Wideband Power Reflectance and Power Transmittance as Tools for Assessing Middle-Ear Function

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Abstract

Hearing screening programs using otoacoustic emissions can have high false positive rates, due to temporary middle-ear and outer-ear disorders. This is especially the case for newborns, infants, and young children. Standard tympanometry is limited, uncomfortable, and unreliable in young ears. By incorporating wideband acoustic power flow measurements into hearing screening (using the same equipment), middle-ear and outer-ear disorders can be detected, thus allowing for rescreening rather than more expensive audiological referrals. Wideband acoustic power flow is described in detail and four case examples are provided for adults and children.

Science is much like a game of leapfrog. Each new advance introduces new obstacles and new opportunities for further advances. A case in point is the development of improved hearing screening procedures using evoked otoacoustic emissions, which has many advantages over earlier methods. Reliable objective measurements are obtained rapidly and conveniently.

Further, a behavioral response is not required thereby enabling practical, cost-effective screening programs for newborns, infants, young children, and other difficult to test populations.

False positives (incorrectly detecting a disorder) are a problem with any screening procedure. Hearing screening by means of evoked otoacoustic emissions requires that the signals of interest pass through the middle ear twice: once for the input test signal to evoke the otoacoustic emission and again, in the opposite direction, for the evoked otoacoustic response. A middle-ear disorder, such as fluid in the middle ear, can easily cause a false positive (i.e., a false indication of an inner ear disorder) because the otoacoustic stimulus and emission are both attenuated by the middle ear. Middle-ear disorders are far more frequent than inner-ear disorders and are often temporary. The relatively high incidence of middle-ear disorders, particularly in the screening populations of greatest interest (neonates, infants, and children), is a major concern in the development of improved screening programs. The cost of a false positive rate is not only high in terms of the additional time and effort required for more extensive testing, it is also an unnecessary cause of concern and worry for the child's family.

Whereas the problem of false positives in hearing screening has introduced a new focus on middle-ear disorders, it has long been realized that virtually every hearing test is dependent on the status of the middle ear. Even tests of hearing by bone conduction involve the middle ear indirectly. Despite the importance of knowing the status of middle-ear function, current tests for evaluating middle-ear function are relatively primitive. Audiologists routinely use bone conduction and the so-called air-bone gap, along with tympanometry, to evaluate middle-ear function. Each of these measurement techniques are confounded by an incomplete understanding of the physics of acoustic energy flow into and around the middle ear and cochlea. Bone conduction is still not well understood, because the physical path of the sound has yet to be fully specified.

Tympanometry has been a key clinical tool since as early as 1946 (Metz, 1946), and, although it is better understood than bone conduction, several problems remain with this traditional measure. First, it is typically measured at only 226 Hz, which limits what can be deduced about middle-ear function. While there are procedures at other frequencies, multi-frequency tympanometry is not easily interpreted in terms of the physics of the middle ear. What is needed is an improved understanding of acoustic power flow from the ear canal into the cochlea. This is the realm of wideband acoustic power flow.

Hearing measurement by means of evoked otoacoustic emissions was an important advance in hearing science that leapfrogged on several significant advances in computer technology, specifically the development of powerful low-cost computers, followed by the implementation of advanced digital signal processing techniques, such as the Fast Fourier transform which, in turn, led to significant advances in digital audio. These advances have provided the means for developing clinically viable methods of measuring acoustic power flow in the ear over a wide frequency range.

Wideband Acoustic Power Flow

In a normal ear, when an acoustic signal reaches the eardrum, a portion of the acoustic power is absorbed and transmitted to the middle ear. The remaining power is reflected back into the ear canal except for a negligibly small amount that is lost as a result of friction. The reflected signal travels back along the ear canal and interacts with forward moving signals creating standing waves. Reflectance is a direct measure of the amount of sound reflected from the ear, relative to the amount of sound delivered to the ear (power reflectance is defined as |R(f)|2; the squared magnitude of the ratio of reflected to incident pressure as a function of frequency, f). If a middle ear disorder is detected, the way in which the reflectance varies as a function of frequency provides clinically useful information on the nature of the disorder.

Power reflectance is only one of several possible acoustic power-flow variables that can provide useful information on the status of the middle ear. Other variables of interest are power absorption (1 - |R(f)|2) and transmittance (power absorption in dB, 10log[1 - |R(f)|2]). Another view of acoustic power flow is that the eardrum impedes the flow of acoustic power into the middle ear (by reflecting some of it back into the ear canal). This property of the eardrum is known as acoustic impedance (Z(f)). If the reflectance of the eardrum is known, its acoustic impedance is readily derived. Similarly, if the acoustic impedance of the eardrum is known, its reflectance is readily derived; that is, impedance and reflectance provide different views of the same physical phenomenon and each of the two concepts is in essence a mathematical transformation of the other. Similarly, impedance and admittance provide different views of how the eardrum impedes or facilitates the transmission of acoustic power into the middle ear, respectively, and each may be derived from the other by means of a mathematical transformation (Allen, 1986; Rabinowitz, 1981). Reflectance and impedance are complex quantities in the mathematical sense; that is, they have both amplitude and phase components (these variables can also be represented mathematically in terms of complex quantities with real and imaginary components). Each component can provide a different view on middle-ear status. For instance, the real component of Z(f) is resistance while the imaginary component of Z(f) is reactance.

Acoustic power flow in a pathological ear differs from that of a normal ear, depending on the nature of the pathology. Fluid in the middle ear, for example, will result in more power reflected back into the ear canal. A perforated eardrum will result in a significant amount of power flow into the middle-ear cavity and not through the middle ear via the ossicular chain. The loss in acoustic power can be quite substantial in contrast to the normal ear where there is negligible loss.

The measurement of acoustic power flow, or factors related to power flow such as acoustic impedance, provides a wealth of information on the status of the middle and outer ear. Prior to the development of modern computer techniques, the measurement of acoustic impedance—and, concomitantly, the measurement of acoustic reflectance—was a delicate, time-consuming process that was also not very reliable above about 1000 Hz. Allen (1986) developed a practical technique for measuring wideband impedance and later used this method to define wideband power reflectance using a high-speed personal computer. Variations and improvements of the technique soon followed (Keefe, Ling, & Bulen, 1992; Puria, 1991; Voss & Allen, 1994). These developments, in turn, have led to a substantial growth of interest in the diagnostic potential of wideband acoustic power flow measurements (Feeney, Grant, & Marryott, 2003; Hunter, 2004; Keefe, Bulen, Arehart, & Burns, 1993; Margolis, Saly, & Keefe, 1999).

The revolutionary aspect of modern measurements of wideband acoustic power flow and acoustic impedance is that a complete set of measurements up to 6 kHz, and higher, can be obtained within minutes in a convenient and practical way. The term “complete set of measurements” is used to emphasize the point that reflectance, impedance, and admittance are characterized by two variables—amplitude and phase—that vary with frequency (these variables are often expressed mathematically in terms of complex numbers with real and imaginary components). A major limitation of early instrumentation for the measurement of impedance was that only the amplitude of the complex measure was available and only for a few frequencies below 1,000 Hz. These instruments provided no information on impedance or admittance above 1,000 Hz (or in some cases, 2,000 Hz), yet that is where important diagnostic information may be found. Most of the acoustic impedance and admittance of the ear below 1,000 Hz, as measured with clinical instruments, is determined by the column of air in the ear canal and provides limited information on the status of the middle ear. Modern methods of measuring wideband acoustic power flow have opened up a new world of clinical measurement. Speech frequencies are between 0.3 and 8 kHz; thus, it is important to have a test over this frequency range.

Allen, Jeng, and Levitt (2005) describe several important applications of wideband acoustic power flow measurements. One practical aspect of power reflectance, as opposed to pressure reflectance measurements, is that the problem of standing waves in the ear canal may be avoided. A backward moving pressure wave interacts with a forward moving pressure wave in the ear canal to form standing waves. In contrast, acoustic power flow in the ear canal is continuous with no standing waves. This is because power is the product of pressure (analogous to voltage in an electric circuit) and volume velocity (analogous to current in an electric circuit). The interaction between the forward moving and reflected backward moving (phasic) acoustic wave in the ear canal produces both a pressure and a volume velocity standing wave in the ear canal. However, as the pressure standing wave increases with distance in the ear canal, the volume velocity standing wave decreases proportionally, so that the product is a constant and the power flow is constant along the ear canal (this assumes we ignore the loss of power with distance due to friction with the walls of the ear canal). An important practical consequence of this is that the transducer for power measurement can be placed almost anywhere in the ear canal since there is no power standing wave. However, for pressure measurements, the placement of the transducer relative to the standing wave is of critical importance and improper placement can lead to substantial errors.

Another very useful aspect of the wideband acoustic power flow measurement is that the same instrumentation may be used for the measurement of otoacoustic emissions (HearID™ from Mimosa Acoustics, Inc.). This instrument can be used for screening both middle-ear and inner-ear disorders within the same test session without refitting the probe. As noted earlier, a major problem in hearing screening is the high false positive rate resulting from middle-ear disorders, which are far more prevalent than inner ear disorders. The capability of screening for both middle-ear and inner-ear disorders simultaneously can produce a substantial increase in the cost effectiveness of the screening program.

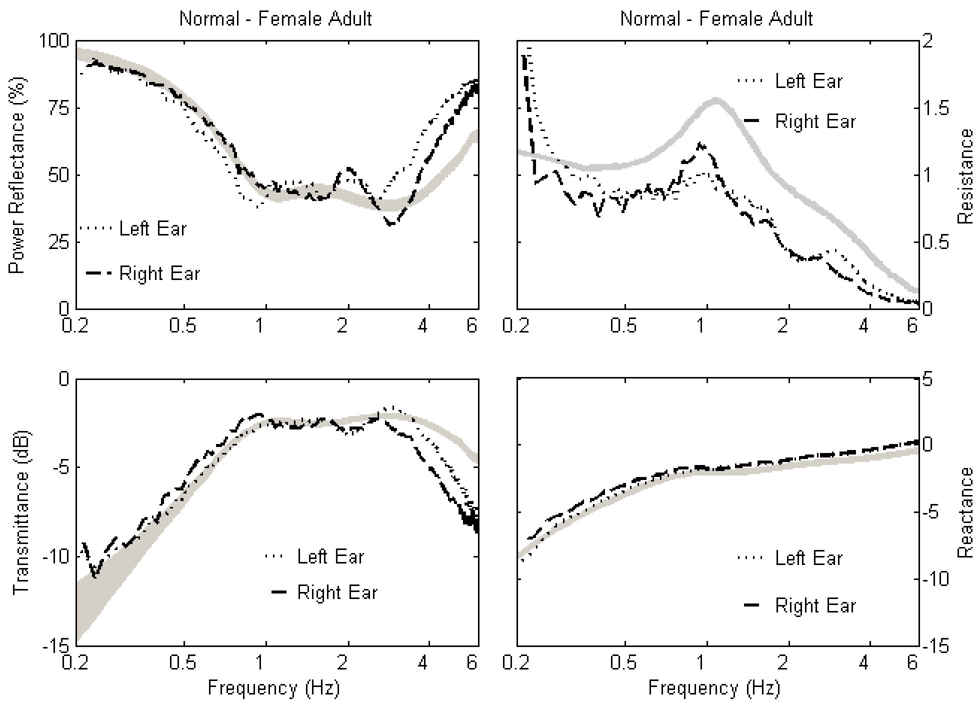
From a clinical perspective, it is of interest to determine which of the variables discussed above are the most revealing with respect to the status of the middle ear. Figures 1 through 4 (based on Allen et al., 2005) provide an illustrative comparison of information on the acoustic characteristics of the middle ear provided by diagrams of power reflectance, transmittance, acoustic resistance, and acoustic reactance, respectively. In each case, the variable of interest is shown as a function of frequency (on a logarithmic axis). The frequency range shown is from 0.2 kHz to 6 kHz. Each figure consists of two columns of two diagrams each. The left column shows power reflectance (in %), and transmittance (in dB). The right column shows normalized resistance and normalized reactance. The normalized values were obtained by dividing acoustic resistance and reactance by the characteristic impedance of the ear canal, which for the adult ear is 41/A (acoustic ohms), where A is the area in cgs units.

Normalized values are used to reduce between-subject and between-test variability. The normalization process takes into account between-subject differences in the physical size of the ear (an important consideration when comparing data for male, female, and children's ears) as well as differences in ambient temperature and atmospheric pressure at the time of testing. It is important to bear this in mind when comparing coupler and in-the-ear measurements of acoustic impedance. The use of normalized acoustic impedance circumvents this difficulty.

Example 1: Normal Adult Ear

Figure 1 shows middle-ear measurements for an adult with clinically normal hearing compared with a standard coupler, which is representative of the average adult ear. The power reflectance of the standard coupler is close to 100 percent at 0.2 kHz and decreases with increasing frequency to 1 kHz. It is then close to 50%, with a very shallow minimum below 50% in the region of 3 kHz. Power reflectance then increases with increasing frequency up to 6 kHz. The data for the two ears are very similar to that of the standard coupler up to 3 kHz. At higher frequencies, the power reflectance of the two ears differs slightly from each other and both have a higher reflectance than that of the coupler.

Figure 1. Normal Adult. The power reflectance, transmittance, normalized resistance, and normalized reactance measured from both left (dotted line) and right (dashed line) ears of the subject are plotted as a function of logarithmic frequency, and compared to that measured with a B&K 4157 artificial ear coupler (gray patch), which represents an average adult ear with normal hearing. (Based on Fig 1 from Allen et al., 2005).



The physical interpretation is that at frequencies below 1 kHz there is an increasing impedance mismatch at the entrance to the middle ear and that most of the acoustic power reaching the eardrum at these frequencies is reflected back into the ear canal. In contrast, most of the acoustic power is absorbed by the middle ear in the frequency region between 1 kHz and 5 kHz. This also happens to be the frequency region in which the ear is most sensitive to sound.

The bottom left panel shows the transmittance that is the absorbed power transformed to a logarithmic (dB) scale. Transmittance increases linearly with frequency in the low frequency region below 1 kHz and decreases slightly with frequency in the high frequency region above 4 kHz. The low frequency (<1 kHz) slope is approximately 6 dB/octave (20 dB/decade), which corresponds to the impedance of a simple compliance. This diagram not only provides a clear illustration of the absorption of acoustic power by the middle ear, it also provides a relatively simple picture, in terms of straight-line approximations of normal power absorption as a function of frequency. In addition, the use of a decibel scale allows for direct comparisons with other relevant data, such as the threshold of audibility in dB SPL.

The top right panel shows the normalized acoustic resistance (real part of the acoustic impedance) of the ear canal. The normalized resistance varies between 1 and 2 for frequencies up to 1 kHz and then decreases monotonically with frequency to about 0.2 at 6 kHz. Note that the vertical scale of this diagram has been expanded so that the deviation between the coupler response and the two measured ears appear to be larger than that in the reactance diagram (bottom right) which has a relatively contracted scale. To a first approximation, the resistance of the eardrum is roughly equal to the characteristic impedance of the ear canal up to 1 kHz after which it falls gradually.

In contrast, the normalized acoustic reactance (bottom right panel), increases monotonically with frequency, but with a reduction in slope above 1 kHz. Bear in mind that the reactance in the low frequencies is quite negative, indicating that it is stiffness based. In the mid-frequency region between 1 and 3 kHz, reactance is small but not negligible, so that the impedance of the eardrum is not entirely resistive at these frequencies. Note that the reactance of the two measured ears and that of the standard coupler are in excellent agreement over the entire frequency range.

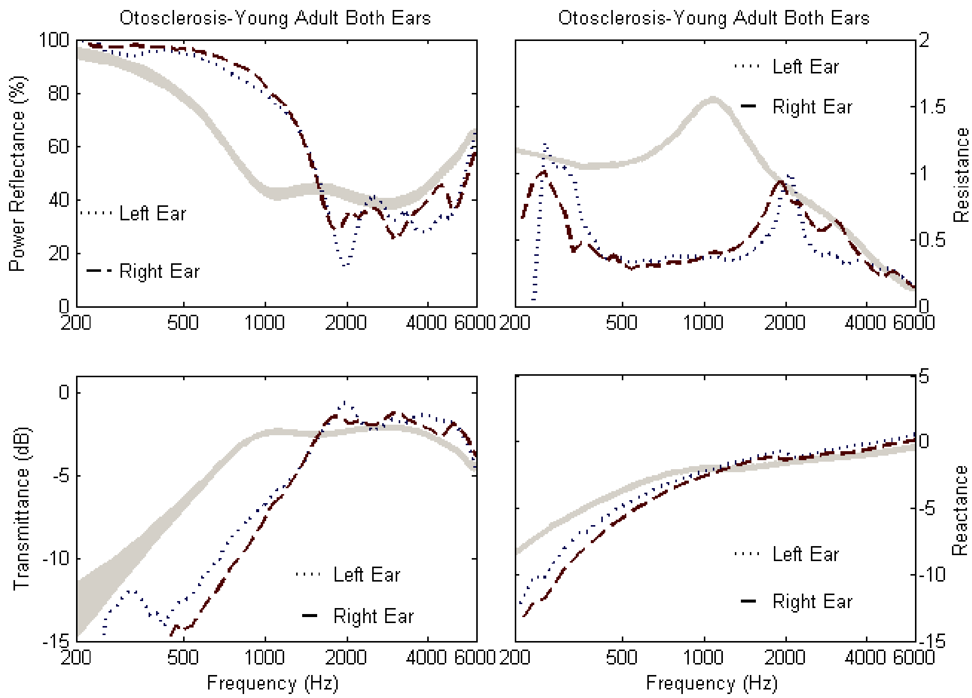
The combination of reactance and resistance in the mid-frequency region provides a moderately good match to the impedance of the ear canal over the range from 1 to 3 kHz. As result, a fair amount of the incident power is reflected back into the ear canal (a little under 50%, as shown in the power reflectance diagram). In terms of transmittance, this corresponds to a loss of 2 to 3 dB in this frequency region. Note also that because of the approximate match in the mid-frequency region between the impedance of the eardrum and the impedance of the ear canal, the transmittance shows a relatively high, flat peak over a broad frequency range.

In summary, the resistance and reactance diagrams show that the middle-ear impedance is dominated by a stiffness-based reactance in the low frequencies and that, as a result, power transmission into the middle ear is relatively poor at low frequencies. Over most of the mid-frequency range, the reactance is small and comparable in magnitude to the resistance that, in turn, is approximately equal to the characteristic impedance of the ear canal resulting in relatively efficient power transmission into the middle ear. At very high frequencies (not shown in the diagram), the impedance of the ear is dominated by a mass-based reactance and power transmission into the middle ear is relatively poor. In some ears, the impedance may become mass dominated at frequencies lower than about 8 kHz. In these ears, the transmittance will be poorer at moderately high frequencies, which may be an early indication of a slight high-frequency conductive hearing loss.

Example 2: Adult Ear With Otosclerosis

Figure 2 shows middle-ear measurements for a young adult female with a bilateral otosclerosis. The reflectance diagram (top left panel) shows that below about 1.5 kHz, most of the acoustic power reaching the middle ear is reflected back into the ear canal. Concomitantly, power transmittance (bottom left panel) is substantially below the normal range in this frequency region, as may be seen in bottom left panel.

Figure 2. Bilateral Otosclerosis. The average power reflectance, transmittance, normalized resistance, and normalized reactance measured from both left (dotted line) and right (dashed line) ears of the subject are plotted as a function of logarithmic frequency, and compared to that measured with a B&K 4157 artificial ear coupler (gray patch), which represents an average adult ear with normal hearing. All measures in the otosclerotic ears differ noticeably from the coupler results below 1.5 kHz. (Based on Fig 2 from Allen et al.,2005).

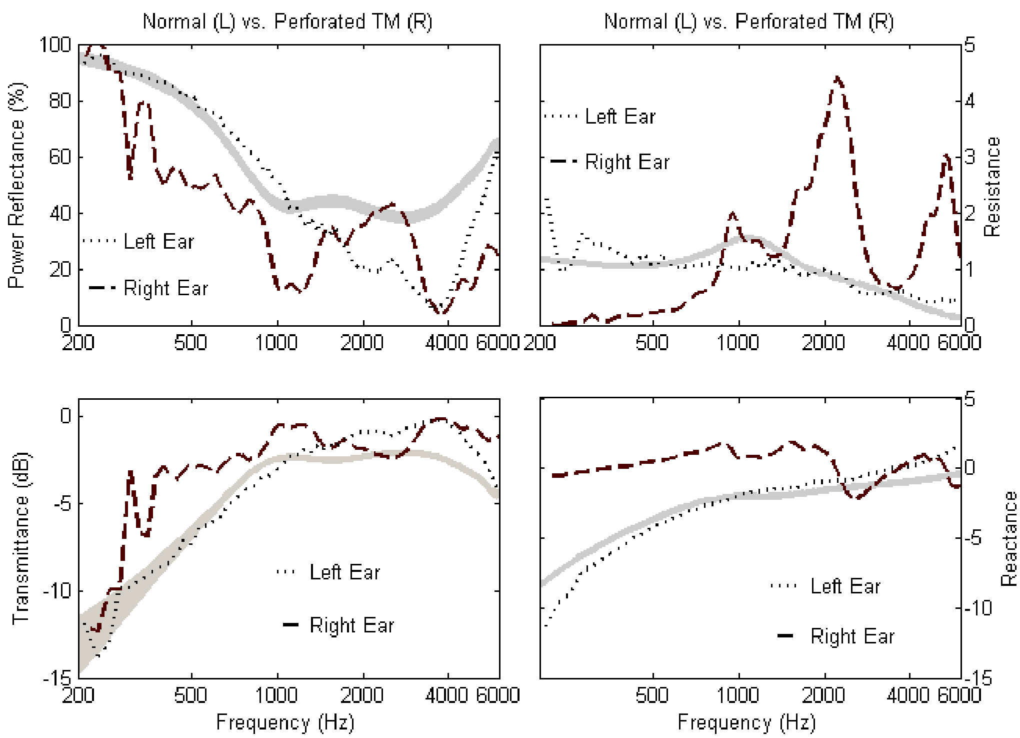


Between 0.4 kHz and 2 kHz, the normalized resistance (top right panel) of the otosclerotic ears is below that of normal middle-ear resistance as represented with the coupler measurement, which varies between 1 (at 0.4 and 2 kHz) and 1.5 (at 1 kHz). In a normal ear, the middle ear is a low-loss transmission system, and resistance is due to the matched cochlear load. Because of the stiff annular ligament in the otosclerotic ear, a large mismatch in impedance is seen below 2 kHz, and this causes the incident energy to be reflected back into the ear canal where it propagates with small attenuation. Thus, below 2 kHz, the reflectance magnitude approaches 100% with decreasing frequency and the resistance is less than half of the normal value. The abnormality of these otosclerotic ears is consistent with increasing stiffness below 0.8 kHz in the reactance diagram (bottom right panel), with a decrease in reactance, compared to the coupler.

Example 3: Perforated Eardrum

Figure 3 shows middle-ear measurements obtained from a subject having a perforated eardrum in the right ear and a normal left ear. The perforation was about 3 to 4 mm in diameter. The power reflectance curve (top left panel) for the good ear is very similar to that of a normal ear, as represented by the standard coupler measurements up to about 1 kHz. At higher frequencies, the good ear shows a lower reflectance than the standard coupler with a relatively low minimum value at 3.5 kHz. In comparison, the ear with a perforated eardrum (right ear) shows a lower than normal power reflectance in the low frequency region below 1.5 kHz. At higher frequencies, the power reflectance varies over a wide range, although it is consistently below that for the standard coupler. This diagram illustrates the high variation with measurements of power reflectance, in that these measurements tend to be variable in the region of a minimum, which happens to be a region of particular interest in evaluating the status of the middle ear.

Figure 3. Perforated eardrum (3 to 4 mm diameter perforation). Shown is the average power reflectance,transmittance, normalized resistance, and reactance measured from both the normal left ear (dotted line) and abnormal right ear (dashed line) plotted as a function of logarithmic frequency, and compared to that measured with a B&K 4157 artificial ear coupler (gray patch), which represents an average adult ear with normal hearing. (Based on Fig 3 from Allen et al., 2005).



For frequencies below 1 kHz, the power transmittance (bottom left panel) into the middle ear is substantially greater than that for a normal ear. It is not clear in this case that the energy absorbed is conducted into the ossicles. Given the huge abnormality, the normal rules of a lossless middle ear must be reconsidered. The perforation allows sound to be lost in the middle-ear cavity, increasing the power absorbed in the middle ear. The transmittance curve, in contrast to the power reflectance curves, shows relatively little variability over a wide frequency range (0.4 kHz to 6 kHz). Average curves are plotted here; however, it should be noted that for both power reflectance and transmittance, there was a high degree of variability below 400 Hz. This variability is believed to be the result of noise being picked up during the measurement procedure due to the open Eustachian tube of the subject facing the measurement microphone.

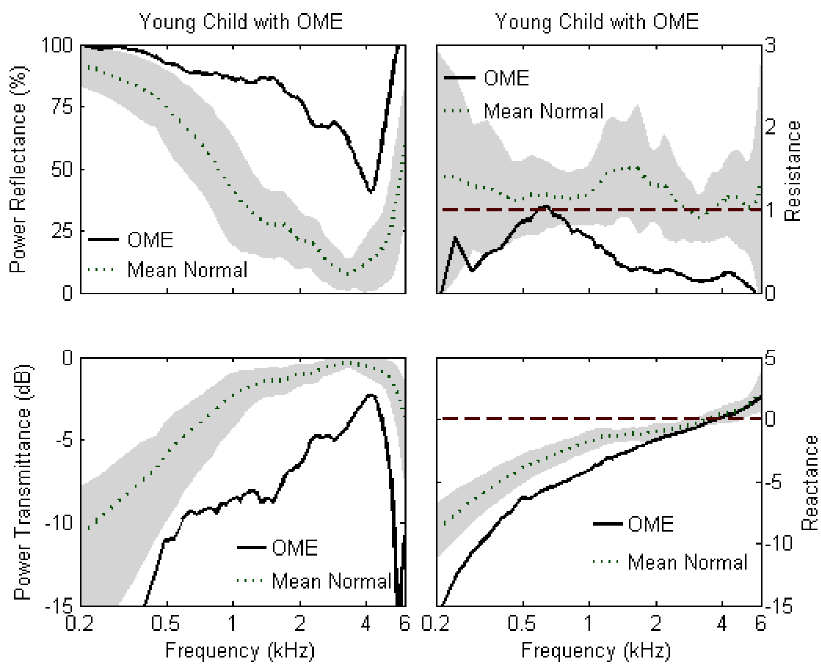
In the intermediate frequency range, between 1 kHz and 4 kHz, the transmittance is still consistently higher than that for the average normal ear, but only by a small amount, since the transmittance for both the normal and damaged ear is close to the maximum transmittance of 0 dB. At frequencies above 4 kHz, the transmittance for the damaged ear remains high, while that for the normal ear decreases with increasing frequency. This interesting case needs further study, but it is likely that at the lower frequencies, the acoustic energy is being dissipated in the middle ear-cavity air cells rather than in the cochlea.

For the normal ear, the curves for normalized resistance (top right panel) and reactance (top left panel) are close to the corresponding curves for the standard coupler over almost the entire frequency range, the only differences of any significance occurring at either very high or very low frequencies. The data for the damaged ear tell a very different story. The normalized resistance differs substantially from that of a normal ear with a major peak at 2 kHz. The normalized reactance curve also deviates substantially from normal. At low frequencies, where stiffness-based reactance is dominant in a normal ear, the reactance of the damaged ear is essentially zero. It is evident that the ossicles are not being displaced by the incoming signal, and there is no deformation of the annular ligament and other structures supporting the ossicles. This is consistent with the idea that the losses are due to the energy not being transmitted to the inner ear. There is a small positive normalized reactance between 0.5 kHz and 4 kHz, indicating that there may be some movement of a middle-ear component with a small mass, but not necessarily that of an ossicle. The negative normalized reactance above 2 kHz appears to be an artifact induced by a small standing wave in the ear canal.

Example 4: Otitis Media with Effusion (OME)

Figure 4 shows middle-ear measurements obtained on a young child with OME. The solid black line represents the data for the OME ear while the dotted line and gray patch represents the mean ±1 standard deviation for 31 normal ears in the same age group (2.5 to 4 years of age). These data were collected at Albert Einstein College of Medicine as part of a larger study directed by Judy Gravel (Jeng, Levitt, Lee, & Gravel, 2001).

Figure 4. Young Child with Otitis Media with Effusion (OME). The power reflectance, power transmittance,normalized resistance, and normalized reactance measured from the ear with OME (solid black line) are compared to those of 31 ears with normal middle-ear function (dotted mean line and ±1SD gray patch) as determined by tympanometry, otoscopic evaluation, and the children's medical history. (Based on Fig 4 from Allen et al., 2005.)



The power reflectance (top left panel) for the ear with OME is substantially higher than normal, showing that at almost every frequency most of the acoustic power reaching the middle ear is reflected back into the ear canal. The transmittance for this ear (bottom left panel) is more than 6 dB below that of the average normal ear over virtually the entire frequency range. Since 6 dB corresponds to a power ratio of 4:1, the transmittance diagram indicates that less than one quarter of the incident power is transmitted to the middle ear over essentially the entire frequency range.

These observations are not surprising, since fluid in the middle ear restricts movement of the ossicles, such that substantially more power is needed to drive them. It is interesting to note, however, that the reduction in transmittance is largely independent of frequency; that is, transmittance for the ear with OME is consistently below that of the average normal ear by just over 6 dB except in the region around 4 kHz, where the difference is less than 6 dB.

The data on normalized resistance (top right panel) and reactance (bottom right panel) also show consistent differences between the ear with OME and the average normal ear. The normalized resistance is less than that of the average normal ear over the entire frequency range. While the arithmetic difference is not very large, the ratio is substantial, particularly in the frequency region above 2 kHz where the normalized resistance for the OME ear is close to zero. As before, this finding is not surprising since the resistance represents that component of the middle-ear impedance that absorbs power.

The normalized reactance of the OME ear (bottom right panel) is clearly larger in magnitude (stiffer) than that of the average normal ear for frequencies below 2 kHz, which is consistent with a fluid-filled middle-ear cavity. At higher frequencies the reactance is approximately the same as that of the normal ear. All of the diagrams show the data for the OME ear to be considerably different from that of a normal ear. The differences, however, are larger and more noticeable in the two reflectance based diagrams (the left column of panels).

Discussion

The data reported in this study are consistent with previous research on the use of reflectance measurements to evaluate middle-ear function. For example, Feeney et al. (2003) found abnormal reflectance for otosclerosis, ossicular discontinuity, hypermobile tympanic membrane, perforations of the TM, and a pressurized middle-ear space. Others have showed similar results (e.g., Hunter, 2004; Keefe, Gorga, Neely, Zhao, & Vohr, 2003).

The measurements selected for comparison were two reflectance-based measurements (power reflectance and transmittance) and two impedance-based measurements (normalized acoustic resistance and normalized acoustic reactance). Percent power reflectance was selected because of the growing interest in this property of the ear (e.g., Feeney et al., 2003; Hunter, 2004; Keefe et al., 2003). Transmittance was selected, since it specifies power absorption in decibels and, in so doing, provides a useful link to other widely used audiological measurements such as hearing level. Measurements of acoustic impedance were included because of their clinical importance in assessing middle-ear function.

Of the reflectance-based measurements, transmittance appears to be the most useful, since it is closely related to the middle-ear transfer function and is specified in decibels. The effect of a middle-ear impairment on transmittance might thus be compared directly to the change in hearing level caused by the impairment. The transmittance of the OME ear in Figure 4 was 6 to 10 dB below normal which was consistent with the elevation in auditory threshold resulting for this ear. To the best of our knowledge, no study has yet made detailed comparisons between the transmittance and the hearing loss.

The normal transmittance curve also has a simple shape that is useful for purposes of comparison. The transmittance of the normal ear is approximated quite well by three straight lines: an upward sloping line of 6 dB/octave at frequencies below 1 kHz, a horizontal line (slope of 0) within 3 dB of the maximum transmittance of 0 dB between 1 kHz and 4 kHz, and a downward sloping line at higher frequencies, having a slope that is typically between -4 and 0 dB (this effect is not well understood today). This overall pattern provides a convenient, well-defined reference in testing for abnormal power flow into the middle ear.

A problem with power-reflectance measurements is their relatively high variability in the region of a minimum. These measurements can be highly dependent on small experimental errors when the reflectance itself is small. In contrast, the transmittance data showed little variability in frequency regions where reflectance is small thereby making it easier to determine if the power flow into the ear is normal. The transmittance is more characteristic of hearing threshold measurements than the power reflectance. Another problem with reflectance measurements is the difficulty of establishing the normal curve in the region of the minimum. Simply averaging over many curves can result in a highly biased estimate of the minimum. Again, this is not a problem with the transmittance.

The measurements of normalized acoustic resistance and normalized acoustic reactance appear to be equally useful and need to be used in conjunction when evaluating the status of the middle ear, conditioned on the transmittance measures. Of the measurements considered, transmittance appears to be the most useful single measure. It shows distinct differences among the different middle-ear pathologies that are easy to identify since the transmittance curves are relatively smooth. In addition, the deviation from normal transmittance may be specified in decibels, thereby specifying the effect of the impairment in audiologically relevant terms. The observation that the shape of the normal transmittance curve approximates the middle-ear transfer function also allows for convenient assessment of abnormal transmittance data. Transmittance, however, does not tell the whole story, and it is advisable to use transmittance measurements (or any other reflectance-based measurements) in conjunction with both resistance and reactance measurements.

In conclusion, the early detection of hearing loss has been improved substantially by the use of evoked otoacoustic emissions. As in the game of leapfrog, each new advance introduces new obstacles and new opportunities for further advances. The problem of false positives in hearing screening presents an immediate challenge that needs to be addressed. The technology that provided the means for improved hearing screening using evoked otoacoustic emissions also provides the means for assessing middle-ear function using wideband measurements of acoustic power flow in the ear. This leap forward can be used not only to address the problem of false positives in hearing screening, but also to develop powerful new diagnostic techniques.

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