Using wideband reflectance to measure the impedance of the middle ear

By Robert H. Withnell, Pierre Parent, Patricia S. Jeng, and Jont B. Allen

The human ear processes a wide range of frequencies, as depicted in Figure 1. It is notable in this figure that hearing threshold is not constant as a function of frequency, hearing thresholds being poorer at low and high frequencies. In fact, the human audiogram describes a filter, sound being processed in a frequency-dependent manner.

Figure 1 shows hearing in dB SPL versus frequency, as distinct from the more common clinical representation of dB HL versus frequency, where the frequency dependence is not apparent. The outer and middle ear contribute significantly to this frequency dependence at low frequencies, sound being filtered by the outer and middle ear before being received by the cochlea. Characterizing this filtering of sound by the outer and middle ear provides a measure of the status of the outer and middle ear. This is important diagnostically for detecting middle ear pathology and its contribution to hearing loss.

The outer and middle ear transmit sound in air to a fluid-filled cochlea. How well this is achieved is characterized by the sound reflected from the ear. As sound is transmitted along the ear canal and through the middle ear, it is reflected wherever there is an impedance mismatch. The most notable such mismatch is between the ear canal and the eardrum/middle ear. For the middle ear, the impedance match with the ear canal can be determined by measuring the sound pressure in the ear canal and quantifying the amount of sound reflected. This provides a measure of the filtering of sound by the middle ear.

Two techniques are currently available clinically for measuring the amount of sound reflected by the middle ear: tympanometry and wideband power reflectance (WBR). Tympanometry was introduced as a clinical tool in the mid-1940s. Reflectance was first described in the early 1980s, although the principles were well known prior to this.

For both tympanometry and reflectance, a microphone is used to measure sound pressure in the ear canal. The microphone is typically contained in a probe

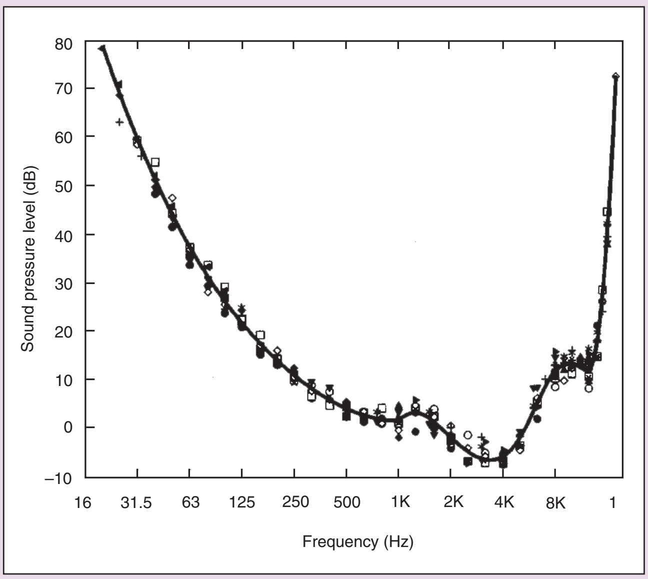

Figure 1. *Human hearing in dB SPL versus frequency (Hz). Reprinted with permission from Suzuki and Takeshima, Journal of the Acoustical Society of America, 116(2), 918-933, 2004. Copyright 2004, Acoustical Society of America.*

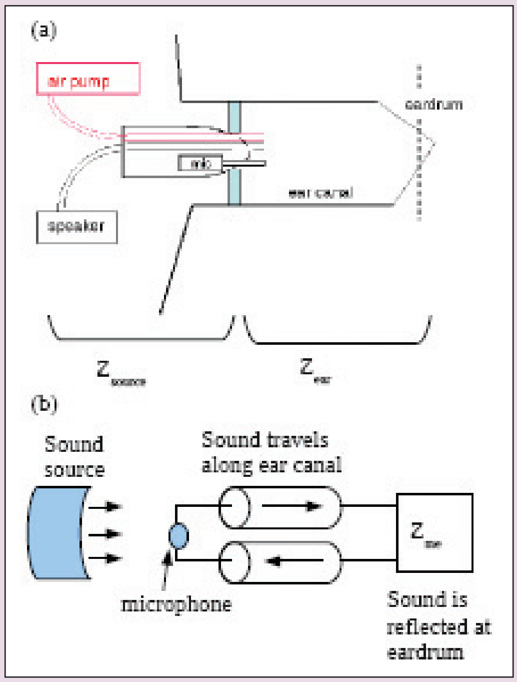

Figure 2. *(a) A schematic of the measurement apparatus for tympanometry and WBR (air pump is for tympanometry only). (b) A depiction of sound propagation along the ear canal reflected at the eardrum. The sum of the incident and reflected waves is measured at the microphone.* Z_{me} *= impedance of middle ear.*

assembly that couples to the ear via an eartip. The stimulus or probe-tone frequency range for tympanometry is restricted to less than 2000 Hz. Typically, one to three stimulus frequencies are used e.g., 226, 678, and 1000 Hz. In contrast, for reflectance the upper frequency limit is at least 6000 Hz.[2] Either the probe speaker or ear canal acoustics define this frequency limit.

The goal of tympanometry and reflectance is to determine the (input) impedance of the middle ear. Figure 2 shows a schematic of the measurement apparatus and depicts the propagation of sound in the ear canal subsequent to the delivery of a sound stimulus. The sound pressure measured in the ear canal is the sum of the incident and reflected sound waves (Figure 2b).

Tympanometry seeks to determine the impedance of the middle ear, but the acoustic impedance of the sound source and of the ear canal are not known. Static pressure change in the ear canal is used to address this problem. At a large positive or negative static pressure in the ear canal, the stiffness of the middle ear increases significantly.

Tympanometry assumes that the subsequent impedance mismatch between the ear canal and middle ear causes all of the incident sound to be reflected from the eardrum. The sound pressure measured with a large positive or negative static pressure in the ear canal then depends solely on the acoustic impedance of the sound source and ear canal. Sound pressure measurements are calibrated against simple acoustic volumes so that each sound pressure measurement in the ear canal has an equivalent acoustic admittance (this calibration limits tympanometry to frequencies below 2000 Hz). A plot of sound pressure measured in the ear canal versus static pressure in the ear canal produces the clinically well-known tympanogram with the sound pressure values converted to an "equivalent volume" or admittance.

Reflectance seeks to determine the (input) impedance of the ear. Unlike tympanometry, the acoustic impedance of the sound source is determined prior to measurement in the ear (see Allen, 1986[3]). Calibration of the sound source means that static pressure in the ear canal

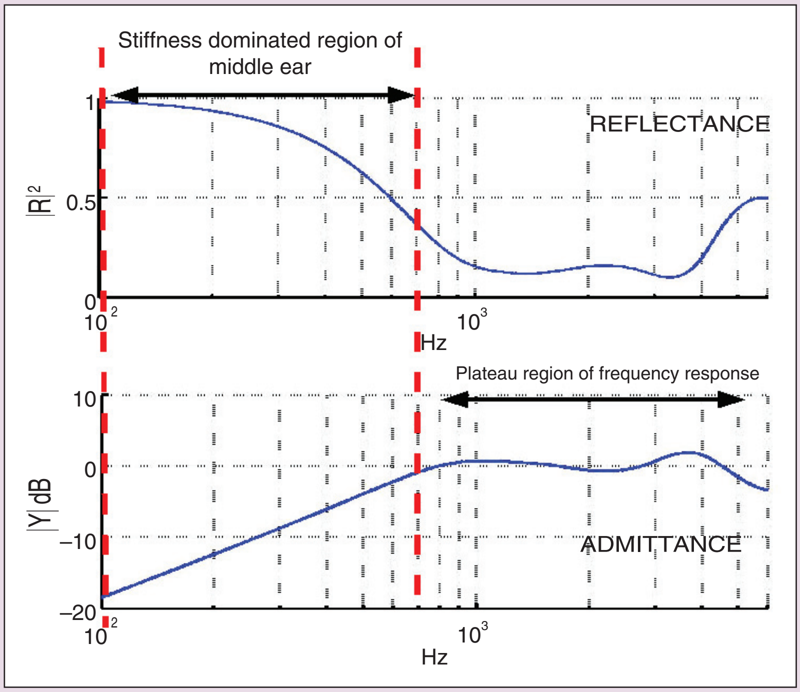

Figure 3. *(a) A typical wideband reflectance curve from a human ear. (b) The admittance magnitude frequency response (at the eardrum) depicting the frequency-dependence of sound transfer into the middle ear and cochlea. Corresponds to the reflectance curve of (a). Curves generated by a model of the middle ear.*

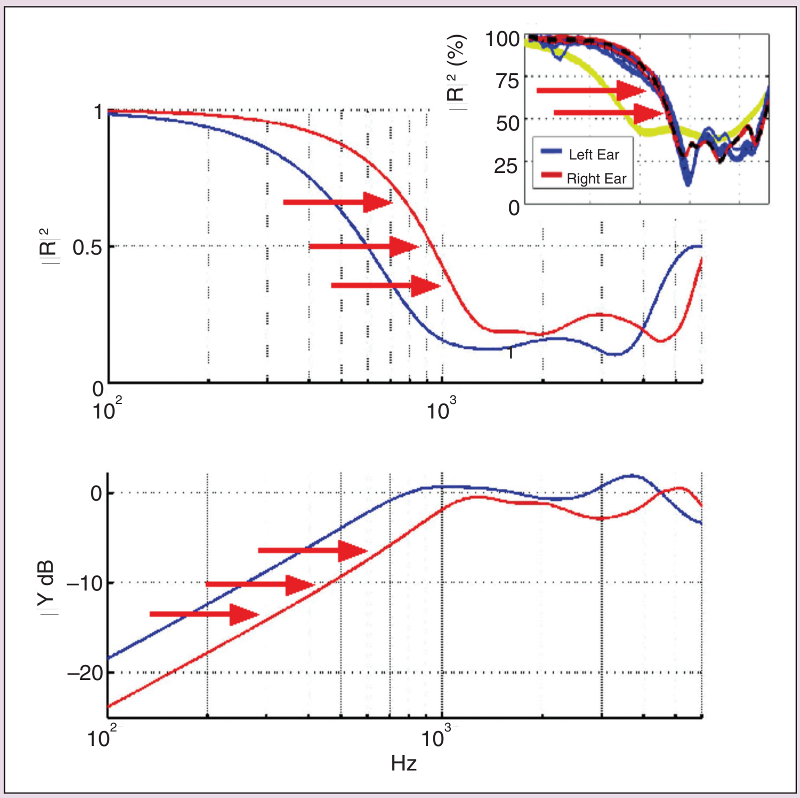

Figure 4. *Power reflectance and admittance frequency responses showing both curves shift to the right with an increase in the stiffness of the middle ear. The inset shows reflectance from a subject with otosclerosis (from Allen et al., 2005[4]).*

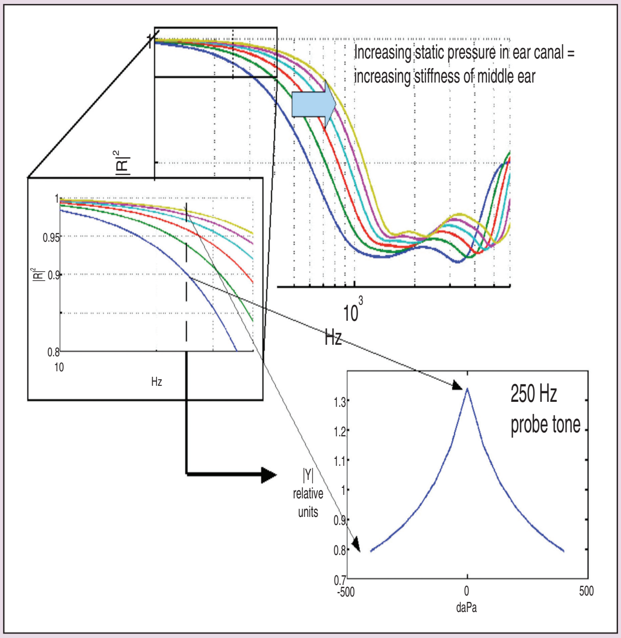

Figure 5. *A series of reflectance curves corresponding to varying values for the stiffness of the middle ear. Increasing stiffness shifts the reflectance curve further and further to the right, corresponding to increasing the static pressure in the ear canal. From this series of reflectance curves, the change in reflectance magnitude at 250 Hz, when combined with reflectance phase, generates a tympanogram for a 250-Hz tone.*

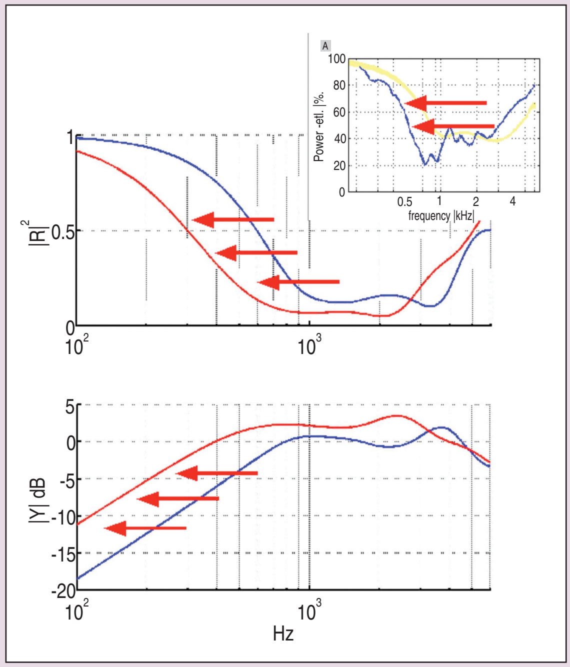

Figure 6. *Reflectance and admittance frequency responses corresponding to a decrease in the stiffness of the middle ear. Both curves shift to the left. The inset shows reflectance from a subject who had middle ear disease as a child, the reflectance pattern suggesting a decrease in stiffness of the middle ear.*

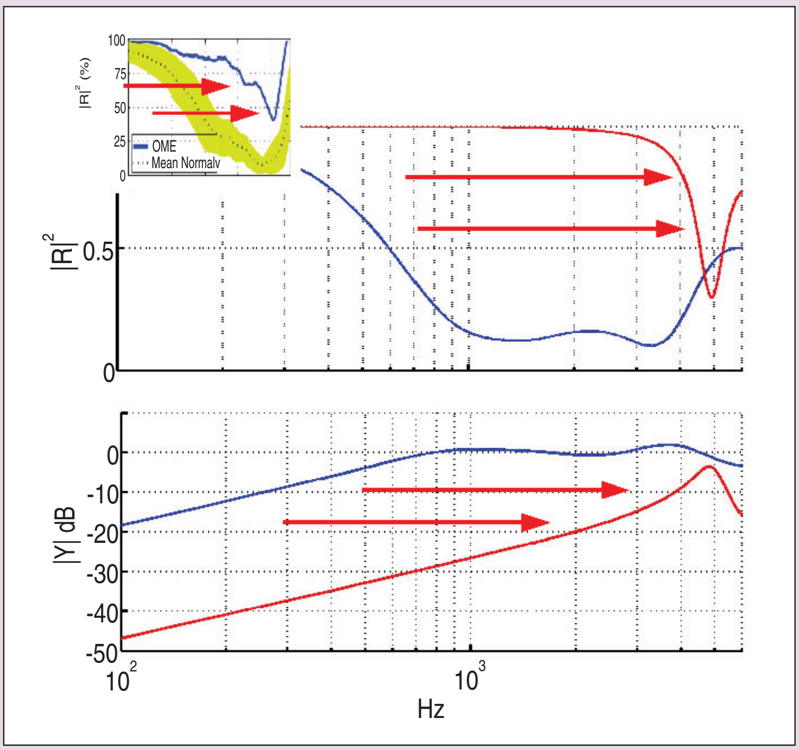

Figure 7. *Reflectance and admittance frequency responses corresponding to a significant increase in the stiffness of the middle ear, such as would be seen in otitis media with effusion. The inset shows reflectance from a subject who had otitis media with effusion (from Allen et al., 2005[4]).*

need not be altered. From the sound pressure measured in the ear canal, the (input) impedance can be calculated. The impedance of the ear can also be expressed in terms of the reflectance (the ratio of the reflected sound and the incident sound). Reflectance is equivalent to impedance but easier to understand.

Figure 3 depicts the reflectance magnitude as a function of frequency for a typical human ear. Reflectance is plotted in terms of the magnitude squared. Also shown in Figure 3 is the admittance magnitude as a function of frequency at the eardrum, being a measure of how sound is received by the middle ear and cochlea.

Figure 3 and subsequent figures were generated using a very simple model of the middle ear. In Figure 3, the magnitude of the reflectance depicts how much sound is reflected. A low reflectance value means that most of the sound power is transmitted to the middle ear, while a large reflectance value means that most of the sound power is reflected from the middle ear. The admittance frequency response (Figure 3b), corresponding to the reflectance curve, has a low frequency, stiffness-dominated region and a plateau region where damping presumably plays a significant role. It is evident from Figure 3 that wideband power reflectance expresses the filtering properties of the middle ear, being a function of the sound power that is not transmitted to the middle ear.

Given that reflectance quantifies the filtering properties of the middle ear, impedance changes due to pathology produce predictable alterations in the reflectance curve or frequency response. Figure 4 shows the effect of an increase in stiffness on the reflectance and admittance. An increase in the stiffness of the middle ear will shift the admittance frequency response to the right. The reflectance function will also shift to the right. An increase in the stiffness of the middle ear is most commonly associated with otosclerosis. An example of reflectance obtained from an ear with otosclerosis is shown in inset, the reflectance curve having shifted to the right.

An increase in the stiffness of the middle ear also occurs with an increase in the static pressure in the ear canal. Figure 5 shows a series of reflectance curves, increasing stiffness shifting the curve further and further to the right (corresponding to increasing the static pressure in the ear canal). From this series of reflectance curves, the change in reflectance magnitude at 250 Hz, when combined with reflectance phase, generates a tympanogram for a 250-Hz tone. Tympanograms for other probetone frequencies can be generated similarly.

A decrease in the stiffness of the middle ear will decrease the resonant frequencies of the middle ear, shifting the admittance frequency response to the left. The reflectance function will also shift to the left, as Figure 6 illustrates. Also shown in inset is an example of reflectance obtained from an adult ear where the middle ear is less stiff as a result of childhood middle ear disease.

The most common pathology of the middle ear is otitis media. Otitis media with effusion (OME) is a disease of the middle ear where the stiffness of the middle ear has been increased significantly due to the presence of fluid in the middle ear. If the middle ear is fluid-filled it is very stiff and so reflectance magnitude has a value of one at all frequencies, since nearly all of the sound is reflected at the nearly rigid eardrum.

Figure 7 shows a reflectance curve where the stiffness of the middle ear has increased significantly, such as might be observed in OME. Note that reflectance magnitude is not one at all frequencies; a notch in the reflectance is evident, showing energy is being absorbed by the middle ear over the frequency range of the notch. One possible explanation for this reflectance pattern is that the middle ear space has an air bubble.

Wideband power reflectance provides a broad spectrum measure of the impedance mismatch between the ear canal and middle ear. The reflectance frequency response alters predictably with middle ear pathology, emphasizing that the reflectance curve is a measure of the filtering properties of the middle ear. The wide range of frequencies examined and the fact that static pressure changes in the ear canal are not required make wideband reflectance a powerful alternative to tympanometry for assessing the status of the middle ear.

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