Effects of Tympanic Membrane Abnormalities on Auditory Function

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Abstract
This article discusses how several diagnostic tools used by audiologists inter-relate to anatomical abnormalities viewed by video otoscopy. Background of common middle ear pathology is reviewed, with emphasis on new research findings regarding pathophysiology. A review of video otoscopy, multifrequency tympanometry, and otoreflectance is provided. Case studies illustrate the integrated use of these diagnostic tools. Audiologic results are integrated with video otoscopy through case study analysis and interpretation. Understanding of the complexity of the physiologic and behavioral measurements is enhanced with the ability to closely inspect tympanic membrane pathology through video otoscopy. Multifrequency tympanometry, otoreflectance, and otoacoustic emissions (OAEs) allow us to more easily detect pathologic conditions such as cholesteatoma and chronic (silent) otitis media with effusion (OME).

Key Words: Audiometry, middle ear disease, otoacoustic emissions, otoreflectance, tympanometry, video otoscopy

Abbreviations: AOM = acute otitis media, EHF = extended high-frequency range, MFT = multifrequency tympanometry, OAE = otoacoustic emission, OM = otitis media, OME = otitis media with effusion, TM = tympanic membrane, TPP = tympanometric peak pressure, TT = tympanostomy tubes, TW = tympanometric width

Video otoscopy is a tool that contributes to a better understanding of external and middle ear anatomy and, therefore, a better understanding of the source of conductive hearing loss. Multifrequency tympanometry (MFT) provides comprehensive measurement of middle ear function and can be useful for distinguishing among various middle ear conditions. However, MFT is most useful when combined with otoscopic and audiometric findings. Video otoscopy and MFT have become practical techniques that audiologists can use to provide better information about the nature of conductive pathologies involving the tympanic membrane (TM) and changes over time with treatment.

In this article, integrated use of video otoscopy, MFT, otoreflectance, and audiologic results will be demonstrated through case study analysis and interpretation. Background of common middle ear pathology is reviewed, with emphasis on new research findings regarding pathophysiology. Basics of MFT, otoreflectance, high-frequency audiometry, and otoacoustic emissions (OAEs) are also reviewed, with emphasis on correlating these results with anatomical information gleaned from video otoscopy. Finally, several case studies are provided illustrating the combined use of these diagnostic tools.

We collected video otoscopy images using an operating microscope (Zeiss Model 310187, Carl Zeiss, Thornwood, NY) equipped with a camera (Javelin JE3462HR, Javelin Corp, Japan) and super VHS recorder (JVC HR-S6600U, US JVC Corp., Elmwood Park, NJ). Images of the TM during static and pneumatic pressure conditions were video-recorded at 25 power. The video recordings were converted to still photos using frame grabber software and the S-VHS input to
an audio-visual board in a Power Macintosh
computer. Tymanometric data were collected
using Virtual (Virtual Corp., Portland, OR) soft-
ware and hardware and Macintosh computer
hardware. These examples apply to MFTs
obtained with other equipment, although norm-
ative data needs to account for any differences
that could affect data, including pump speed,
direction of pressure change, and compensation
method used.

TYMPANIC MEMBRANE
ABNORMALITIES ASSOCIATED WITH
MIDDLE EAR DISEASE

Otitis Media

Otitis media (OM) is the most common of all
ear diseases in childhood and is second only to
upper respiratory infections in the number of
office visits to primary care physicians. While the
prevalence of OM has not decreased in modern
history, morbidity associated with the disease has
decreased. Prior to the advent of antimicrobial
therapy, OM was a serious, potentially life-
threatening disease, while it is now considered
almost a normal part of childhood and generally
transitory. A survey of office practices showed
that in 1990, 14 percent of all pediatric office vis-
its (including well-child visits) resulted in a
diagnosis of OM, and there were 24.5 million
office visits resulting in a diagnosis of OM in the
United States the same year (Schappert, 1992).
Two studies in Boston and Nashville showed
that peak incidence of OM is between 6 and 13
months of age (Teele et al, 1989; Wright et al,
1988), and that the majority of children, more
than 60 percent, have at least one episode of OM
by the age of 1 year. OM complications such as
chronic perforation with drainage, mastoiditis,
meningitis, and brain abscess are now rare in the
United States but are more common in develop-
ing countries and aboriginal populations (Blue-
stone and Klein, 1995). Usually, some amount of middle ear
fluid is present behind an inflamed TM. Infants
and young children often have fever associated
with AOM, and hearing loss may be present,
depending upon the amount of infected fluid
trapped within the middle ear space. By defini-
tion, AOM has a duration of less than 3 weeks.

OME is an inflammation of the middle ear
in which a collection of fluid is present in the mid-
dle ear space and the TM is intact (Bluestone,
1984). In OME, signs and symptoms of acute
infection (such as otalgia or fever) are not pre-
sent, and duration of the fluid is 3 weeks or
more. In subacute OME, fluid is present for 3
weeks to 2 to 3 months, while chronic OME is
defined as fluid present for 3 months or longer.
Even with antibiotic treatment (e.g., amoxi-
cillin), fluid associated with OME lasts 10 to 14
days in 70 percent of children following an
episode of AOM, in 29 percent for 2 months or
more, and in 10 percent for 3 months or more
(Teele et al, 1980). In children with glue ear
(defined as fluid persisting longer than 3 months,
with hearing loss), Maw and Bawden (1993)
showed that episodic fluid persists for 6 years
in 50 percent of ears not treated with tympa-
nostomy tubes (TTs). With insertion of tubes,
significantly fewer (25%) still had episodic fluid
6 years later.

Tympanosclerosis

Tympanosclerosis is a common sequela of
OM, particularly when TTs have been used to
treat OME. Tympanosclerosis is hyaline degen-
eration of the connective tissue within the mid-
dle layer of the TM (Bluestone et al, 1993). Bhaya
et al described a continuum of tympanosclerosis
from “early” (derangement of the middle fibrous
layer appearance), to “intermediate” (distinct
hyalinized area), to “late or mature” (distinct
plaque with or without calcification or ossifi-
cation). Tympanosclerosis occurs only in areas
of the TM that contain connective tissue, so it
is not seen in the pars flaccida and is most com-
mon in the anterior-inferior and posterior-infe-
rior quadrants, often appearing in a horseshoe
shape. Tympanosclerosis rarely occurs within
the middle ear space but may envelop the ossi-
cles in rare instances. Tympanosclerosis does
not appear to be associated with significant
hearing loss, unless it involves the ossicular
chain. Tympanosclerosis is frequently associ-
ated with changes in the tympanogram, includ-
ing decreased resonant frequency, possibly due
to mass loading of the TM (Hunter et al, 1993).
Often, areas of atrophy coexist with tympanosclerosis.

**Tympanic Membrane Atrophy**

Thinning or destruction of the middle fibrous layer of the TM results in decreased stiffness, or hypermobility. Atrophy can occur in small, segmented areas, often at the site of a previous spontaneous perforation or at a previous myringotomy site, or atrophy may be more generalized across the TM (Maw and Bawden, 1994b). While the mechanism that results in atrophy is not well understood, it occurs in conjunction with OM, due to inflammation (Ruhan et al., 1992). Activity of collagenase and negative middle ear pressure associated with eustachian tube dysfunction may be important factors. Atrophy may lead to atelectasis (retraction or collapse of the TM against middle ear structures) when combined with eustachian tube dysfunction.

Atrophy of the TM is associated with increased acoustic admittance, notching at low frequencies, and narrowed tympanometric width (TW) (Feldman, 1974; Osguthorpe, 1986). These changes result from the loss of stiffness that accompanies loss of connective tissue within the middle layer of the TM. Along with increased admittance and decreased width, the resonant frequency is also often decreased when measured with MFT. These changes are consistent with theoretical predictions based on decreases in stiffness reactance (Vanhuysse et al., 1975). Atrophy may be associated with conductive hearing loss if it is followed by retraction of the TM (Giebink et al., 1996).

**Tympanic Membrane Retraction and Atelectasis**

As with other sequelae of otitis media, atelectasis of the TM occurs on a continuum. Stages of pars tensa atelectasis, which have been described in the literature (Sadé et al., 1981; Maw and Bawden, 1994), can be organized into an anatomically defined hierarchical grading system for pars tensa retraction. We have used and refined a grading system over the past 5 years in a prospective longitudinal study of TM sequelae in children with chronic OME (Giebink et al., 1996). In Grade 0, the position of the TM is neutral, with no foreshortening of the long process of the malleus. In Grade 1, the malleus is foreshortened and the TM has a concave appearance, but there is no evidence of atrophy (the TM is without retraction pockets or areas of hypermobility, viewed using pneumatic otoscopy). Grade 2 involves both retraction and atrophy of the TM (either segmental or generalized) but the TM is not touching any bony structures (ossicles or promontory). In Grade 3, retraction and atrophy progress such that the TM touches bone, usually the incus or the promontory, but none of the retracted area(s) is pulled out of view. In the most severe form (Grade 4), the retracted area is touching bone and a portion of the retraction pocket is hidden from view. Because stages 3 and 4 may be precursors to cholesteatoma, referral to an otolaryngologist is essential. Atelectasis may lead to cholesteatoma by forming collections of squamous debris and granulation tissue. These require careful otologic observation. Retraction and atrophy can lead to conductive hearing loss, and these sequelae appear to be late outcomes of earlier chronic OME (Giebink et al., 1996). A prospective, randomized study found no significant effect of tubes upon incidence of atelectasis, pars flaccida retraction, or hearing levels 12 years after TT treatment (Maw and Bawden, 1994).

**Cholesteatoma**

More properly called a keratoma, cholesteatoma is "a collection of keratinizing stratified squamous epithelium and an accumulation of desquamating epithelium" (Bluestone and Klein, 1995). In a study of acquired cholesteatoma in 1024 children and adults, Sheehy et al. (1977) found that the majority occurred in the attic or the posterosuperior quadrant (73%), while 18 percent had a complete marginal perforation, 6 percent had a partial, central perforation, and only 3 percent had an intact TM. Cholesteatomas are rare, even among people with histories of chronic OME. In two groups of over 300 children children treated with TT, prevalence of cholesteatoma 6 to 16 years later ranged from 1 to 2 percent (Daly et al., 1997).

**MEASUREMENT OF MIDDLE EAR FUNCTION**

**Multifrequency Tympanometry**

Tympanometry is typically performed using a single, low-frequency probe tone, usually 220 or 226 Hz, as has been done since the early 1960s when the first commercial tympanometry instrument, the Madsen Z061, was developed based on research instruments designed by
(Terkildsen and Scott-Nielsen, 1960). The single-frequency, single-component tympanogram might be thought of as analogous to measuring hearing sensitivity at a single frequency. While many cases of hearing loss will be detected, a significant number will go unnoticed since hearing sensitivity varies with frequency. The acoustic admittance of the ear also varies with frequency. Wideband measurements of complex admittance (susceptance and conductance) provide more information about performance of the middle ear than does admittance alone at a single frequency. Tympanograms at 226 Hz can be easily quantified to obtain (1) peak compensated static acoustic admittance, abbreviated Y (will be referred to here as static admittance for simplicity); (2) tympanometric gradient or width (TW); and (3) tympanometric peak pressure (TPP). These quantities are not so easily applicable to MFTs. Calculation of static admittance at higher frequencies where tympanograms have multiple peaks is complicated. At frequencies above 226 Hz, qualitative assessment of tympanometric patterns, as well as quantitative measurement of the resonant frequency of the middle ear, is useful.

A theoretical model of tympanometry patterns obtained by MFT was developed by Vanhuyse et al (1975) at the University of Antwerp. The Vanhuyse model has been validated for normal adults (Margolis and Goycoolea, 1993) and children (Hunter et al, 1993), but tympanograms of infant ears do not follow expected patterns until approximately 4 months of age (Holte et al, 1991). The Vanhuyse model is useful for understanding the effects of pathology on middle ear function. A detailed description of the Vanhuyse model is beyond the scope of this article but the reader is referred to Shanks and Shelton (1991) or Hunter and Margolis (1992) for a discussion of the clinical application of the model. Briefly, normal ears exhibit an orderly progression from a 1B1G (one peak in susceptance and conductance) pattern at low frequencies to a 3B1G pattern, then 3B3G, and finally a 5B3G pattern at higher frequencies. However, many normal ears will not progress through all four Vanhuyse types below 2000 Hz. Although the 1B1G, 3B1G, 3B3G, and 5B3G patterns occupy progressively higher frequency regions, respectively, there is considerable overlap among the pattern types at a given frequency in any group of normal individuals. Patterns that are not described by the Vanhuyse categories (and so are called "irregular") occur with increasing prevalence as a function of increasing frequency. In addition to orderly progression through the Vanhuyse types, notches should occur centrally in the tympanogram and within a relatively narrow pressure range. Broad notches or laterally located notches may indicate abnormal middle ear function.

Resonant frequency can be easily measured by examining the susceptance tympanograms as a function of frequency. When the central notch in susceptance falls at or below the tail of the tympanogram on the positive pressure side, then resonant frequency has been reached. Resonant frequency cannot be reliably measured, however, if the tympanograms do not follow shapes according to the Vanhuyse model. Clinical interpretation of resonant frequency requires norms that are specific to the methods used to obtain MFTs and to the population tested. Normative studies (Hunter and Margolis, 1992; Hunter, 1993; Margolis and Goycoolea, 1993) demonstrate that resonant frequency is lower (1) in adults compared to children, (2) for the positive pressure compensation method compared to negative pressure compensation, and (3) for faster rates of earcanal pressure change during tympanometry. Normative data is provided in Table 1.

<table>
<thead>
<tr>
<th>Y (mmho)</th>
<th>TW (daPa)</th>
<th>Res F SF (Hz)</th>
<th>Res F SP (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Children</td>
<td>0.52</td>
<td>114</td>
<td>1153</td>
</tr>
<tr>
<td>3-10 yr</td>
<td>0.25-1.05</td>
<td>80-159</td>
<td>850-1525</td>
</tr>
<tr>
<td>Adults</td>
<td>0.79</td>
<td>106</td>
<td>1135</td>
</tr>
<tr>
<td>19-49 yr</td>
<td>0.30-1.70</td>
<td>42-183</td>
<td>800-2000</td>
</tr>
</tbody>
</table>

*Means and 90% ranges for each of the variables are listed.
1From Hunter (1993); n = 56; 2From Margolis and Goycoolea (1993); n = 56.
Y = peak compensated static acoustic admittance; TW = tympanometric width at 50% of Y; Res F SF = resonant frequency measured at +200 daPa from the susceptance tympanogram, measured by sweeping frequency from 500 to 2000 Hz as the air pressure is changed in 14 daPa steps from positive to negative; Res F SP = resonant frequency measured at +200 daPa from the susceptance tympanogram, measured by sweep pressure (tympanograms performed at each of 13 frequencies between 500 and 2000 Hz, with pump speed of 250 daPa/sec).
Table 1 for 226-Hz variables as well as resonant frequency measured with multifrequency susceptance tympanograms.

Because it involves more time and cost, MFT is appropriately used as a second-line diagnostic test. When the 226-Hz tympanogram is flat, dysfunction is obviously present, and MFT probably provides little additional information. For cases of normal hearing or sensorineural hearing loss, with normal 226-Hz tympanograms and reflexes, MFT also is unlikely to provide useful clinical information, unless there are subjective complaints or history or examination suggesting middle ear disease. However, in cases of conductive hearing loss and tympanograms that are not flat, MFT may provide valuable information about the physical state of the middle ear. Specifically, wideband measurements of susceptance and conductance are sensitive to some middle ear pathologies that are not detected by single-frequency tympanometry. In addition, MFT can provide information on the nature of the abnormality by evaluating the mass and stiffness components of the middle ear admittance.

Otoreflectance

Currently available instruments for MFT are limited to frequencies below 2 kHz. At higher frequencies, the complexity of ear canal acoustics and standing waves in the ear canal require a more complex calibration method than is currently implemented by clinical instruments. Laboratory systems have been developed that solve these calibration problems and provide the capability to measure the impedance of the ear over a much wider frequency range (Keefe et al., 1993; Voss and Allen, 1994). In addition to measuring the admittance or impedance in the ear canal, these systems have been used to measure the energy reflectance of the ear, the proportion of energy that is reflected by the eardrum. Energy reflectance is a potentially useful tool for evaluating middle ear function because it is relatively free of the ear canal effects that complicate admittance measurements at high frequencies. A project is underway in our laboratory to study the clinical utility of this technique.

Figure 1 shows average reflectance measurements from 12 normal adult ears at three ear canal air pressures (ambient, +300 daPa, −300 daPa). At ambient pressure, the reflectance of the ear is very high at low frequencies, indicating that very little energy is absorbed by the middle ear. At higher frequencies, there are two broad minima in the regions of 1200 and 4000 Hz. When the ear canal is pressurized, a single, sharp, high-frequency minimum occurs, suggesting that transmission into the middle ear actually improves in that frequency region. This is the result of stiffening the middle ear by applying air pressure on one side of the eardrum.

MEASUREMENT OF AUDITORY FUNCTION IN MIDDLE EAR DISEASE

Conventional and Extended High-Frequency Thresholds

Conductive hearing loss associated with middle ear disease can give some clues to the underlying pathology by examining the shape, or configuration, of the loss. The magnitude of loss depends upon the degree of interference with ossicular vibration and does not indicate the seriousness of the pathology (Margolis and Shanks, 1991). For example, we will illustrate a case of cholesteatoma in this article on two separate areas of the TM that resulted in no measurable conductive loss. OME can result in conductive hearing loss of up to 50 dB HL (Fria et al., 1985; Hunter et al., 1994) and is mainly dependent on the level of fluid within the middle ear space. The higher the fluid level, the greater the degree of ossicular damping.

OME can also result in sensorineural hearing loss, particularly in the extended high-frequency (EHF) range. The EHF range appears to be more sensitive to cochlear effects of OME, possibly due to the proximity of high-frequency
regions of the cochlea to the round window membrane and the middle ear space. We reported that significant EHF persists following complete clinical resolution of OME and may progress over time (Hunter et al., 1996). In that study, EHF loss correlated with severity of OM and number of tubes. However, in the conventional frequency range, there is rarely an effect on bone-conduction levels unless cholesteatoma or ossicular erosion has occurred.

Otoacoustic Emissions

OAEs have proven to be useful for a variety of clinical purposes, including infant hearing screening, evaluation of difficult-to-test patients, distinguishing cochlear from retrocochlear pathology, and evaluation of patients for pseudo-hypacusis. (See Robinette and Glattke [1997] for a thorough review of the clinical applications of OAEs.) Because OAEs are affected by disturbances of the middle ear, they are also useful for evaluation of middle ear function.

Studies of the effects of ecarcanal air pressure (Naeva et al., 1982) and middle ear pressure (Trine et al., 1993) on OAEs have shown that air pressure on either side of the eardrum reduces OAE amplitudes and reproducibilities. OAEs recorded at ambient ecarcanal air pressure may be abnormal due to cochlear disease, conductive hearing loss, or middle ear pressure. By recording emissions with the ecarcanal air pressure adjusted to compensate for middle ear pressure, the effect of air pressure can be eliminated as a source of abnormal OAE test results. This is illustrated in Case 2.

INTEGRATION OF DIAGNOSTIC TOOLS: CASE STUDIES

Case 1: Acute Otitis Media

ES is a 5-year-old girl with no previous history of chronic OME, hearing loss, or ear surgery. She had an upper respiratory infection 2 weeks previously and has not been hearing well the past 2 days. She awoke with acute otalgia of the right ear during the night and was brought to clinic the next morning. Video otoscopy showed a reddened, bulging TM in the posterior and anterior regions on the right (Fig. 2). Superiorly, the TM was retracted, with severe foreshortening of the long process of the malleus. The TM had poor mobility. On the left, there was severe retraction with foreshortening of the malleus (see Fig. 2), but no redness or evidence of fluid. Audiometry showed a flat to downsloping conductive loss on the right and a rising, conductive loss on the left (Fig. 3). Tympanometry showed flat/rising tympanometry on the right, suggesting positive pressure consistent with AOM and an extreme negative pressure on the left. The pressure differential between ears was over 500 daPa (Fig. 4). OAEs were performed to confirm the pure-tone audiogram (Fig. 5). On the right, only very weak responses with poor reliability were obtained in the low frequencies and responses were absent in the high frequencies. On the left, emissions were present at high frequencies but were absent for low frequencies. Antibiotics were prescribed, and follow-up otoscopy and audiometry was recommended. This case illustrates excellent agreement between

Figure 2  Video otoscopy for patient ES. Left panel: right TM, showing AOM, with reddened and bulging areas inferiorly. Retraction along malleus is evident shown by arrow. Right panel: left TM, showing severe foreshortening of the long process of the malleus.

Figure 3 Audiogram of patient ES. Note rising configuration on left and sloping-flat configuration on right.
behavioral audiometry and OAEs, which showed frequency-specific findings that validated the audiogram. The tympanogram was unusual in the extreme positive pressure recorded but was consistent with the severely bulging TM on the right. The combination of tympanometry and OAEs provides a powerful supplement to otoscopy in pediatric diagnosis of ear and hearing disorders.

Case 2: Eustachian Tube Dysfunction and OAEs

This case illustrates the complicating effects of eustachian tube dysfunction and the resulting middle ear pressure on the interpretation of OAEs.

SR is an 8-year-old boy who had recurrent OM. He had a history of providing unreliable responses to pure-tone testing. The audiogram (Fig. 6) shows an air-bone gap in the left ear but the speech-recognition threshold suggested that the pure-tone thresholds were not accurate. Otomicroscopy (Fig. 7) indicated a severe retraction of the left TM with contact between the pars tensa and the incus. Because of the questionable pure-tone responses, the audiogram did not clearly indicate whether or not there was a mechanical disturbance of the middle ear affecting transmission to the cochlea. Conventional and MFT and OAEs were recorded to help resolve this question.
Compared to the normative data in Table 1, 226-Hz tympanograms (Fig. 8) indicated normal static admittance in the right, high admittance in the left, normal TWs, and significant negative middle ear pressures bilaterally (210 and 180 daPa in the right and left, respectively). MFT indicated a normal resonance frequency on the right and an abnormally low resonance frequency on the left (Fig. 9). An abnormal resonance frequency in the presence of high admittance is frequently due to a monomeric TM and is typically not associated with conductive hearing loss.

OAEs recorded with ambient earcanal air pressure were abnormal bilaterally. In the right ear, a small response was present, only at 2 kHz. In the left ear, there was no response. The apparent response at 4 kHz in the left was due to stimulus ringing, which occurs more frequently when there is high middle ear pressure.

When OAEs were recorded with the earcanal air pressure adjusted to compensate for the middle ear pressure, robust responses were obtained from both ears, with larger responses from the right (Fig. 10). These results indicate that there is, at worst, a slight reduction in middle ear transmission on the left. This is not unexpected in view of the abnormal TM appearance and
suggests that there is no serious impairment of the function of the ossicular chain.

This case illustrates the value of compensating for negative middle ear pressure when recording OAEs.

**Case 3: Tympanosclerosis**

JF is a 9-year-old girl with a history of recurrent OME and AOM, treated with tubes at the age of 1 year. She has had periodic conductive hearing loss associated with recurrences of OME and has been followed routinely for 8 years. Her hearing has gradually improved, and she currently has no evidence of OME and no ear-related symptoms. She has had tympanosclerosis noted on examination for several years, covering the peripheral portion of both TMs in a horseshoe configuration (Fig. 11). The sclerosis has not changed over time in size or area. Hearing sensitivity was normal in the conventional frequencies (Fig. 12).

Hearing in the extended high frequencies was below age-referenced norms. For both ears, 226-Hz tympanograms showed normal peak pressure, high static admittance, and narrow TW (Fig. 13). MFT showed a low resonant frequency for both ears. Patterns were normal Vanhuyse types at all frequencies (Fig. 14). This case illustrates that despite large areas of tympanosclerosis, there is little or no effect on hearing sensitivity for the conventional region, at least when the sclerosis is not generalized across the central portion of the TM. The tympanograms show patterns consistent with decreased stiffness or increased mass, which is often seen in conjunction with tympanosclerosis. This may occur due to loss of connective tissue within the middle layer of the TM and increased mass due to tympanosclerosis.

**Case 4: Cholesteatoma**

This case illustrates the value of MFT and video otoscopy in conjunction to detect cholesteatoma. SP is an 8-year-old boy who had tubes placed at the age of 1 year for chronic OME. He required reinsertion of tubes but then did well for a number of years with only occasional episodes of OME. However, he developed retraction pockets in the right ear, which were followed closely and were observed to deepen. SP was seen for a routine follow-up visit, during which no ear problems or symptoms were reported.
Figure 14 Multifrequency tympanograms for patient JF (left ear on left panel, right ear on right panel). Note low frequency for resonance on the right (900 Hz left ear, 710 Hz right ear) and normal Vanhuyse patterns.

Hearing was normal for the conventional range and were borderline-normal for the EHF region, with no evidence of air-bone gaps (Fig. 15). For the left ear, 226-Hz tympanometry showed abnormally high admittance with normal TW. The right ear showed an asymmetric shape with slightly positive pressure, normal admittance, and width (Fig. 16). The slope of the negative pressure side of the tympanogram on the right was shallow compared to the slope on the positive pressure side. In contrast to the normal 226-Hz tympanogram, MFTs showed flat susceptance and conductance at all frequencies for the right ear (Fig. 17). Video otoscopy showed suspicious retraction pockets filled with debris in the anterior-inferior quadrant of the pars tensa and in the pars flaccida (Fig. 18). He was referred immediately to an otolaryngologist, who performed exploratory tympanotomy and found early cholesteatoma material, restricted to the TM, and no erosion of the ossicles.

In this case, there was no indication from the audiogram or 226-Hz tympanogram that serious ear disease was present. Additionally, there were no symptoms that raised a warning sign. MFT was distinctly abnormal and this correlated with the abnormal video otoscopy exam. Early detection and treatment was possible in this case, while the cholesteatoma was restricted to the TM. This child is at risk for future development of cholesteatoma so will be followed regularly by his otolaryngologist.

Case 5: Chronic OME

JT is a 7-year-old boy who is being followed for recurrent OM. On a routine follow-up visit, his mother reported that there have been no recent symptoms of ear disease. His audiogram...
Figure 17  MFT for patient SP for the right ear. Tympanograms are flat at all frequencies 500 Hz and above, in contrast to the 226-Hz tympanogram.

(Fig. 19) indicated essentially normal hearing with a slight air-bone gap on the right. His 226-Hz tympanograms were normal (Fig. 20) but MFTs were abnormal on the right (Fig. 21). Normally, susceptance and conductance tympanograms should have a single peak at low frequencies. Susceptance will show a notch when the resonant frequency is approached, and the center of the notch will drop below the tails of the tympanogram when the middle ear is in resonance. The frequency at which this occurs is known as the resonant frequency. In this case, the susceptance notch at 500 Hz indicates a very low resonant frequency compared to the values in Table 1; the patterns at 710 and 1250 Hz do not conform to the Vanhuyse model, and the 1800-Hz tympanograms are nearly flat. Video otoscopy indicated severe disease on the right (Fig. 22). No landmarks were visible. On pneumatic otoscopy, only a small portion of the right eardrum was mobile (shown by arrow in Fig. 22).

This case illustrates that severe middle ear disease can be relatively asymptomatic. The audiogram and 226-Hz tympanograms probably would not have raised any suspicion that would have led to medical referral. There was no otalgia or otorrhea and the parent had no

Figure 18  Video otoscopy for patient SP. Note suspicious areas in pars tensa (left panel) and pars flaccida (right panel).

Figure 19  Audiogram of patient JT. Note the slight air-bone gap in the right ear.

Figure 20  Patient JT: 226-Hz tympanograms. Static admittance is high in both ears (2.0 mmho); width is normal on the right (84.5 daPa) and narrow on the left (37.6 daPa).
Figure 21  Multifrequency susceptance (B) and conductance (G) tympanograms from patient JT for the right ear. The abnormal resonant frequency is evident from the susceptance notch at 500 Hz. Note also the irregular conductance tympanograms at 710 and 1250 Hz and the nearly flat patterns at 1800 Hz.

Figure 22  Otomicroscopy of the right ear of patient JT. The eardrum is devoid of landmarks. On pneumatic otoscopy only the region indicated by the arrow was mobile.

Figure 23  Audiogram of patient JB. Note the air-bone gaps in the right ear.

Figure 24  Patient JB: 226-Hz tympanograms. The right ear tympanogram is characterized by normal static admittance and width and a TPP of –260 daPa. The left ear tympanogram shows high static admittance, normal width, and a TPP of –14 daPa.

Case 6: Otorelectance

JB is a 9-year-old girl who was being followed for recurrent OM. She had TTs inserted at age 4 and surgical removal of a middle ear osteoma at age 5. Since then she has had several more episodes of OM. On a follow-up visit, her audiogram showed 10- to 20-dB air-bone gaps in the right ear (Fig. 23). In the right ear, 226-Hz tympanograms (Fig. 24) indicated normal admittance and width with a TPP of –260 daPa. Above 226 Hz, multifrequency tympanograms (Fig. 25) were abnormal, showing irregular, flattened patterns. At 500 Hz, there were multiple peaks and valleys that do not correspond to a Vanhuyse-type pattern. At 560 Hz, a central notch appears in susceptance and seems to indicate resonant frequency. However, this notch persists without progressive development into other Vanhuyse types, and the notch does not deepen and broaden as expected with increases in frequency. At 900 Hz, the tympanograms flatten, which indicates reduced energy transmission. Video otomicroscopy revealed bubbles and fluid lines on the eardrum indicating effusion in the middle ear (Fig. 26). Because the effusion did not occupy the entire middle ear space and an air space remained, a nearly-normal 226-Hz admittance tympanogram was present. The
abnormal tympanograms at higher frequencies demonstrate the sensitivity of MFT to some conditions that are not detected by single-frequency measurements.

Reflectance measurements, recorded at three earcanal air pressures, are shown in Figure 27, along with average results from normal adult ears. Because of the middle ear pressure, reflectance at ambient ear canal pressure resembles that of a normal ear under pressure. When the middle ear pressure is compensated by a like pressure in the earcanal, reflectance values can be compared to those of normal ears at ambient pressure. This comparison reveals that the reflectance is abnormally high in the regions normally associated with low reflectance (1200 and 4000 Hz).

In this case, single-frequency tympanometry did not clearly identify the middle ear pathology. MFTs were grossly abnormal at all frequencies above 226 Hz, providing a clear indication of abnormal middle ear dysfunction. Reflectance measurements appear to indicate an abnormality but adequate norms are not yet available.

Figure 25  Multifrequency susceptance (B) and conductance (G) tympanograms from patient JB for the right ear. Abnormal patterns are found at several frequencies.

Figure 27  Reflectance functions for patient JB (right ear) at three earcanal air pressures (0, +300 daPa, −300 daPa). Also shown is the average reflectance at ambient pressure for 12 normal subjects (from Fig. 1). At 0 and +300 daPa, JB’s reflectance resembles a normal ear under pressure (see Fig. 1). When the earcanal air pressure is set to compensate for the middle ear pressure (−300 daPa), a pattern is revealed that shows elevated reflectance in the regions associated with low reflectance in normal ears (1200 and 4000 Hz).

Figure 26  Both panels: otomicroscopy of the right ear of patient JB. Note the bubbles and fluid line (arrows).

Figure 28  Audiogram for patient JT. Note conductive loss on the right.
Case 7: Cartilage Graft

JT is a 32 year-old-man who received a cartilage graft to repair a TM perforation secondary to chronic OM. This case illustrates the effect of surgical repair of the TM, particularly when the mass and stiffness are altered dramatically, as occurs with use of cartilage. Grafts are used to establish a safe postoperative situation and to improve hearing function. They can result in unusual tympanometric patterns and residual hearing loss due to changes in mass and stiffness elements of the TM, as illustrated in this case.

This patient's audiogram revealed a unilateral, flat conductive loss of 22 dB HL (Fig. 28). Tympanograms at 226 Hz showed normal admittance but broad width, especially on the right (Fig. 29). Tympanograms were irregular between 500 and 710 Hz. At 1000 and 1250 Hz, normal-appearing 3B1G and 3B3G patterns were obtained. The cartilage graft appeared to have the most effect on middle ear function between 226 to 710 Hz (Fig. 30). Video otoscopy revealed a white TM with no visible landmarks (Fig. 31). On pneumatic otoscopy, the drum moved very little, except for a small portion of normal TM tissue near the anterior margin that was relatively translucent. This case illustrates the value of performing video otoscopy in conjunction with audiometric tests. The hearing loss in this case is explained by the surgical alteration and is consistent with the abnormalities in the MFTs.

SUMMARY

Video otoscopy provides a wealth of information about the physical state of the earcanal and TM, which can be recorded permanently to make comparisons with the same ear at a later date. This provides a method to help determine if changes in audiologic tests...
can be correlated with anatomical changes that can be visualized. Understanding of the complexity of the physiologic and behavioral measurements is enhanced with the ability to closely inspect TM pathology.

Tests such as MFT, otoreflectance, and OAEs allow us to improve the sensitivity of detection of pathologic conditions such as cholesteatoma and chronic OME. These tests can provide useful clinical information when placed within the context of video imaging of the ear canal and TM. It is clear from the cases outlined here that single-component 226-Hz tympanometry is insufficient to detect some serious cases of middle ear pathology. Therefore, MFT should be used in cases where video otoscopy is abnormal, or there is conductive hearing loss or a history suggesting middle ear problems. Otoreflectance holds promise as a future broadband test of complex admittance of the ear.

Acknowledgment. This work was supported by a grant from the National Institutes of Health (PO1-DC000133) and the Lion's 5M International Hearing Foundation.

REFERENCES


