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Multi-frequency Tympanometry

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. Currently available immittance instruments typically 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: compliance (the inverse of stiffness), mass, and friction. The first variable is the admittance offered by stiffness elements in the middle ear system which is called compliant susceptance and is denoted by B_c (also stiffness reactance, negative reactance, or $-X_s$ in impedance terms). The second variable is the admittance offered by mass elements in the middle ear system which 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) which store acoustic energy is the algebraic sum of the mass and compliance elements as plotted along the Y-axis in Figure 2-1 (right). That is,

(1) $B_{total} = B_m + B_c$ (Admittance terminology)

(2) $X_{total} = X_s + X_m$ (Impedance terminology)

In Figure 1 (left), the compliant 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 susceptance is positive, a system is stiffness controlled; if this value is negative, the system is mass controlled.

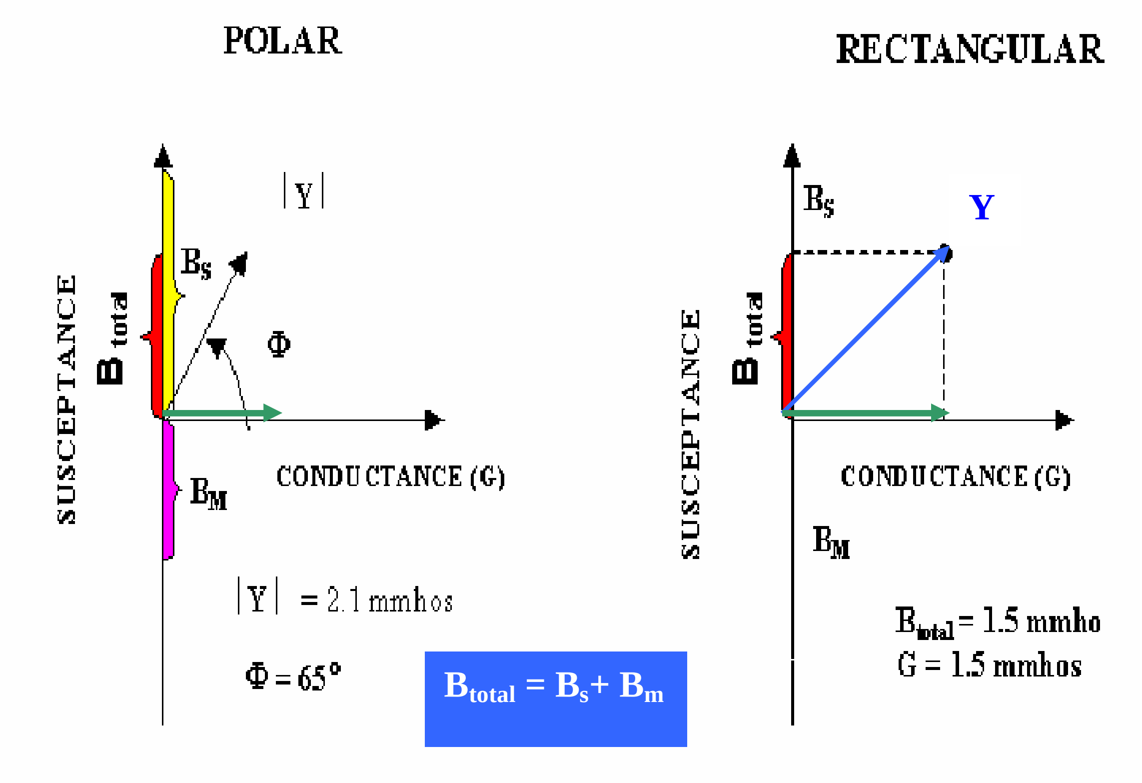


Figure : The admittance terminology [B_m: mass susceptance; B_C: stiffness susceptance; |Y|: absolute admittance magnitude; $Ø_y$: admittance phase angle].

The third variable, friction, determines the absorption or dissipation of acoustic energy. In admittance terms, 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 two dimensional quantity and is a vector sum of conductance (G) and the total susceptance (B_t). Mathematically, admittance can be expressed in rectangular notation or in polar notation. In rectangular notation, admittance is expressed as the sum of its conductance (G) and susceptance (B_t) elements. Thus, acoustic admittance and impedance in rectangular notation can be expressed as:

(3) $Y = G + jB_t$ (Admittance terminology)

(4) $Z = R + jX_t$ (Impedance terminology)

Where j is equal to $\sqrt{-1}$ in complex number notation and indicates that conductance and susceptance cannot 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 magnitude and phase angle. The angle formed by the admittance vector and the horizontal axis in Figure 2-1 (right) is denoted by the phase angle, $Ø_y$. Thus, acoustic admittance in polar notation can be expressed as:

(5) $|Y| \angle Øy$ (Admittance terminology)

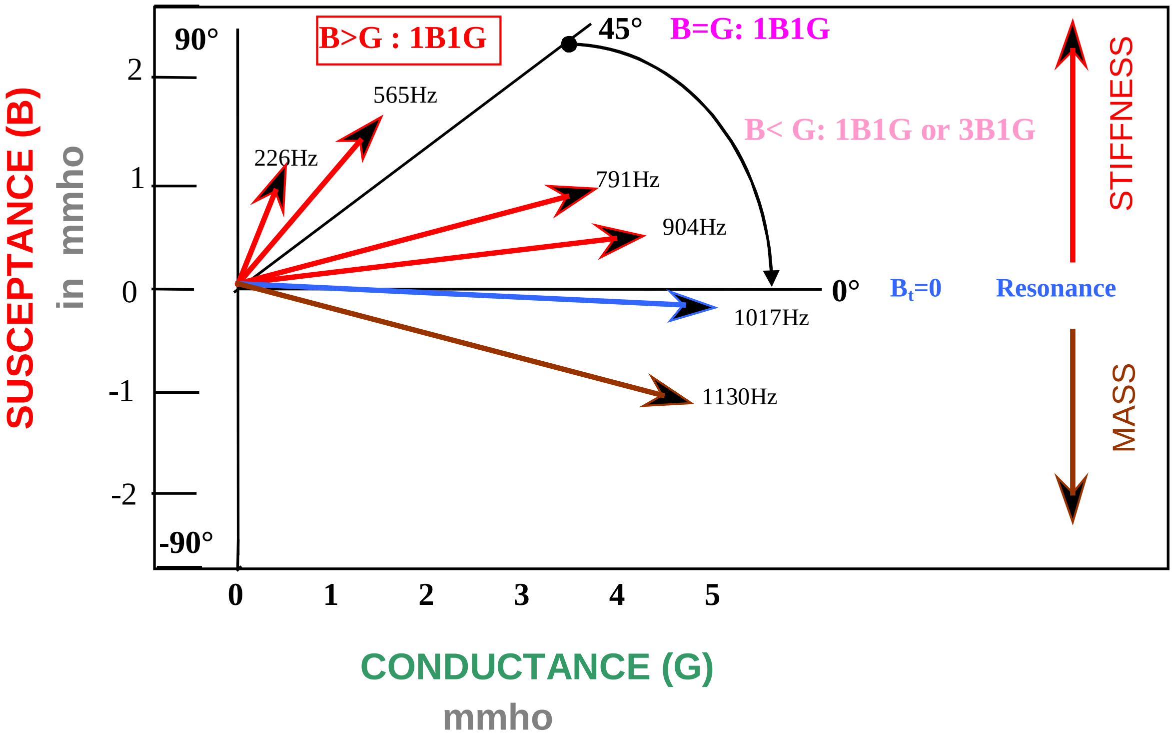
(6) $|Z| \angle Øz$ (Impedance terminology)

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

Admittance_Y
|Y| < Øy (Polar notation) $G + jB_t$ (Rectangular notation) G= |Y| Cos Øy B= |Y| Sin Øy $Y_{tm} = \sqrt{G_{tm}^2 + B_{tm}^2}$ Tan Øy= B/G Øy= 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, using tympanometry, the resonant frequency of the normal adult ear has been reported to fall as low as 630 Hz and as high as 2000 Hz (Margolis & Goycoolea, 1993).

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.



Multifrequency, multicomponent tympanometry.

The 220 or 226 Hz probe tone frequency used in standard tympanometry was originally selected partly for ease of calibration and not because it necessarily provided the most clinically useful information (see Terkildsen & Thomson, 1959). With the appearance of commercially available computer based tympanometry instruments, it is now 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 (Colletti, 1977; Funasaka & Kumakawa, 1988; Hunter & Margolis, 1992; Lilly, 1984; Valvik et al., 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 at 678 Hz in normal ears and in various pathologies. Later, this model was extended to higher probe tone frequencies (Margolis & Goycoolea, 1993). 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 peaks or extrema on the susceptance (B) tympanogram and the conductance (G) tympanogram and predicts four tympanometric patterns at 678 Hz. The patterns are denoted by the number of extrema on the B and G tympanograms. For example, the

1B1G pattern (Figure 3A) 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.

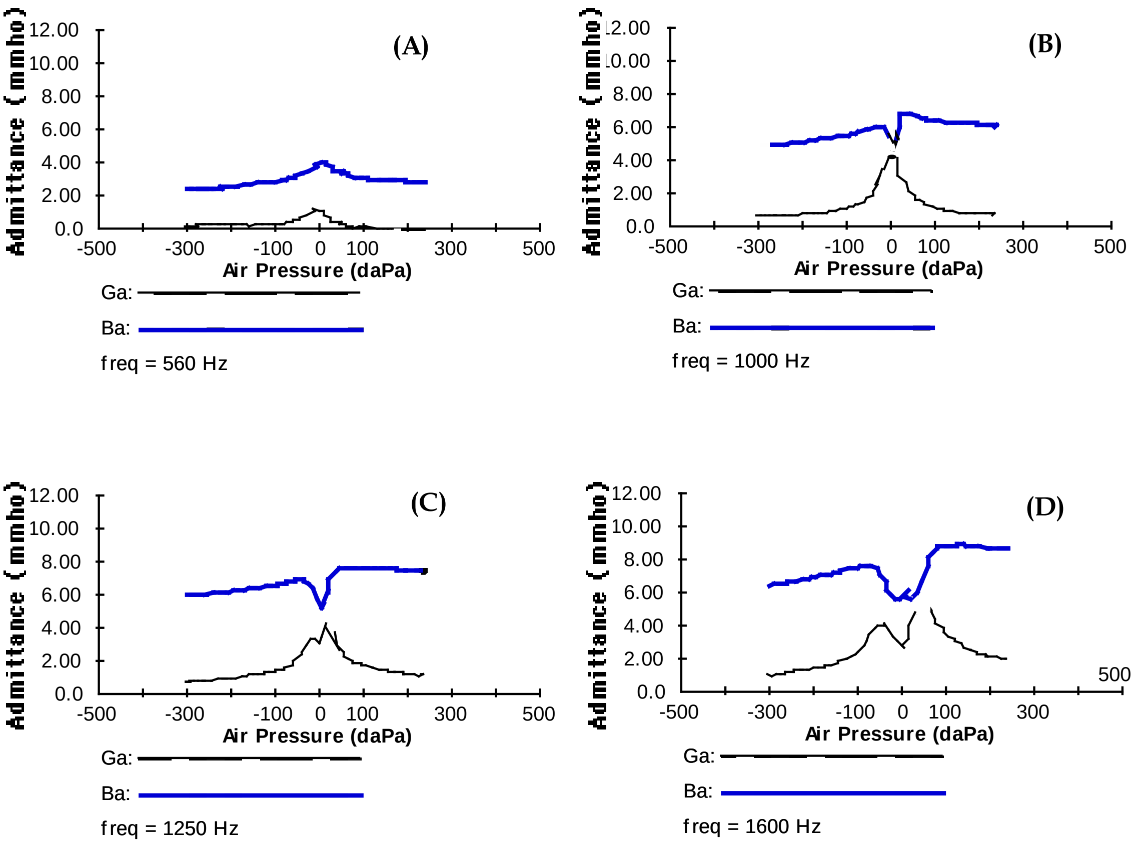


Figure 3:The Vanhuyse et al. (1975) model showing four patterns for susceptance (B_a) and conductance (G_a) tympanograms, 1B1G (A); 3B1G (B); 3B3G (C); and 5B3G (D).

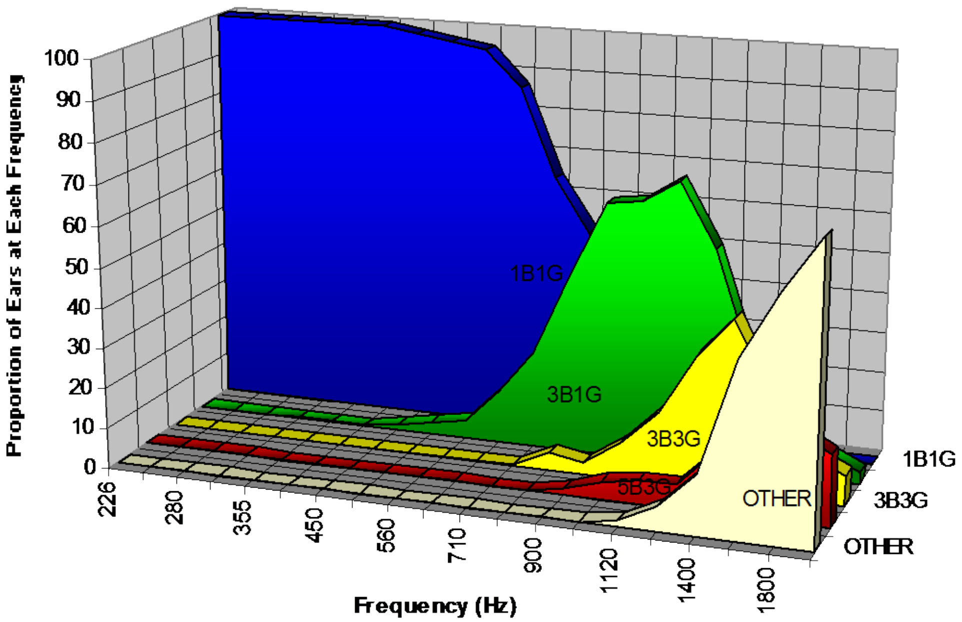
The next pattern observed is 3B1G (Figure 3B), which has three extrema on the susceptance (B) tympanogram (two peaks on the side of a notch in the middle) and has a single peak on the conductance (G) tympanogram. The admittance tympanogram will also have one peak. When this pattern is observed, the ear 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. The middle ear is stiffness controlled when the central notch on the susceptance tympanogram is <u>above</u> either the positive or the negative tail, depending on which extreme is chosen to estimate ear canal volume.

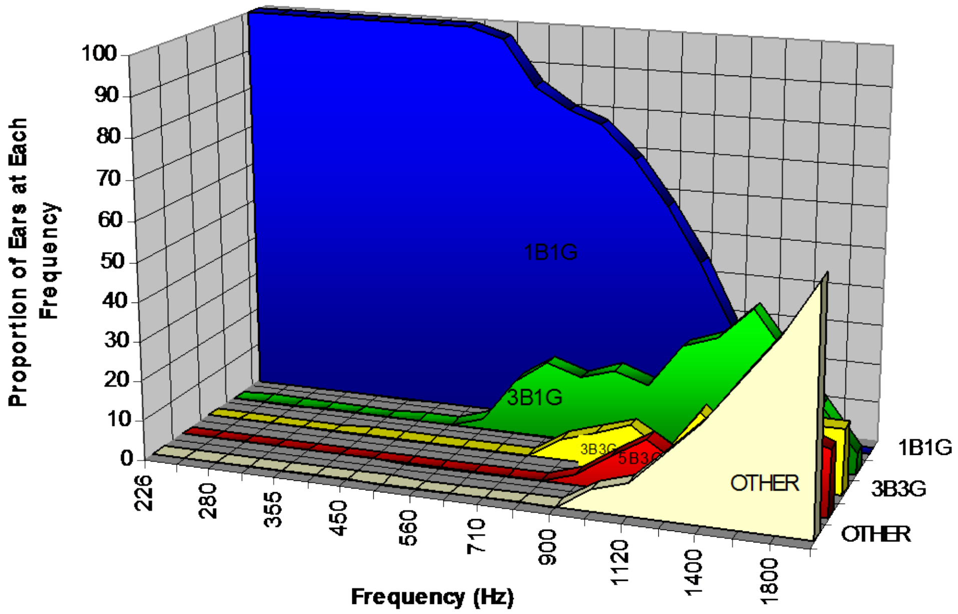
In the 3B3G (Figure 3C) pattern, the susceptance and the conductance tympanograms each have three peaks. The admittance tympanogram will also have three peaks, i.e., it will have a notch. When this pattern is observed, the ear is either at resonance or is mass dominated, i.e., the admittance phase angle is between 0° and -45°. This in turn results in a deep notch on the susceptance tympanogram. The middle ear is at resonance when the central notch on B tympanogram is <u>equal</u> to either the positive or the negative tail as this indicates that susceptance is zero, whereas it is mass controlled when the central notch falls <u>below</u> either the positive or the negative tail as this indicates that susceptance is negative.

In 5B3G (Figure 3D) 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 just described is found as frequency is increased in both normal and abnormal middle ears (Margolis, Van Camp, Wilson, and Creten, 1985).

However, with pathologies the probe frequency at which each pattern occurs may be shifted higher or lower compared to normal ears (Shahnaz, 2001). For example, in a stiffening pathology such as otosclerosis (see Figure 4) in which the resonant frequency is shifted upward, each of the various patterns can be expected to occur at higher frequencies compared to normal ears.


Existence Regions for Vanhuyse Types in Healthy Ears

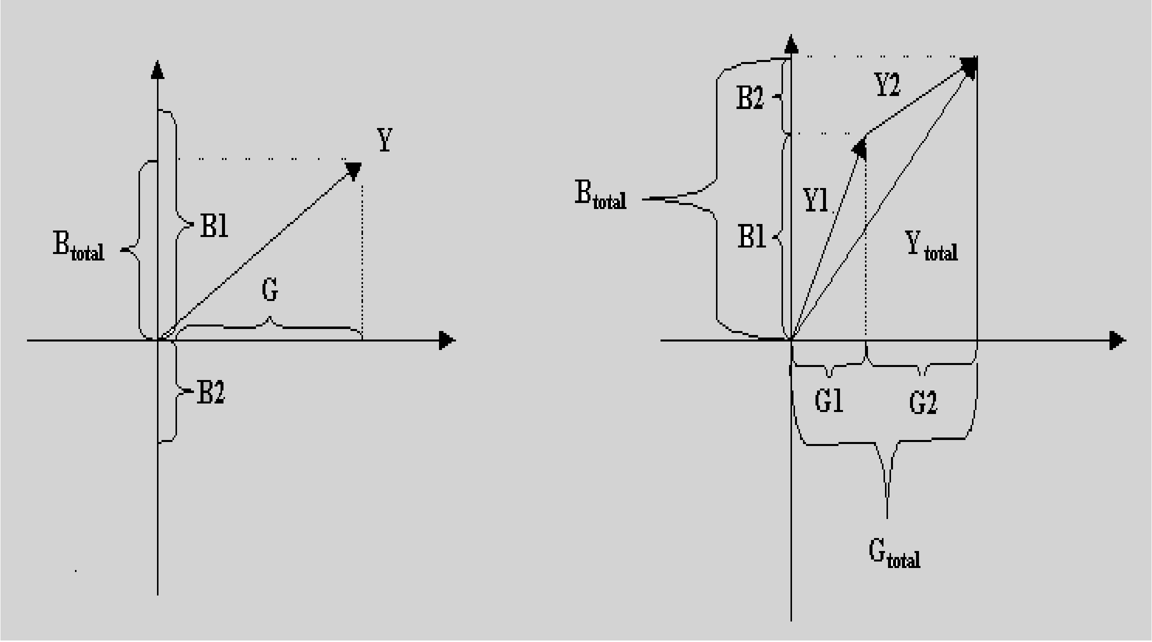

Existence Regions for Vanhuyse Types in Otosclerotic Ears

The Vanhuyse model also 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).

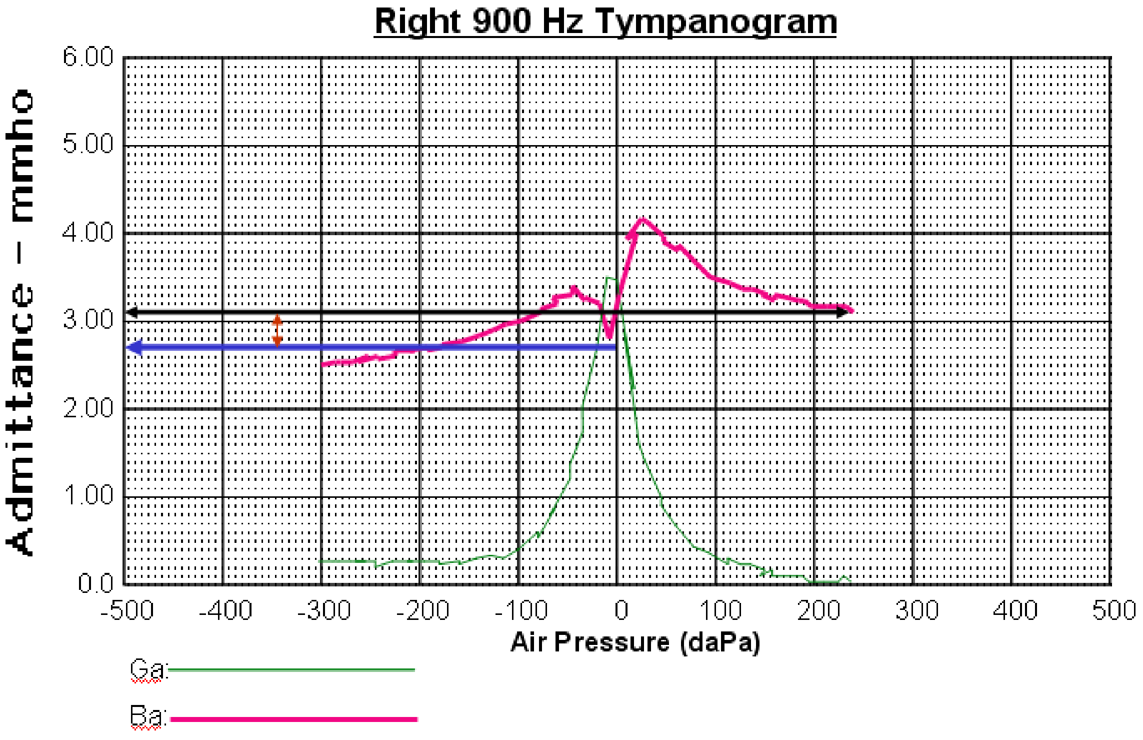
Besides resonant frequency, the frequency corresponding to other susceptance and conductance values or other phase angles can be obtained using multifrequency, multicomponent tympanometry. For example, as will be discussed further in section 4, there has been a recent interest in the frequency corresponding to a 45° phase angle (where susceptance and conductance are approximately equal) as a parameter for distinguishing normal ears and ears with ossicular chain pathology because of the limited range of frequency needed to calculate this index. Overall, there is much yet to be explored with respect to the clinical application of multifrequency, multicomponent tympanometry.

Guidelines For Measuring Static Admittance at Higher Probe Tone Frequencies

- Ear canal correction: Because admittance is a phasor (vector like) quantity, it cannot be added or subtracted unless the phase angle of the two admittance vectors (peak value and tail value) is identical.
- Subtracting admittance vector data at standard low probe tone frequency results in negligible error since the phase difference between the admittance vector of middle ear and the ear canal is small.
- At higher probe tone frequencies a marked error occurs because a significant phase shift for the admittance vector takes place (see Figure 4). Therefore, at higher probe tone frequencies it is necessary to compensate for the effect of ear canal from admittance rectangular components (susceptance and conductance), and then convert the data back to admittance vector (Margolis & Hunter, 1999; Shanks, Wilson, & Cabron, 1993).



- Ear canal volume should be estimated with the ear canal pressurized to the value that results in the minimum admittance value (MIN), however, if test re test reliability is an issue the + 200 daPa should be used.
- SA should be calculated at the ear canal pressure corresponding to the peak value for single peaked tympanograms (MAX). For notched admittance tympanograms, the static value should be calculated at the minimum (the notch value on the susceptance, see Figure 5) in the notch. When susceptance (B) and or conductance (G) tympanograms are notched, Static susceptance should be calculated at the ear canal pressure corresponding to the minimum in the susceptance notch.



- Either direction of ear canal pressure change can be used for tympanograms obtained with a low frequency probe (226 Hz). The decreasing (+/-) pressure direction, however, should be used with high frequency probe (e.g., 678 Hz) to minimize the occurrence of multipeaked tympanograms. In normal ears.
- Both admittance components (B & G) should be recorded simultaneously.

Recording & Measuring Multifrequency Tympanometry

Tympanograms can be obtained at higher probe tone frequencies, by means of sweep frequency recording and sweep pressure recording procedures. In the sweep frequency procedure, admittance magnitude is measured while air pressure in the external ear canal is decreased from +250 daPa to -300 daPa in discrete daPa steps (see Figure 6). At each step, the probe tone frequency swept through a series of probe tones progressing from low to high frequencies. In the sweep pressure method, air pressure of the external ear canal is decreased continuously from positive to negative pressure direction (it is recommended to use this pressure direction at higher probe tone frequencies to reduce the likelihood of notched tympanograms) at a given pressure rate, e.g., 125 daPa/sec (fast pump speed) while the probe tone frequency is held constant.

Multifrequency Tympanometry Parameters

- Tympanometric configuration - Vanhuyse Pattern
    - Vanhuyse, Creten, & Van Camp (1975) developed a model which predicts the shape of susceptance (B) and conductance (G) tympanograms at 678 Hz in normal ears and in various pathologies

- The Vanhuyse model categorizes the tympanograms based on the number of peaks or extrema on the susceptance (B) tympanogram and the conductance (G) tympanogram and predicts four tympanometric patterns at 678 Hz
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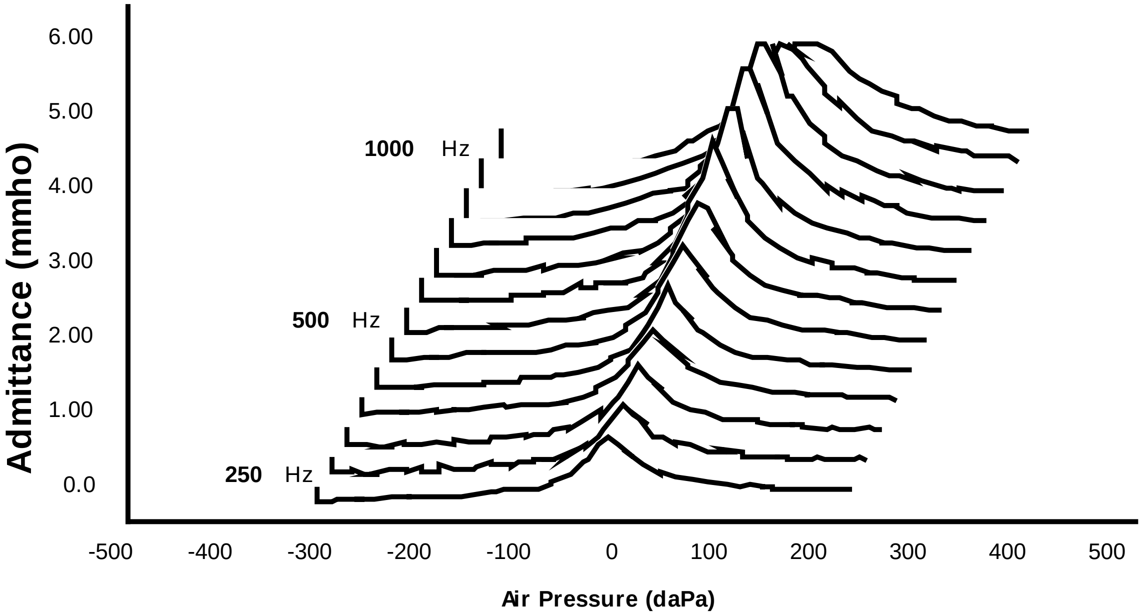
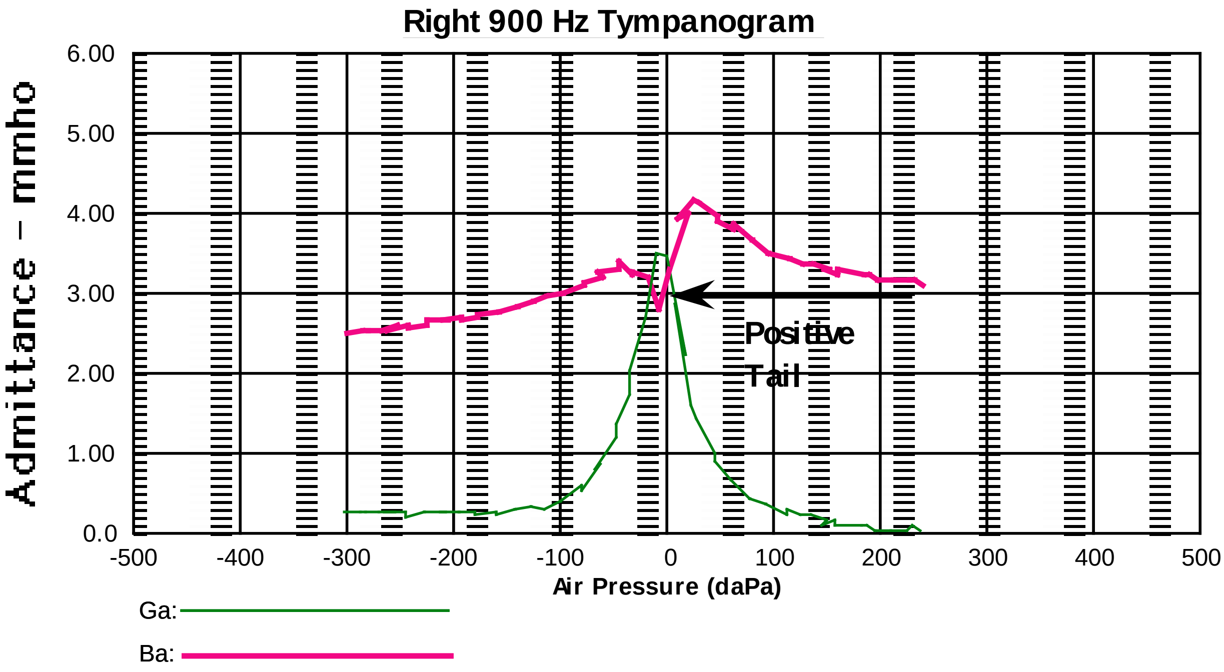
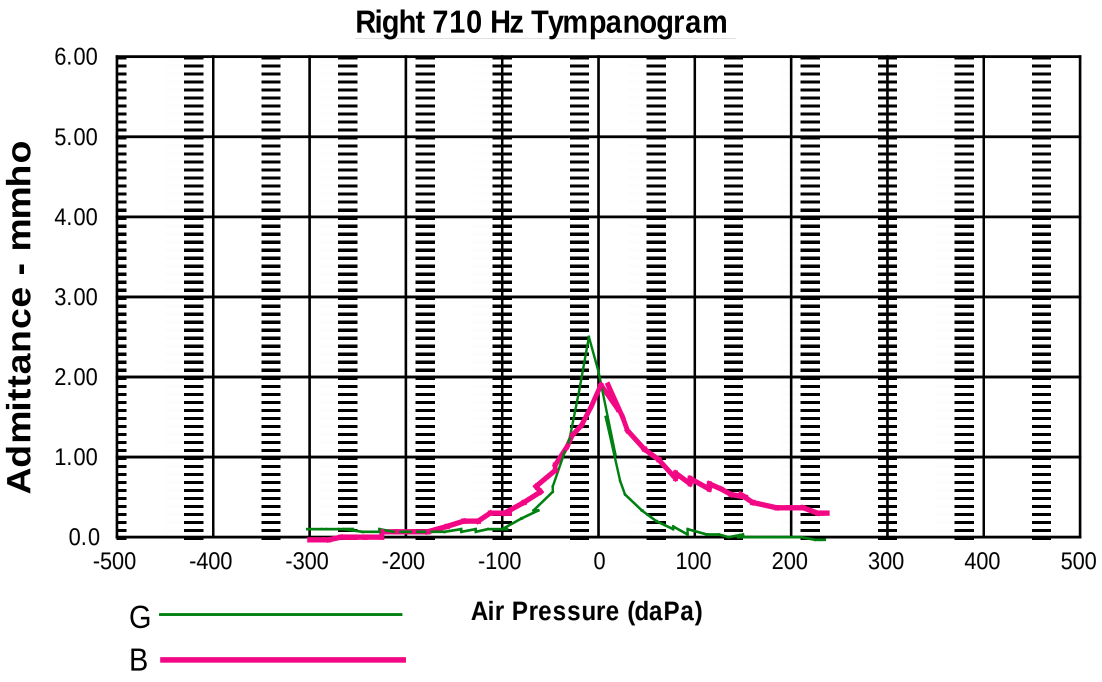


Figure 6. Multifrequency tympanograms (sweep frequency) from a normal adult.

- Resonant frequency (RF):Is the frequency at which the total susceptance is zero. The resonant frequency of the middle ear system may be shifted higher or lower compared to healthy ears by various pathologies
  - Resonant is directly proportional to the stiffness of the middle ear system, e.g., Otosclerosis increases the resonant frequency of the middle ear
  - Resonant is inversely proportional to the mass of the middle ear system
  - Resonant frequency can be measured from the susceptance tympanogram. Whenever the notch value on the susceptance tympanogram becomes equal to a positive tail (positive compensation) or negative tail (negative compensation) the total susceptance is zero and the system is at resonant frequency (see Figure 7)



- Frequency corresponding to admittance phase angle of 45 degree (F45°)
    - This parameter may also be shifted higher or lower by various middle ear pathologies. Preliminary findings suggest that the frequency corresponding to a 45° phase angle may be a better index than resonant frequency with respect to distinguishing healthy ears from otosclerotic ears (Shanks, Wilson, & Palmer, 1987; Shahnaz, Polka, 1997). This parameters can also be measured from susceptance and conductance tympanograms. F45° is a frequency at which compensated (for the effect of the ear canal) susceptance becomes equal to conductance tympanogram (see Figure 8)



Resonant Frequency Norms

Margolis & Goycoolea (1993) Adults	**SF+** (+200 daPa)	**SF-** (-500 daPa)	**SP+** (+200 daPa)	**SP-** (-500 daPa)
Mean	1135	1315	990	1132
Criteria	< 800 Hz & >2000 Hz	< 710 Hz & > 2000 Hz	< 630 Hz & > 1400 Hz	< 710 Hz & > 2000 Hz
90% Range	800 - 2000	710 - 2000	630 - 1400	710 - 2000
Shahnaz & Polka (1997) Adults	**SF+** (+250 daPa)	**SF-** (-300 daPa)	**SP+** (+250 daPa)	**SP-** (-300 daPa)
Mean	894	1043	789	924
Criteria	< 630 Hz & >1120 Hz	< 710 Hz & > 1400 Hz	< 560 Hz & > 1000 Hz	< 630 Hz & > 1250 Hz
90% Range	630 - 1120	710 - 1400	560 - 1000	630 - 1250

Frequency corresponding to admittance phase angle of 45 degree (F45°)

Age Group	SF (Hz)	SP (Hz)
Adults > 18 yrs Shahnaz & Polka (1997)	Mean = 615 90 % range: 400-870 < 400 Hz & > 870 Hz	Mean = 508 90 % range: 355-686 < 400 Hz & > 870 Hz