δ
	Left	X	□
Air (insert)	Right	O	Δ
	Left	X	□
Bone	Right	<	[
	Left	>	]

SF	MCL	UCL	No Resp
S	M	U	↙ ↘

Pure Tone Average

.5,1,2 kHz	Right	Left
Three freq.	41	
Best two	37	

	SRT	SDT	MCL	UCL
Air: Right	35 dB		70 dB	
Left				
SF: Unaided				
Right Aided				
Left Aided				

Recognition (Percent at dB HL)

Right	96% 70 dB		
Left			
Bin			