

Using the 1000-Hz probe tone for immittance measurements in infants

By Johannes Lantz, Michelle Petrak, and Laura Prigge

Recent studies using high-frequency immittance measurements have led to clinical recommendations for middle ear assessment in infants. This is especially important in light of the proliferation of universal neonatal hearing screening programs. This article examines the theory of immittance and the differences between infant and adult middle ear anatomy. It is designed to introduce readers to the high-frequency immittance concepts and their application to infant middle ear assessment.

Fundamentals of immittance

“Impedance” is a collective term for the reciprocals “impedance” and “admittance.” Impedance (measured in ohms) is the opposition to energy flow into a medium and admittance (measured in mhos) is consequently the ease with which energy flows into a medium. In modern middle ear analyzers, admittance is the property that is displayed.

Impedance measurements were first developed in the 1950s by Terkildsen and co-workers to measure middle ear pressure. Over time, the contribution of impedance measurement to clinical diagnostics has become highly valued and it is now a routine part of the audiologic test battery.

The purpose of the middle ear system is to adapt the impedance of air to the impedance of the lymphatic fluids of the inner ear. Without a good impedance match between the two media, much of the incoming acoustic energy will be reflected at the plane of the mismatch and hearing will be compromised. Impedance measurements are used to assess middle ear function by determining whether a normal amount of acoustic energy is transferred through, or reflected from, the middle ear system.

An impedance instrument principally consists of an air pump, a probe with speakers, a microphone, and a manometer. A probe tone is continuously delivered into the ear by one of the probe speakers and the acoustic impedance of the ear is analyzed through monitoring of the probe-tone sound pressure level in the ear canal by means of the probe microphone.

Under optimal conditions for sound transfer and hearing, little sound energy is reflected at the tympanic membrane – the middle ear input. However, under less favorable conditions, a greater portion of the delivered probe tone is reflected back to the probe microphone. During impedance monitoring, some well-defined alterations are made, either an air pressure sweep (tympanometry) or presentations of stapedius reflex-eliciting stimuli (acoustic reflex measurements). The resulting probe-tone reflections are compared with normal

middle ear responses to such pressure sweeps or reflex stimuli.

The resulting amplitude and phase of the reflected probe tone depend on the extent to which the different parts/properties of the middle ear contribute to the transfer or reflection of the particular sound. The mechanic/acoustic middle ear system consists of anatomic structures that increase the force of the incoming sound wave vibrations to match the impedance and transfer the sound successfully into the fluid medium of the cochlea.

Three fundamental properties define the system’s response to incoming sound: compliance, mass, and friction.

- Compliance elements include the tympanic and round window membranes, the ossicular ligaments, the middle ear muscles, and the air in the ear canal and middle ear. These structures transfer the vibration in spring-like movements: compressing and expanding, stretching and slackening. Compliance is the inverse of stiffness.
- Mass elements comprise the ossicles and the air in the middle ear mastoid air cells moving as units without compression or expansion. These are structures with mass inertia.
- Friction is the cause of energy loss through dissipation into heat. All real-life mechanical systems include friction. Energy loss through friction occurs when molecules in motion collide and rub against each other.

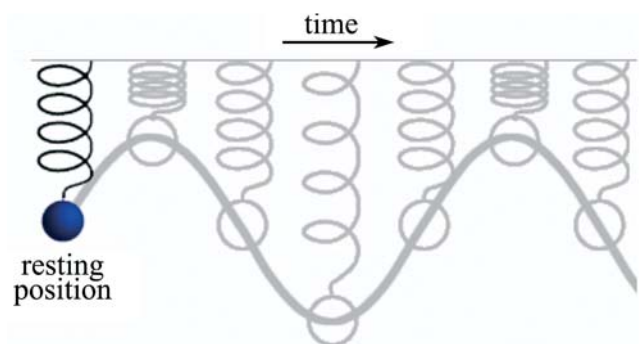


Figure 1. An illustration of the interaction of compliance susceptibility and mass susceptibility.

Susceptance: the interaction of compliance and mass

First we will take a closer look at the compliance and mass elements. The relationship between mass and compliance is best illustrated by a compliant spring with a mass attached to its end (Figure 1). When this basic system is set into motion, the moving mass continues moving forward due to its inertia, gradually transferring its kinetic energy into the spring.

Eventually, when all the kinetic energy is transferred into spring tension, the system reaches one extreme end of its cycle. The energy that is now stored in the spring will change the direction of the movement and start a new, reversed cycle, gradually transferring the energy back into the mass and so on.

If no external force is applied to influence the movement of the system once it has been put into motion, as described above, the system will oscillate back and forth spontaneously at its “resonant frequency.” In order to move the same system more slowly than the resonant frequency, the spring will be the opposing factor of movement. The system is said to be “stiffness-controlled” at these lower frequencies. For the system to be moved faster than the resonant frequency, the mass would be the opposing factor. At these higher frequencies, the system is said to be “mass-controlled.”

The interaction between the compliance elements and the mass elements is called “susceptance” (B). Susceptance is positive at lower frequencies when the system is stiffness-controlled and negative when it is controlled by mass at higher frequencies. At resonance, susceptance is zero.

Conductance

The description above is, of course, simplified since we cannot have a system without friction. If there were no friction, the illustration of mass and compliance at the resonant frequency would be a perpetual motion system that, once started, would continue to oscillate forever. The impact of friction elements is called conductance (G). Since friction cannot be negative, conductance can never take a negative value.

Admittance

The susceptance (B) and conductance (G) components fully determine the admittance (Y) of the system. The admittance is the vector length when plotting susceptance and conductance coordinates in a Cartesian coordinate system (Figure 2).

The conductance component is in phase with the delivered probe tone, whereas the susceptance is an “out-of-phase” component. Consequently, the susceptance can be separated from the conductance by analyzing the phase of the reflected probe tone. This has been used in some middle ear analyzers to plot B/G tympanograms (Figure 3). From the Cartesian graph, it is apparent that the admittance (Y) is always defined by the quantities of the fundamental components, susceptance, and conductance. This is the underlying physical rationale, regardless of which curves are presented in the middle ear analyzer.

The 226-Hz probe tone

The most commonly used probe-tone frequency is 226 Hz. This probe tone has some definitive advantages for testing the adult ear because the adult middle ear system is stiffness-controlled at this frequency. The frequency 226 Hz is below the normal adult resonance, which lies between 650 and 1400 Hz, so the effects of mass and friction are minor. Due to the negligible contribution of mass and friction, most instruments have even labeled their admittance results “compliance.”

The 226-Hz curves are typically single-peaked and result in easy-to-interpret tympanograms. Moreover, the acoustic reflexes can be reliably assessed when using a probe tone that is well below resonant frequency. The admittance change associated with activating the stapedius muscle is very small and could easily be underestimated with the phase shift that occurs in the vicinity of the resonant frequency.¹ These phase shifts are negligible at 226 Hz.

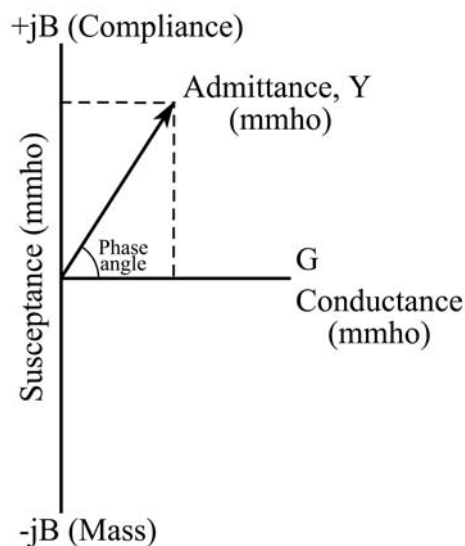


Figure 2. Cartesian plot showing the admittance magnitude at given susceptance and conductance values.

Another advantage of this probe tone, and the very reason why 226 Hz was originally chosen, is that the true compliance value at this frequency is numerically equal to an enclosed volume of air. This is utilized for calibration purposes, since the admittance is 1 mmho when measured in a 1-cc cavity of air. And by using air pressure, e.g., at +200 daPa, to create an impedance mismatch at the level of the tympanic membrane and thereby prohibiting the sound transfer through the middle ear, one can obtain the equivalent ear canal volume (ECV) in cubic centimeters.

Most diagnostic immittance instruments offer only a 226-Hz probe tone, although it has been shown that other probe frequencies can obtain different results.²⁻⁵

Multiple-frequency tympanometry

Multiple-frequency tympanometry (MFT) is a method in which the probe tone is swept through a series of frequencies, e.g., from 250 to 2000 Hz. Through MFT it is possible to assess the resonant frequency of the middle ear system. The resonant frequency is the probe-tone frequency at which susceptance becomes zero due to the counteractive forces of its compliance and mass elements.

The frequency can be determined from the measurement where the notch of the baseline compensated B curve reaches

zero. The mean adult resonant frequency is about 900 Hz. As mentioned, the middle ear system is stiffness-controlled below and mass-controlled above this frequency, depending on which susceptance element (mass or compliance) is more prominent.⁶ The changes in resonant frequency are sometimes used to assess the pathology of the adult middle ear system, especially of the ossicular chain.

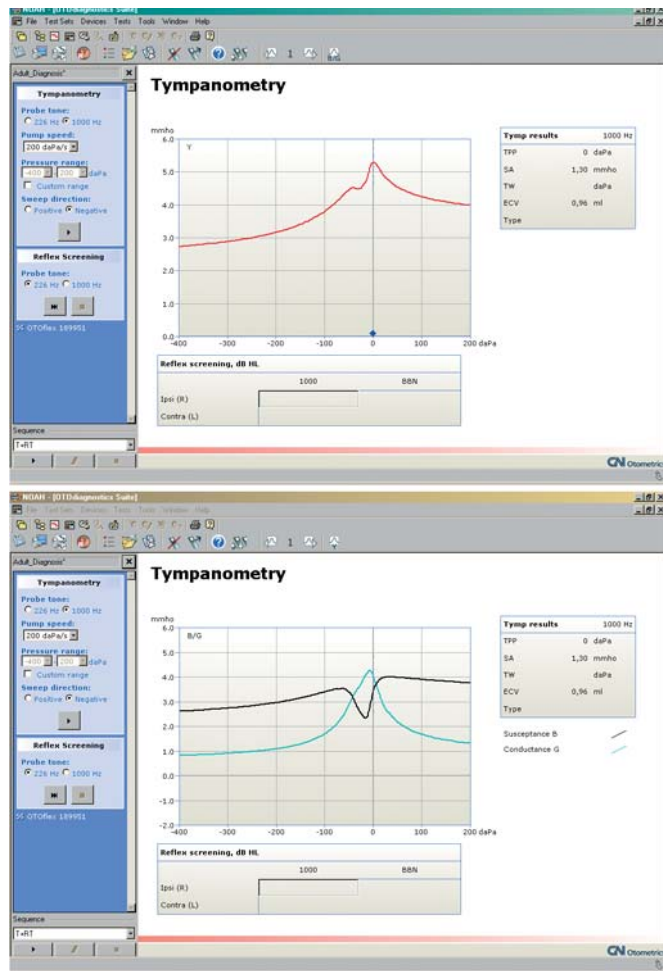


Figure 3. The appearance of susceptance/conductance (top) and admittance magnitude tympanograms (bottom) from the same adult ear, measured with a 1000-Hz probe tone and displayed on the GN Otometrics OTOdiagnostics Suite software.

Immittance measurements in infants

There have been several reports of infants below the age of about 6 months demonstrating what appear to be normal 226-Hz tympanograms even with confirmed middle ear effusion.⁷ It is also possible to obtain abnormal 226-Hz tympanograms in normal ears in this age group.⁸

Tympanograms collected from infant ears clearly progress differently from those collected from adult ears. It has also been shown that acoustic reflexes cannot be reliably measured using a 226-Hz probe tone in this population. There are many anatomic differences in the developing infant ear and, while we

do not fully know the impact of each, the sum of differences account for the peculiar 226-Hz immittance findings reported by different investigators.

External and middle ear changes after birth that could account for the acoustic alterations include:

- size increase of the external ear, middle ear cavity, and mastoid
- a change in the orientation of the tympanic membrane
- fusion of the tympanic ring
- a decrease in the overall mass of the middle ear (due to changes in bone density, loss of mesenchyme)
- tightening of the ossicular joints
- closer coupling of the stapes to the annular ligament
- the formation of the bony ear canal wall.

Unlike the adult middle ear, which is a stiffness-controlled system at low frequencies, the infant middle ear is a mass-dominated system with a lower resonant frequency.⁹ During development of the infant ear, several changes also take place that influence the mechanical properties of the ear canal. Ear canal changes include the fusing of the tympanic ring and formation of the bony region. This process involves mechanical changes, which influence the tympanogram. It has been recognized that the external and middle ear systems can vary significantly in their acoustic response properties over the first 2 years after birth.⁸

Tympanograms in pediatric audiology are most commonly used to identify the presence of middle ear fluid, i.e., effusion. Acoustic reflexes have also proven a very good complement to tympanometry, since any conductive malfunction will diminish the reflex-induced immittance change. Hence, a present reflex is a strong indicator that the middle ear is healthy.¹⁰ Because of the lower resonant frequency of the infant ear, higher-frequency probe tones have been explored for tympanometric and acoustic reflex immittance measurements. Through the use of either MFT or single high-frequency probe tones, many researchers have concluded that higher probe-tone frequency tympanometry can accurately identify middle ear effusion.^{3,5} (For an extensive review see Purdy and Williams.¹¹) While it has been concluded that the use of mainly 678-Hz and 1000-Hz probe tones is preferable to use of 226-Hz probe tone for infants, the 1000-Hz probe tone is preferred.¹²

The 1000-Hz probe tone has typically not been available in diagnostic immittance instruments. Yet, it is clearly required for use in diagnostic testing when neonatal screening ABR or OAE are abnormal. As Purdy and Williams note, "...low-frequency tympanometry is unreliable and should not be used."¹²

Using 1000 Hz as a standard tool

Although MFT may have some advantages in the amount of data collected, the procedure has proven far too awkward and slow for use with the infant population. As further research continues to support high-frequency tympanometry, the literature presently concludes that the best choice of a tympanometric probe frequency for infants under about 6 months of age is 1000 Hz.

Research facilities are currently collecting data on normative values, and some material has already been published.^{13,14} Still, there are many unknowns regarding the sensitivity and specificity of 1000-Hz tympanometry to the presence of middle ear effusion in infants. Further research is needed into more population-specific 1000-Hz susceptance, conductance, and admittance normative data, as well as in assessing the sensitivity and specificity of these measures.

Finally, it is recommended that high-frequency immittance measurements be included in a battery of tests to identify any abnormality in an infant's hearing, but tympanometry and acoustic reflex measurements are most effective when they are interpreted along with behavioral thresholds and ABR and OAE results.



Figure 4. A infant referred from a neonatal screening program is measured with a 1000-Hz probe tone using the MADSEN OTOflex 100 from GN Otometrics.

Current literature recommendations include the following:

- Below 4-7 months of age, a 1000-Hz probe tone should be used for detecting middle ear effusion.
- Acoustic reflexes complement tympanometry and should be present in healthy ears when using 1000-Hz probe tone and ipsilateral broad-band noise stimulus.
- The following 1000-Hz tympanograms are considered normal: single or double-peaked curves and discernible Y, B or G peak.
- If normative data are not available for the specific age group, a susceptance (B) curve with no discernible peak is considered indicative of effusion.

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"...there have been reports of infants with normal 226-Hz tymps despite confirmed middle ear effusion..."

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