NIH Public Access
Author Manuscript
Ear Hear. Author manuscript; available in PMC 2013 January 1.

Published in final edited form as:
Ear Hear. 2012 January ; 33(1): 19–34. doi:10.1097/AUD.0b013e31822ccb76.

NIH-PA Author Manuscript
NIH-PA Author Manuscript
NIH-PA Author Manuscript

Ear-Canal Reflectance, Umbo Velocity and Tympanometry in Normal Hearing Adults

John J Rosowski, PhD[1,2,3,*], **Hideko H. Nakajima, MD, PhD**[1,2,3,*], **Mohamad A. Hamade, MD**[1,2], **Lorice Mafoud, MD**[1,2], **Gabrielle R. Merchant, BA**[1,3], **Christopher F. Halpin, CCC-A, PhD**[4], and **Saumil N. Merchant, MD**[1,2,3]

[1]Eaton-Peabody Laboratory, Massachusetts Eye and Ear Infirmary, Boston, MA

[2]Department of Otology and Laryngology, Harvard Medical School, Boston, MA

[3]Speech and Hearing Bioscience and Technology Program, Harvard-MIT Division of Health Sciences and Technology, Cambridge, MA

[4]Department of Audiology, Massachusetts Eye and Ear Infirmary, Boston, MA

Abstract

Objective—This study compares measurements of ear-canal reflectance (*ECR)* to other objective measurements of middle-ear function including, audiometry, umbo velocity (V_U), and tympanometry in a population of strictly defined normal hearing ears.

Design—Data were prospectively gathered from 58 ears of 29 normal hearing subjects, 16 female and 13 male, aged 22–64 years. Subjects met all of the following criteria to be considered as having normal hearing. (1) No history of significant middle-ear disease. (2) No history of otologic surgery. (3) Normal tympanic membrane (TM) on otoscopy. (4) Pure-tone audiometric thresholds of 20 dB HL or better for 0.25 – 8 kHz. (5) Air-bone gaps no greater than 15 dB at 0.25 kHz and 10 dB for 0.5 – 4 kHz. (6) Normal, type-A peaked tympanograms. (7) All subjects had two “normal” ears (as defined by these criteria). Measurements included pure-tone audiometry for 0.25 – 8 kHz, standard 226 Hz tympanometry, Ear canal reflectance(*ECR)* for 0.2 – 6 kHz at 60 dB SPL using the Mimosa Acoustics HearID system, and Umbo Velocity (V_U) for 0.3 – 6 kHz at 70–90 dB SPL using the HLV-1000 laser Doppler vibrometer (Polytec Inc).

Results—Mean power reflectance ($|ECR|^2$) was near 1.0 at 0.2– 0.3 kHz, decreased to a broad minimum of 0.3 to 0.4 between 1 and 4 kHz, and then sharply increased to almost 0.8 by 6 kHz. The mean pressure reflectance phase angle ($\angle ECR$) plotted on a linear frequency scale showed a group delay of approximately 0.1 ms for 0.2 – 6 kHz. Small significant differences were observed in $|ECR|^2$ at the lowest frequencies between right and left ears, and between males and females at 4 kHz. $|ECR|^2$ decreased with age, but reached significance only at 1 kHz. Our *ECR* measurements were generally similar to previous published reports. Highly significant negative correlations were found between $|ECR|^2$ and V_U for frequencies below 1 kHz. Significant correlations were also found between the tympanometrically determined peak total compliance and $|ECR|^2$ and The results suggest that middle-ear compliance V_U at frequencies below 1 kHz. contributes significantly to the measured power reflectance and umbo velocity at frequencies below 1 kHz, but not at higher frequencies.

Conclusions—This study has established a database of objective measurements of middle ear function (ear-canal reflectance, umbo velocity, tympanometry) in a population of strictly defined

---

Corresponding Author: John J Rosowski, Eaton-Peabody Laboratory, Massachusetts Eye and Ear Infirmary, 243 Charles Street, Boston, MA 02114, Phone: 617 573 4237, Fax: 617 720 4408, John_Rosowski@meei.harvard.edu.

[*]Drs. Rosowski and Nakajima shared the responsibilities of first authorship.

NIH-PA Author Manuscript NIH-PA Author Manuscript NIH-PA Author Manuscript

normal hearing ears. The data will promote our understanding of normal middle ear function, and will serve as a control for comparison to similar measurements made in pathological ears.

INTRODUCTION

Given the widespread occurrence of middle-ear disease and the difficulty of accurately identifying the cause of conductive hearing loss (Merchant, McKenna & Rosowski 1998; Merchant. Ravicz et al. 1998; Nadol & McKenna 2004; Gulya et al. 2010), non-invasive, cost-effective diagnostic tools that reliably distinguish among middle-ear pathologies would be valuable. These would aid in better selection of cases for surgery, surgical preparation, patient counseling, as well as help prevent unnecessary surgeries, e.g. avoid exploratory middle-ear surgery for superior semicircular-canal dehiscence presenting with conductive hearing loss.

The most common clinical objective measurement performed to assess middle-ear abnormality is 226 Hz tympanometry. Tympanometry is often used for the diagnosis of middle-ear effusion (Jerger 1975; Feldman 1976; Alberti & Jerger 1974; Margolis & Shanks 1985). Publications have also reported on tympanometry's ability to aid in the diagnosis of pathological fixation of the malleus and stapes as well as ossicular discontinuity (Feldman 1976; Margolis et al. 1978; Margolis and Shanks 1985). However, the wide range of normal tympanometric values coupled with the relative insensitivity of tympanometry to many instances of ossicular pathology argue against its use as a stand-alone objective measure of ossicular pathologies (Jerger 1975; Margolis & Hunter 1999; Nakajima, Ravicz, Rosowski et al. 2005). This insensitivity results because the compliance of the tympanic membrane (TM) generally dominates the tympanometric results, and an unusually compliant or stiff TM, or compliant ossicular joints, can mask the effects of ossicular pathology and interfere with diagnosis. Because of this interference, diagnostic schemes that include tympanometry use a combination of different test results, including audiometry and acoustic reflex testing before deciding on a diagnosis.

Several authors have suggested an increased sensitivity of multi-frequency tympanometry to various middle-ear pathologies (Wada et al. 1989; Lilly 1984; Margolis & Goycollea 1993; Zhao et al. 2002; Shahnaz & Polka 1997, 2002). However, while multifrequency-tympanometry does add more objective diagnostic information, such as the frequency of middle-ear resonance, the added information has not raised the sensitivity or selectivity of tympanometric diagnoses of middle-ear disease to the point where they can stand alone. Indeed, there is no single objective measure that can by itself accurately diagnose most forms of conductive hearing loss.

Umbo velocity (V_U) measurement performed by laser Doppler vibrometry (LDV), in combination with audiometry has been shown to discriminate various middle-ear and inner-ear diseases quickly and with a high degree of sensitivity and selectivity (Huber et al. 2001; Rosowski et al. 2008). Unlike tympanometry, which measures the response of the whole TM, umbo velocity measurements are less influenced by the compliance of the TM, and are a more direct measure of the dynamic state of the middle-ear ossicles (Nakajima, Ravicz, Merchant et al. 2005). For example, Nakajima and coworkers (Nakajima, Ravicz, Merchant et al. 2005) showed that while umbo velocity measurements were sensitive to changes in ossicular stiffness, tympanometry measurements on the same temporal bones were not.

Although the combination of LDV and audiometry performs well in diagnosing various ossicular pathologies, there are practical limitations regarding the use of the device and technique: The commercially available LDV systems in use are not FDA approved for clinical application and are therefore restricted to research facilities. Secondly, measuring

NIH-PA Author Manuscript

NIH-PA Author Manuscript

NIH-PA Author Manuscript

umbo velocity requires a clinician with comfort and experience in otoscopic examinations of pathological ears under microscopy, e.g. skill is required to successfully and consistently aim the laser on the umbo. (Arechevo et al. (2009) have a different view of the importance of experience in LDV measurements; however, we have observed an increase in the error of laser placement in more inexperienced clinicians.) Thirdly, the data collection process requires calibration and measurement software that is not standardized across the different research facilities.

Ear-canal reflectance (*ECR*) is another measure of the mechano-acoustic response of the middle ear to sound stimulation in the ear canal. Like tympanometry *ECR* is affected by the motion of the entire TM, where *ECR* can be calculated by taking the complex ratio of sound pressure reflected by the TM to the sound pressure incident on the lateral surface of the TM (Keefe et al. 1992). Figure 1 shows an illustration of the incident sound wave, reflected sound wave and the absorbed sound wave. Power reflectance (also known as energy reflectance) is calculated by taking the square of the magnitude of the ear canal reflectance, $|ECR|^2$. In the case of a completely passive response of the TM, the power reflectance varies from 1, when all the energy of sound is reflected back to the ear canal (100% reflectance), to 0 when all of the incident sound energy is absorbed by the middle and inner ear.

Ear-canal reflectance is related to the acoustic impedance looking into the ear canal:

$$ECR=\frac{\frac{Z}{Z_0}-1}{\frac{Z}{Z_0}+1} \quad \text{(Eqn. 1)}$$

where: Z is the impedance measured looking into the ear canal, and $Z_0 = \rho c/A$ is the characteristic impedance of the ear canal, with ρ the density of air, c the speed of sound in air (both at the measurement's temperature and atmospheric pressure), and A the cross-sectional area of the ear canal. (The ear-canal impedance Z and *ECR* can vary with frequency.) Z is computed from the sound pressure produced in the ear canal by a calibrated sound source (Allen 1986; Keefe et al. 1993,94; Lynch et al. 1994; Voss & Allen 1994).

Ear-canal reflectance has been used to quantify the acoustic response of the TM since the 1970's (Blauert & Platte 1974; Mehrgardt & Mellert 1977; Stinson et al. 1982; Hudde 1983; Keefe et al. 1993; Voss & Allen 1994), and studies regarding its clinical application have been increasing since the mid 1990's (Allen et al. 2005; Feeney & Keefe 1999, 2001; Feeney et al. 2003; Keefe & Levi 1996; Margolis et al. 1999; Shahnaz et al. 2009; Vander Werff et al. 2007). Keefe and Levi (1996) proposed measuring ear-canal power reflectance, $|ECR|^2$, because it is less dependent on the measurement location within the ear canal compared to impedance or admittance, which are greatly affected by the presence of longitudinal standing waves in the sound pressure within the canal, particularly at frequencies above 1 kHz. Major assumptions in the calculation of *ECR* are that the ear canal is a tube of uniform area with rigid walls, and that there is no loss of acoustic power within the external ear. If these assumptions are valid, the power reflectance measured at any point in the ear canal equals the power reflectance at the TM. The efficacy of power reflectance measurements in the diagnosis of various middle-ear pathologies is still under study (Feeney et al. 2003; Allen et al. 2005; Hunter et al. 2010; Shanaz and Polka 2012), and is the point of our interest in *ECR*. However, while we are presently gathering clinical data to address efficacy (our preliminary studies in this regard have been submitted for publication (Nakajima et al. submitted)), it is important to understand what *ECR* says about middle-ear function in normal ears.

NIH-PA Author Manuscript NIH-PA Author Manuscript NIH-PA Author Manuscript

In this study we compare measurements of *ECR* to other objective measurements of middle-ear function including: audiometry, umbo velocity, and tympanometry in a population of normal hearing ears. Many of these comparisons have not been made previously. Correlations between *ECR*, audiometry, umbo velocity and tympanometry are reported and discussed. These correlations demonstrate how variations in *ECR* in normal ears relate to variations observed in other objective measurements of middle-ear function.

METHODS

Overview

Subjects recruited for this study had tests performed during two different sessions that were separated in time by a duration that varied between hours and several days. In one session, ear-canal reflectance and umbo velocity were measured in an open room in our human middle-ear measurement laboratory during a span of less than 30 minutes. In the other session, standard air and bone-conduction audiometry and 226 Hz tympanometry were performed in a double-walled sound booth within the Audiology Department at the Massachusetts Eye and Ear Infirmary using Interacoustic Equinox audiometers and GSI Tympstar Middle Ear Analyzers.

Subjects

This study was approved by the Human Studies Committee of the Massachusetts Eye and Ear Infirmary. Subjects for this study were generally staff members of the local institution, including health-care workers, researchers, administrators and students. Fifty-eight subjects were tested and informed consent and a brief medical and surgical history related to hearing were initially obtained. Umbo velocity (V_U) by laser Doppler vibrometry was measured, followed by ear-canal reflectance (*ECR*) measurements. In all subjects, pure-tone audiometric thresholds for air and bone conduction, in addition to 226 Hz tympanograms, were gathered by a certified audiologist (mostly by author CH).

Inclusion Criteria for Subjects to be Considered “Normal Hearing”—Out of the 58 subjects tested, 29 subjects (58 ears), which included 16 females and 13 males between the ages of 22–64 years, met our criteria of “normal hearing” (Table 1 details the demographics). To be considered “normal hearing”, subjects met all the following criteria: (1) There was no history of significant middle-ear disease (e.g. otitis media or effusion two or more years previously were not considered significant if there were no known residual consequences). (2) There was no history of otologic surgery, with the exception of myringotomy or tympanostomy tube placement over 2 years prior. (3) The external ear and TM revealed no abnormalities on otoscopic exam. (4) Audiometric measurements had pure-tone thresholds of 20 dB HL or better at octave frequencies between 0.250 and 8 kHz. (5) Air-bone gaps were no greater than 15 dB at 0.25 kHz and 10 dB between frequencies of 0.5 to 4 kHz. Most subjects had air and bone thresholds between 0 and 10 dB HL with an average near 8 to 9 dB HL at the highest frequencies (Table 2). (6) Tympanograms were Type-A peaked, with peak pressures of -100 to +50 daPa, static compliance of 0.3 to 2.0 cc, total tympanometric volumes (static compliance + ear canal volume) between 0.7 and 2.7 cc, and normal-appearing shape that is neither rounded nor sharp. (7) All subjects included in the “normal hearing” population were required to have two “normal” ears (as defined by criteria described above). Exceptions to normality included subjects with hearing loss, abnormal tympanograms, and otoscopic abnormalities, e.g., tympanosclerois as well as tympanic membranes that were ‘dull’ or had a poor light reflex. Several of the normal subjects noted instances of occasional tinnitus, but had no other hearing complaints.

NIH-PA Author Manuscript

NIH-PA Author Manuscript

NIH-PA Author Manuscript

Ear-Canal Reflectance (*ECR*)

Instrumentation and Experimental Set-up—Ear-canal reflectance was measured using the Mimosa Acoustics HearID system (software v3.4.45.1), which is an FDA-approved, commercially–available oto-reflectance tool used by multiple groups (Allen et al. 2005; Shahnaz & Bork 2006; Vander Werff et al. 2007; Withnell et al. 2009; Hunter et al. 2010). In making measurements with this device, we performed a new calibration of the measurment system for each tip that we used; the results of these individual source-tip calibrations were used to compute the reflectance (see below under Calibration, Shahnaz & Bork 2006; Voss et al. 2008). The Mimosa system consists of an ER-10C probe (acoustical probe) that contains two output transducers (although only one of the 'speakers' was used) and one input transducer (a microphone) coupled to a foam probe tip, and connected to a laptop computer. Wideband chirp sound stimuli and a set of tone stimuli for nine frequencies between 0.2 and 6 kHz at 60 dB SPL were used. The averaging time was set to 3 seconds, (FFT length of 2048, sampling rate of 48000/sec). The microphone voltage measurements were stored for later conversion to power reflectance $|ECR|^2$ and the phase of the reflectance $\angle ECR$.

Calibration—Mimosa's calibration procedure – which determines the Thévenin equivalent source parameters of the combined sound source, microphone and attached foam tip – utilizes sound pressure measurements at the entrance of four cylindrical tubes of different lengths (Allen 1986, Voss & Allen 1994; Shahnaz & Bork 2006; Voss et al. 2008). We performed separate calibrations for each foam tip and used the individualized Thévenin parameters to calculate the reflectance measured by each tip. Mimosa's software requires the calculated Thévenin equivalent to be within a set of predetermined boundaries before one can proceed with reflectance measurements. Various conditions result in poor calibrations, e.g. (i) imperfections in the foam probe tip, where the glue holding the plastic tubing within the surrounding foam loosens, resulting in an air leak between the tubing and the tip; (ii) the foam would not expand adequately to seal the tip within the calibration fixture; or (iii) excessive room or electrical noise. To increase the chance of passing calibrations, certain maneuvers were necessary and recommended by Mimosa: (1) placing the calibration cavity system on a thick foam base over a solid stable surface to decrease mechanical vibration; (2) inserting the probe maximally in the cavity at position "0" and letting it expand there for at least 5 minutes prior to performing the calibration; (3) stabilizing the electrical cord that couples the source to the computer to ensure that the probe tip was perpendicular to the cavity opening; (4) unplugging the AC wall power supply of the laptop computer (to use battery power) to decrease electrical noise; (5) trying no more than twice to pass a calibration because the foam ear-tip can become worn from repeated squeezing prior to insertion into the calibration cavity, thereby preventing adequate recoil of the foam for a proper seal. Calibrations for several foam tips were performed on the same day or day prior to subject measurements, and each tip was marked to identify its specific calibration measurement. Because of the uncertainties within the calibration process that sometimes led to many calibration trials before defining an adequate tip and calibration, it was impractical to calibrate immediately before each subject measurement.

Measurements—Subjects were seated comfortably. Before inserting the foam probe tip, the subject was asked to swallow to attempt equalization of the middle-ear pressure to atmospheric pressure, then to refrain from swallowing after the insertion of the foam probe tip into the ear canal. The cord of the probe tube was positioned around the neck or shoulder with a stabilizing clip so as to avoid tension on the cord and to keep the foam-tip positioned straight and stable in the ear canal. At least 2 minutes was provided to allow expansion of the foam probe tip after insertion. Full expansion was marked by a feeling of blockage in the ear by the subject. As a leak-free seal is necessary for an accurate measurement, leaks were

NIH-PA Author Manuscript

NIH-PA Author Manuscript

NIH-PA Author Manuscript

identified by: (1) excessive noise in power reflectance (significant variations with varied frequencies) at low frequencies; (2) an ear-canal impedance phase (one of the standard outputs of the Mimosa system) with an atypical pattern (typically, the impedance phase is negative and slowly increasing at low frequencies); and (3) increases in power reflectance at low frequencies with repeated measurements, which indicated the foam tip was still expanding.

Generally, it required about 10 minutes to complete measurements for both ears. In each test ear, wideband chirp responses were repeated until two sequential measurements varied by less than a few percent, followed by a response to a set of tone stimuli. The tone measurements were used to confirm the repeatability of the measurements. The two repeatable chirp responses were then averaged and used for further analyses. Responses from the tone stimuli were only used to check for repeatability. No manipulations of the chirp data, such as a smoothing algorithm, were performed.

Umbo Velocity (V_U)

Umbo velocity was measured with an HLV-1000 laser Doppler vibrometer (Polytec, Irvine CA). The laser had a power of <1 mW (US FDA Class II), a minimum spot diameter of 100 micrometers, and was mounted on a Zeiss OPMI-1 operating microscope. A speculum with a glass-backed sound coupler including an ER3 earphone and ER7 microphone (Etymotic Research, Elk Grove IL) was used to present controlled sound stimuli and provide visual access to the eardrum following the techniques described in previous publications (Whittemore et al. 2004; Rosowski et al. 2008). The laser beam was aimed near the anterior border of the umbo where there is generally a bright reflection of laser light. The technique measures V_U and sound pressure near the TM (between 1 and 0.5 cm from the umbo) during a one-second presentation of 9 simultaneous frequency tones between 0.3 and 6 kHz at 70–90 dB SPL. Several responses (3–5) are averaged and analyzed. Generally, measurements for both ears took approximately 5–10 minutes. (Whittemore et al. 2004; Rosowski et al. 2008). All measurements of umbo velocity reported in this publication have been normalized by the measured sound pressure and have units of velocity per sound pressure (mm-s^{-1}-Pa^{-1}).

RESULTS

Acoustic Reflectance Measurements

Power Reflectance, $|ECR|^2$—Power reflectance, the square of the magnitude of the pressure reflectance, $|ECR|^2$, describes the fraction of the incident acoustic power that is reflected back by the TM, where a power reflectance of 1 corresponds to the condition where all acoustic power is reflected back and reflectance of 0 corresponds to the condition where all power is absorbed at the TM. Power reflectances for the 58 normal ears vary considerably, especially in the fine structure of repeated local minima and maxima. Figure 2a plots the power reflectance $|ECR|^2$ from seven representative individuals that were selected to represent the measurements obtained from the whole group of 58 ears. This plot demonstrates the variety of frequency responses obtained. The seven examples include two ears with the most extreme reflectance measurements (plotted with gray lines) that illustrate the largest and smallest power reflectance data recorded at frequencies less than 2 kHz. The other five examples (plotted with black lines) are individual measurements that are mostly within one standard deviation from the mean; note the varying number and frequency locations of the local minima and maxima in reflectance in these ears. The seven examples include four right and three left ears. Each curve has been computed from the sound pressures produced by the source using the calibrations performed for the individual foam tip used in the measurement.

NIH-PA Author Manuscript

NIH-PA Author Manuscript

NIH-PA Author Manuscript

Fig 2b plots the mean and standard deviation of $|ECR|^2$ from the 58 normal ears (29 subjects). The mean power reflectance is near 1.0 at the lowest measured frequencies (0.2–0.3 kHz), suggesting almost all incident acoustic energy at those frequencies is being reflected back from the TM with little absorption of energy by the middle and inner ear. With increasing frequency, the mean power reflectance decreases monotonically to a broad minimum of 0.3 to 0.4 between 1 and 4 kHz. This minimum of power reflectance suggests a maximum transmission of energy to structures behind the TM at these frequencies. Of note, the individual power reflectances often have narrow-band fluctuations of magnitude within the 1 to 4 kHz range (Fig. 2a). Above 4 kHz, the average power reflectance sharply increases with increasing frequency, to almost 0.8 by 6 kHz.

Reflectance Phase, ∠ECR—The phase of the pressure reflectance, $\angle ECR$, unlike the power reflectance, is sensitive to the distance between the tip of the foam plug and the TM. For our data, the reflectance phase varies between 0 to 360 degrees. Figure 3a shows representative $\angle ECR$ measurements for the seven subjects plotted in Fig. 2a. The ears with the most extreme $|ECR|^2$ (plotted with gray lines in Fig 2a) also had the most extreme $\angle ECR$ (Fig. 3a) at frequencies less than 1 kHz together with near maximal and minimal angle measurements at higher frequencies. Figure 3b plots the mean and standard deviation of $\angle ECR$. On this log-frequency scale, $\angle ECR$ changes faster as frequency increases above approximately 2 kHz.

Figure 4 plots the mean and standard deviation of $\angle ECR$ on a linear frequency scale, allowing one to study the group delay (the derivative of reflectance phase with respect to radian frequency). The group delay of the pressure reflectance, estimated for the wide frequency range (0.2 – 6 kHz) is approximately 100 μs. However, Figure 4 points out that the group delay is not constant with frequency. The group delay is slightly higher for frequencies below 0.7 kHz and between 1.7–3.7 kHz, compared to the group delays between 0.8–1.7 kHz and above 3.7 kHz. At the higher frequencies, the group delay of $\angle ECR$ is of a size consistent with the length of the ear canal: A delay of about 100 μs multiplied by a speed of sound in the ear canal of 350 meter per second yields a length of about 3.5 cm, which is about twice the distance between the probe tip and the tympanic membrane, and accounts for the forward travel of the incident wave and the backward travel of the reflection. The frequency-dependent deviations from a simple delay are discussed later.

Repeatability of Power Reflectance Measurements—Both ears of seven subjects were tested repeatedly, where after the first recording, subsequent measurements were made once a week for three weeks. Figures 5(a & b) show the arithmetic differences between the 1st and the 2nd, 3rd and 4th recordings of $|ECR|^2$, together with similarly calculated differences in $\angle ECR$. The seven subjects included two subjects that were not considered “normal” by our strict criteria, and were not included in Figs. 1–3: Tympanometry on one of the two additional subjects showed an unusually compliant (“hypercompliant”) TM (gray dashed lines in Fig. 5a and 5c), and the second had a low-frequency air-bone gap due to a hypersensitive bone curve for 0.25 and 0.5 kHz although his/her air conduction thresholds were normal (gray dotted lines in Fig. 5a and 5c). These two subjects not included in the “normal hearing” category had some of the largest test-retest differences. The subject with the abnormally compliant TM (gray dotted lines) had large test-retest differences between 0.3–0.7 kHz, and the subject with the low-frequency air-bone gap (gray dashed lines) had large test-retest differences above 3 kHz. Figures 5(b & d) plot the mean and standard deviations of the test-retest differences in $|ECR|^2$ and $\angle ECR$ along with the standard deviation calculated from the normal population. The mean of the differences is near 0.0 consistent with random variations around the central value. The standard deviations of these test-retest measurements are only a little smaller than the standard deviation measured across the normal population, which suggests a significant fraction of the differences seen

NIH-PA Author Manuscript NIH-PA Author Manuscript NIH-PA Author Manuscript

between individuals may be explained by intra-subject variations in reflectance measurements.

Comparison of Power Reflectance to Previous Reports—The power reflectance obtained in this study is compared to previously published data in Figure 6. Figure 6a compares our mean (black thick line) ± 1 standard deviation (shaded area), with previously published means (colored lines and markers) and standard deviations (vertical bars). Published data includes: Feeney and Sanford (2004) "elderly" and "young" populations; Shahnaz & Shaw (2010, Caucasian only), and Voss & Allen (1994). Our data is generally similar to data recorded by other investigators. The data from the "young" population obtained by Feeney and Sanford (2004) deviates the most from ours as well as other investigators by having higher power reflectance below 2 kHz. The populations of the various studies have generally similar ages, except for the "elderly" group of Feeney and Sanford (2004). The average age of the Feeney and Sanford (2004) "elderly" group (n=30) was 72.6 years old, and the "young" group (n=40) was 21.4. The subjects in the Shahnaz & Shaw (2010) study (n=60) were 27.8 years old on average with a range of 20–45 years old. Voss and Allen (1994) used subjects (n=10) with a range of age between 18–24 years old. Our present study (n=72) used subjects with an average age of 36 years old, with a range of 22–64 years old. In the mid-frequency region (1–3 kHz), our data are very similar to Shahnaz & Shaw (2010) who used the same measuring device (Mimosa) with similar calibration technique as ours, as well as the measurements of Voss and Allen (1994). At lower frequencies (<1 kHz), our mean is very similar to Voss & Allen (1994), but slightly higher than Shahnaz & Shaw (2010).

We also compared the median of our $|ECR|^2$ to published reports by Werner et al. (2010) and Shahnaz (2010) in Fig. 6b. Werner et al. (2010) used subjects (n=210) with ages between 18–30 years old. Generally the median for our data is similar to the median of other investigators' data. The mean and median from our measurements are similar.

Differences Between Power Reflectance Measurements of Right and Left Ears —The power reflectance measured in the left and right ears of each subject were similar, the means of the difference in $|ECR|^2$ between the left ear and right ear at 9 selected frequencies varied between - 0.041 and 0.044 with the largest absolute differences at 1 and 2 kHz. The standard deviation about these differences varied from 0.04 to 0.24 with the larger standard deviations at the higher frequencies. The significance at each frequency was determined with a paired t-test using two-tailed probabilities and the Holm variation of the Bonferroni correction (Norman and Streiner. 2008). Using these criteria, the left-right difference in $|ECR|^2$ of −0.23 ± 0.041 at 0.3 kHz, just reaches the $p= 0.05$ level.

Differences Between Power Reflectance in Males and Females—We observed small but generally not significant gender-related differences in the power reflectance. At frequencies of 2 kHz and below the average $|ECR|^2$ in female ears was larger, with female – male differences of between 10 to 15% of the female value at frequencies between 0.5 and 2 kHz. At 3, 4 and 6 kHz the female – male difference was negative and varied from −20 to −40%. Using t-tests and the Holm variation described above, we found these differences only reached the $p<0.05$ level at 4 kHz. Feeney & Sanford (2004) noted similar gender effects in their young adult group.

Absorbance Level: $10\times\log_{10}$ [1-$|ECR|^2$]—Another way to express measurements of power reflectance is in terms of power absorption. Power absorbance ($1-|ECR|^2$) (Ansi S1.1-1994; Liu et al. 2008) mirrors power reflectance, $|ECR|^2$, in that 1 now represents total absorption (no reflection) and 0 no absorption (total reflection). The dB representation of the power absorption (called transmittance by Allen et al. (2005)) is an *absorbance level*, equal

NIH-PA Author Manuscript

NIH-PA Author Manuscript

NIH-PA Author Manuscript

to $10 \times log_{10}\,[1\text{-}|ECR|^2]$ The *absorbance level*, from our normal population (Fig. 7) quantifies how much energy is absorbed by the middle/inner ear on a logarithmic scale, allowing for useful comparisons to other logarithmic measures of hearing function (Allen et al., 2005). The mean absorbance level from our normals increases almost as a straight line in the logarithmic plot, at about 15 dB/decade below 1 kHz, consistent with an absorbance that varies as the 1.5 power of frequency. Above 4 kHz, the absorbance level decreases at about 23 dB/decade.

Umbo Velocity Measurements

Umbo Velocity (V_U)—Figures 8a & c plot the magnitude and phase of V_U, the umbo velocity normalized by the ear-canal pressure, from the same seven representative individuals illustrated in Figs. 2a & 3a. Unlike the reflectance measurements, which were made in response to a broadband chirp, the V_U measurements are responses to a nine-tone complex and the resultant data show coarser frequency resolution than the reflectance. The V_U from the two ears with the most extreme power reflectance is plotted with gray lines, as in Figs. 2a & 3a. The ear with the highest reflectance at frequencies below 2 kHz (23 - Right) shows low V_U magnitude, while the ear with the lowest reflectance magnitude below 2 kHz (6 – Right) has a V_U phase that accumulates more rapidly than the other ears. On the right column, Figs. 8b & d, the mean magnitude and phase of the umbo velocity for this study is plotted in solid black line and the range of the mean +/− the standard deviation is shaded gray.

The V_U data from this study were compared to a previous study from our laboratory (Whittemore et al. 2004) plotted in Figs. 8b & d with dashed lines for the mean and the striped area for the range of the mean +/− standard deviation. The mean and standard deviations from the two studies are very similar. However, the criteria used to define “normal” differed slightly. The criteria used by Whittemore et al. (2004) for “normal hearing” included: otoscopic examination showing no abnormality, medical history showing no significant ear disease, and air and bone conduction thresholds less than or equal to 20 dB. The present study’s criteria for “normal” was stricter requiring: no air-bone gap greater than 15 dB at 0.25 kHz and 10 dB between 0.25 and 8 kHz, normal tympanograms (see Methods section), and the requirement that both ears fit the normal criteria for the two ears to be included in the “normal” category (Whittemore only included one ear from each subject). The mean age of the Whittemore et al. (2004) study population was 35.8 yrs (N=56), while the mean age of our population was 36.6 (N=29).

DISCUSSION

Test Population

This paper deals with comparisons between different objective measurements of middle-ear function in a “normal” population, where our definition of “normal” is fairly strict. While our restriction to ears with normal clinical history, audiometry and tympanometry are common to most studies, a significant difference is that we require both ears to meet the normal criteria for any subject to be counted as normal. This restriction was placed because of our informal and unpublished observations that patients with unilateral conductive hearing loss due to otosclerosis, who exhibit low-normal middle-ear function (as determined by umbo-velocity measurements) in the affected ear, often show similar low-normal middle-ear function in the contralateral ear despite having normal hearing thresholds. One interpretation of this observation is that the contralateral ear is affected by sub-clinical middle-ear disease and is not strictly normal. Our requirement that both ears of a subject meet normal criteria before either ear is considered normal, limits the possibility that subclinical pathology is included in the normal population.

NIH-PA Author Manuscript

NIH-PA Author Manuscript

NIH-PA Author Manuscript

Another difference in our normal population compared to a few others is that we include both ears of each normal subject. Such an inclusion is consistent with the small but significant left-right differences others (Arechevo et al. 2009) have observed in measurements of tympanic-membrane mobility.

Acoustic Reflectance Measurements

The reflectance measurements in our normal population are consistent with a high power reflectance at frequencies below 0.5 kHz as well as at frequencies above 5 kHz. Between these limits is a range of relatively low-reflectance region that corresponds roughly with the frequency range of lowest hearing threshold under earphones (Allen et al. 2005). While these general trends are apparent in the individual measurements there is also significant variability in reflectance between different ears and subjects at any one frequency as well as from frequency to frequency in an individual ear.

Interpretation of ECR measurements—*ECR* is a complex variable (with magnitude and phase) that varies with frequency and describes the magnitude and phase of the ratio of the sound pressure in a ‘backward’ reflected wave to the sound pressure in the ‘forward’ incident wave at a specific location. The terms ‘backward’ and ‘forward’ imply a one-dimensional system with the reference direction proceeding from a source toward the reflecting surface. Since sound-propagation in the ear canal approximates such a system, reflectance has been used to quantify sound power transfer through the canal. In a truly ‘one-dimensional’ tube system of constant cross section, rigid (lossless) walls, and an inviscid (lossless) sound conducting media, the pressure reflectance depends on the combination of the terminating impedance and the canal cross-section, and the magnitude of the reflectance $|ECR|$ is independent of the distance between the measurement location within the tube and the terminating ‘reflecting’ surface. The power reflectance, the square of the pressure reflectance magnitude ($|ECR|^2$) and its derivatives the absorbance ($1-|ECR|^2$) and absorbance level ($10\times\log(1-|ECR|^2)$) similarly depend on the tube’s cross-section and termination and are also independent of the position in the tube.

In response to stimulus frequencies of 0.2 to 0.6 kHz, most normal ears exhibited a power reflectance of 0.7 or higher with reflectance decreasing as frequency increases (Figure 2a & b). In the same frequency range the absorbance level increases at a rate of 15 dB per decade (Figure 7) from a mean value of approximately −14 dB at 0.2 kHz to −6 dB at 0.6 kHz. This change in absorbance level approximates the nearly 20 dB (factor of 10) per decade increase in normalized umbo velocity over the same frequency range (Figure 8); an increase consistent with a compliance dominated mobility. However, the comparison of absorbance and velocity is more complicated. A purely compliant termination absorbs no power and will produce a reflectance magnitude of 1 at all frequencies. What determines the decrease in reflectance and the increase in absorbance, as frequency increases from 0.2 to 0.6 kHz, is the transition from compliance-dominated to resistance-dominated middle-ear mechanics that occurs in human ears at frequencies near 0.6 kHz (Zwislocki 1962); as the resistance becomes dominant, more power is absorbed. A second feature essential to this near-linear increase in absorbance with frequency is that the middle-ear input resistance measured at the TM is similar (within an order of magnitude) to the characteristic impedance of the external-ear canal.

In response to stimulus frequencies of 1 to 4 kHz the mean power reflectance is below 0.4 (Figure 2) and the absorbance level (Figure 7) is about −2.5 dB. This is the frequency range where the largest fraction of incident power is absorbed by the TM and the structures behind it (and the smallest fraction reflected). As noted above, this frequency range corresponds to the frequency range of the most sensitive human thresholds to sound. It also corresponds to

NIH-PA Author Manuscript

NIH-PA Author Manuscript

NIH-PA Author Manuscript

the frequency range where measurements of middle-ear input impedance in human ears are most resistive (Rabinowitz 1981). It should be remembered that while the average power reflectance and absorbance level curves show near uniform power reflectance and absorption in this frequency range, the individual reflectance data usually show multiple minima and maxima in reflectance in this range, which would lead to +/− 2 dB variations in absorbance level in individual ears (Figure 2a&b).

At frequencies above 4 kHz, the average (and most individual) power reflectance increases back towards a value of 1. This increase was noted by Stinson, Shaw and coworkers in the early 1980s, and they attributed it to an effect of a mass-like component in high-frequency human middle-ear mechanics associated with overcoming the inertance of the TM, ossicles and inner-ear fluids (Stinson et al. 1982; Shaw and Stinson 1983).

The phase angle of the pressure reflectance, $\angle ECR$, is the phase of the reflected pressure relative to the incident pressure, and can be used to estimate the length of time (group delay) it takes the incident wave to travel to the TM plus the time associated with the reflection from the TM and the time it takes for the reflected sound to return to the microphone. The averaged group delay estimated across the whole frequency range measured is approximately 100 μs, consistent with a distance between the TM and the source in the ear canal of about 1.75 cm However, the averaged phase versus frequency plot is not a perfectly straight line throughout the whole frequency range (Fig. 4). Frequencies below 1.7 kHz and above 3.7 kHz have a somewhat shorter group delay (76 and 98 μs), compared to the group delay calculated between 1.7–3.6 kHz (150 μs) where there is low power reflectance (high absorbance). The longer delay in the mid-frequency region suggests a distance between source and TM of 2.5 cm.

The variations we see in group delay with frequency can be simply explained. $\angle ECR$ has two components: One component is the angle of the reflectance measured at the TM, where this reflectance angle depends on the middle-ear input impedance and the cross-sectional area of the canal at the TM. A simple mass-stiffness-damper model of the TM produces a reflectance angle that varies over 180° as frequency varies. Furthermore, the frequency variations tend to occur in steps related to the transitional frequencies where the impedance value shifts from stiffness to damper to mass control. The second component of $\angle ECR$ is the phase accumulated during the round trip travel of sound between the source and the TM. This component varies proportionally with frequency and will have a group delay that depends on canal length. This second component will dominate the group delay of the $\angle ECR$ over frequency ranges where the contribution of the impedance-determined component changes slowly with frequency. If we assume the more rapid transition in $\angle ECR$ in Figure 4 observed at frequencies less than 0.5 kHz and near 2 kHz are due to the load-impedance-related component, then the delay observed at high frequencies may be a better estimator of canal length.

Sources of Variability in Power Reflectance Measurements—One source of variability in our measurements is the intra-subject variation we observed between tests and re-tests of *ECR* in a small population (Figure 5). The +/− 0.1 variations we see in repeated measurements of power reflectance made over a four-week interval accounts for a significant fraction of the +/− 0.15 standard deviation observed in the normal population. This test-retest performance is similar to that of Werner et al. (2010). Several factors may contribute to the test-retest variability. (a) Small differences in middle-ear pressure between measurements can affect reflectance (Margolis et al. 1999) just as they affect the measured middle-ear impedance during tympanometry. We attempted to control for such variations by having the subjects swallow several times before our measurements, but the effectiveness of such procedures is variable. (b) Small differences in the placement of the probe and ear tip

NIH-PA Author Manuscript

NIH-PA Author Manuscript

NIH-PA Author Manuscript

within the external ear can contribute to test-retest variability in measurements of middle-ear impedance and reflectance (Huang et al. 2000a, b). Differences in the cross-sectional area of the canal at different locations may play a role, since the cross-sectional area of real ear canals vary along their length (Stinson 1985). Voss et al. (2008) also described small differences in reflectance related to differences in the length of the ear canal between the probe and the TM.

Factors that contribute to inter-subject differences in *ECR* and power reflectance include: (a) Inter-individual differences in the impedance at the TM (including contributions from the TM, ossicular, cochlear and cavity impedances) are known to be significant (Zwislocki and Feldman 1970; Margolis and Shanks 1985; Stepp and Voss 2006; Voss et al. 2008). The static compliances we measured in our normal subjects varied between 0.3 and 1.3 cc of equivalent volume. This difference reflects inter-subject variations in the impedance of the TM itself, as well as variations in the impedance of the middle-ear cavities, the stiffness of the ossicular joints and the impedance of the inner ear (Nakajima et al. 2009; Aibara et al. 2001). (b) Inter-individual differences in the cross-sectional area, length of the canal and rigidity of the ear canal may also contribute to inter-subject variations in reflectance (Voss et al. 2008). Equation 1 describes how the computed reflectance depends on the characteristic impedance of the ear canal (Z_0), where this impedance is inversely related to the cross-section of the ear canal at the measurement location. The Mimosa software calculates the reflectance based on the type of tip (small medium or large) used to seal the ear canal, where associated with each tip type is a specific canal cross-sectional area. Small differences between the actual canal cross-section and the cross-section used in the measurements are known to cause small but consistent deviations in the computed *ECR* (Keefe et al 1993, 1994; Huang et al. 2000a). While the uniform ear canal approximation used in defining reflectance suggests that the measured reflectance is independent of length of the canal between the measurements site and the TM, Voss et al. (2008) in human temporal bones and Huang et al. (2000b) in cat demonstrated that the measured reflectance showed small but consistent differences that varied with the length of the canal between the tip and the TM. Also, since the assumption of rigidity of the ear-canal wall used in computing reflectance has been shown to not hold true in infants (Keefe et al. 1994), perhaps small inter-individual deviations in canal-wall compliance in adults may contribute to inter-individual differences in *ECR* measurements. (c) A third potential cause of inter-individual differences is age differences. Our subject group is heterogeneous in age, with a range between 22 to 64 years. Feeney and Sanford (2004) have reported age-related differences in power reflectance and such differences would contribute to the inter-individual variation in our study population.

Differences within Sub Groups of the Normal Population—Significant variations in pressure reflectance between different subject populations have been reported. For example, Shahnaz and Bork (2006) reported variations in reflectance linked to both ethnicity and gender. While our subject group is primarily Caucasian, with only a few subjects of Asian and African descent, we can investigate gender, age and left-right differences. We did see small but significant gender-related differences in power reflectance. The power reflectance measured in females tends to be higher than that in males at frequencies of 2 kHz and below, and lower than males at frequencies of 3 to 6 kHz. However, only the difference at 4 kHz was significant at the $p < 0.05$ level. Feeney and Sanford (2004) saw similar gender differences in their young-adult population. Werner et al. (2010) found slightly higher ear-canal impedance in females than males, but no gender difference in power reflectance. It may be that these differences are related to differences in ear-canal cross-sectional areas between the two populations. Shahnaz and Bork (2006) suggested such a cause for the similar variations in reflectance observed in Caucasians and Asians (who have smaller than average ear-canal dimensions).

NIH-PA Author Manuscript

NIH-PA Author Manuscript

NIH-PA Author Manuscript

Age related Differences: Because of an uneven distribution of the age of our subjects, with a preponderance of subjects less than 40 years of age, we tested for age effects using correlation and regression analyses in our 29 normal subjects. No strongly significant relationships were found between power reflectance and age. The most significant relationship was observed between age and $|ECR|^2$ at 1 kHz. (Figure 9), where the uncorrected probability that the regression slope equals zero is $p = 0.014$. After applying a Bonferonni correction because of the multiple regression analyses, the significance falls to $p \sim 0.125$. The square of the Pearson-Product correlation coefficient r^2 indicates that 10.2% of the variability in the 1 kHz power reflectance data can be explained by a linear relationship with subject age at 1 kHz. The negative slope fit to the data of Figure 9 suggests the reflectance decreases with age. Such a decrease is consistent with the direction of age-related change in reflectance reported by Feeney and Sanford (2004), however the magnitude of the change that we observe is much smaller, as is the reflectance magnitude we measure in young ears compared to Feeney and Sanford (2004). Slower and less-significant decreases in reflectance with age occur at other frequencies. We also found a mildly significant correlation between the magnitude of the measured umbo velocities and subject age at 1 kHz, but not at other frequencies. (The dB value of ^{2}=0.13, V_U magnitude at 1 kHz was positively correlated to age with a slope of +0.12 db/year and r with an uncorrected significance of the slope of p=0.005 and a corrected significance of $p_B=0.045$). Whittemore et al. (2004) found no significant relationship between V_U and age. The shallow but significant regression slopes between $|ECR|^2$ and age, and V_U and age in this study are consistent with a small increase in eardrum mobility with age.

Left-Right Differences: As discussed in the results, our selection of normal subjects based on binaural criteria allowed us to check for left-right differences in power reflectance. We conducted paired-tests investigating the significance of left-right differences in power reflectance at each of 9 logarithmically spaced frequencies. The differences in reflectance between the left and right ear approached 15% of the grouped mean at 2 and 8 kHz, but were only significantly different from zero (p value < 0.05) at 0.3 kHz. Also as noted in the results, there was a tendency for the right ear to have larger reflectance values at frequencies below 1 kHz. Whether this tendency is significant bears further investigation. Werner et al (2010) also observed small differences between left and right ears in $|ECR|^2$. Small but significant differences between umbo velocity measurements in the left and right ears of individuals have also been reported (Arechevo et al. 2009), while Whittemore et al. (2004) documented significant correlations between umbo velocity measurements in left and right ears. If these differences are indeed real, they may indicate small differences in the dimensions of the left and right ears or small differences in the mechanical parameters that govern middle-ear function.

Comparison to previous reports of $|ECR|^2$—Various publications have reported ear-canal power reflectance $|ECR|^2$ for normal-hearing adult subjects. Definition of “normal” differs among the various studies, and in this present study, both ears had to pass our strict criteria (see Methods section). We required both ears to be normal because our informal experience from umbo velocity measurements suggested that ears with normal hearing levels that are contralateral to ears with otosclerosis or SCD often show mechanical measurements consistent with the pathology in the other ear.

Comparisons between different power reflectance normal studies data (Figure 6) show much similarity between our and most other results. The exception is the study of Feeney and Sanford (2004) in which both their elderly and young populations had higher $|ECR|^2$ than other studies. The discrepancy between both the ‘young’ and ‘old’ age groups from the Feeney and Sanford (2004) and the other studies suggests that age is not a factor in this comparison. All the studies compared used an insert earphone with a foam tip and an

NIH-PA Author Manuscript

NIH-PA Author Manuscript

NIH-PA Author Manuscript

indwelling measurement microphone. Feeney and Sanford (2004) reasoned that their measurements had higher power reflectance compared to others because they had fully inserted the probe tip deeply into the ear canal, and if the energy reflectance at low frequencies was less than 0.8 after 2 minutes of insertion, the probe was reinserted and the process repeated, favoring higher reflectance measurements at low frequencies. In our protocol, we first inserted the probe tip, waited for 2 minutes, and performed multiple measurements separated by about a minute. We continued to repeat measurements until stability was reached (thus assuming that the foam tip had finished expanding enough to seal the ear canal). If the recording was very noisy or unusual (see Methods section), the tip was removed and reinserted or a new tip was used. The study by Voss and Allen (1994) used a similar calibration system and had similar $|ECR|^2$ values to our study (Fig. 6). Shahnaz and Shaw (2010) used the Mimosa system (as we did), and found similar but slightly lower $|ECR|^2$ results compared to this study. The Shahnaz and Shaw (2010) result plotted in Fig. 6 is from their Caucasian population, while our subjects were mostly Caucasian. Shahnaz and Bork (2006) showed that their Chinese ethnic group tended to have lower $|ECR|^2$ than their Caucasian group, which Shahnaz attributed to differences in size (such as ear canal size) between the two groups.

Umbo Velocity Measurements

The umbo velocities measured in this study (N=58) were similar to the umbo velocities measured in our previous study (n=56) (Whittemore et al, 2004) for subjects with normal hearing (Fig. 8). The criteria necessary to be included in the “normal” category was stricter in the present study (see Methods and Results section), and additionally required normal tympanometric measurements which were not included in the old study as well as the limitation that both ears needed to meet the other normal criteria. Unlike the chirp stimulus used in reflectance measurements, the stimulus for umbo velocity was 9 simultaneous tones, resulting in a coarser frequency resolution. The 9-tone stimulus protocol was optimized for measurement speed and high signal to noise ratio. The normal hearing ears with high or low power reflectance measurements (e.g. ears 6R and 23R of Fig. 2a) tended to be outliers in either umbo velocity magnitude or phase (Fig. 8a & c).

Correlations between Reflectance, Umbo Velocity, Tympanometry and Audiometry

The data we, and others, have presented describe a significant amount of variability in the measurements of reflectance and umbo velocity in normal ears. In this section, we describe attempts to use correlation and linear regression to determine if some of this variation comes from common factors in the response of a specific ear to sound. We also investigate correlations between our measurements and tympanometry and audiometry.

Correlations within the Power Reflectance and Umbo Velocity Measurements—Not surprisingly we saw a fair amount of correlation between power reflectance measurements made at different frequencies across the 58 ears. The correlation values were highest ($r^2 > 0.2$) when comparing power reflectances measured at one low frequency ($f < 2$ kHz) with measurements made at another nearby low frequency. Correlations between reflectances measured at pairs of higher frequency were weaker. These trends in across-frequency correlations are consistent with our observations of individual measurements (Figure 2a): At frequencies less than 1 kHz there is a stereotypical smoothly inverse relationship between power reflectance and frequency in many ears. At frequencies between 1 and 4kHz, there are smaller cyclic variations in reflectance, which vary greatly between ears.

Similar patterns are observed when correlating the magnitudes of the umbo velocity measured at different frequencies in the 58 ears. Umbo velocities measured at 0.3, 0.5, 0.7

NIH-PA Author Manuscript

NIH-PA Author Manuscript

NIH-PA Author Manuscript

and 1 kHz are highly correlated with each other ($0.5 < r^2 < 0.92$) and the degree of across-frequency correlations decreases when comparing umbo velocity magnitudes at higher frequencies. Similar correlations between umbo-velocities at different frequencies in normal ears were reported by Whittemore et al. (2004).

Correlations between Power Reflectance and Umbo Velocity—Highly significant negative correlations were found between umbo velocity magnitude and power reflectance measured at frequencies of 0.3, 0.5, 0.7 and 1 kHz (Table 3). Some of these relationships are plotted in Figure 10. A least-squares linear regression analysis between $|ECR|^2$ and V_U at 0.7 kHz is illustrated in Figure 10a, and at 1 kHz in 10b. The probability that either of the pictured regression slopes equals 0 is much less than 0.1% (even after applying a Bonferroni correction). As might be intuited from the mechanics, the slopes are negative, larger umbo velocity magnitudes are expected to be indicative of decreased power reflectance. Correlations of similar significance and sign were found between power reflectance and umbo velocity measured at most frequencies of 1 kHz and lower (Table 3). The r^2 values noted in Table 3 indicate that on the order of 35–45% of the variance in $|ECR|^2$ at low frequencies can be explained by the described linear relationship with V_U. A few weaker, but still significant, correlations were observed between $|ECR|^2$ and V_U at 4 and 6 Hz but not at any other frequency. A conclusion from this analysis is that there is some common underlying feature that determines both the power reflectance and the umbo velocity at sound frequencies of 1 kHz and less, and that the two measurements are less related at higher frequencies. As will be discussed below, the acoustic compliance of the middle ear is a candidate for the coupling of reflectance and umbo velocity at low frequencies. The lack of correlation between the measurements in the middle frequencies may reflect differences in the acoustical-mechanical processes that determine reflectance and umbo velocity. One such difference may be that the complex motions of the TM that contribute to power reflectance are less important in determining how the ossicular chain is stimulated by sound in those frequencies (Tonndorf & Khanna 1970; Shaw & Stinson 1981; de La Rouchefoucaould & Olsen 2010; Cheng et al. 2010). Such differences are consistent with the suggestions of Keefe (2007), who determined that reflectance was better correlated with middle-ear input admittance than it was with measurements of umbo velocity.

Correlations with Tympanometric Measurements—The high correlations between low-frequency measurements of power reflectance and umbo velocity suggest some common underlying feature. One candidate is the compliance of the middle ear, since it is commonly accepted that compliance dominates middle-ear mechanics at frequencies below 1 kHz. Correlation coefficients were calculated between $|ECR|^2$ and V_U at 9 distributed frequencies and the tympanometrically determined static compliance and peak compliance (the sum of the static compliance and the ear canal compliance) in cc. Weak correlations were found between the static compliances and V_U measurements at frequencies of 0.3, 0.5 and 0.7 kHz (Table 4), but not at other frequencies. No noteworthy correlations were found between $|ECR|^2$ and static compliance. We did find stronger correlations between the peak total tympanometrically measured volume (the sum of the tympanometrically determined static compliance and the ear canal compliance) and $|ECR|^2$ and andV_U (Table 4; Fig. 11). These correlations were restricted to $|ECR|^2$ V_U measured at frequencies less than 1 kHz.

These results suggest that the combination of the middle-ear and ear-canal compliances contribute significantly to the measured power reflectance and umbo velocity at frequencies below 1 kHz, but not at higher frequencies. Specifically our analysis suggests that between 8 and 16% of the variance we observed in our measurements of power reflectance and umbo velocity at low frequencies can be explained by differences in the acoustic-compliance measured in the ear canal. In discussing the significance of these correlations, it should be remembered that the tympanometric estimates were performed with a different measurement

NIH-PA Author Manuscript NIH-PA Author Manuscript NIH-PA Author Manuscript

system and at a different time than the reflectance and umbo-velocity measurements, where the effect of these differences are not clear. The difference in sign that we observe in the regression slopes between $|ECR|^2$ and compliance, and V_U and compliance (Table 4 and Figure 11) again reflects simple mechanical models in which compliance and velocity are proportional, while compliance and reflectance are inversely related.

Correlations with Audiometric Thresholds—It has been suggested (e.g. Goode 1986) that variations in middle-ear function can explain part of the wide variability in auditory sensitivity in normal and pathological ears. If this suggestion is true, one might expect to find significant correlations between the auditory thresholds that vary in normal ears by 20 dB (Table 2) and measurements of middle-ear function, such as umbo velocity and power reflectance, that also vary considerably among normal hearing individuals. Our correlational analyses did not reveal any significant relationship between our objective measurements of middle ear mechanics and air-conduction thresholds at any frequency. This is consistent with Whittemore et al. (2004), who failed to find any relationship between air thresholds and umbo-velocity in a similar population.

Whittemore et al. (2004) did report a significant ($p < 0.01$) relationship between umbo velocity measured at 2 kHz and bone thresholds at 1 kHz. The results from our data do not show the same significant relationship, but do indicate at a few mildly significant correlations ($0.08 < r^2 < 0.1$, $p < 0.05$) between the bone thresholds at 1 kHz and the power reflectance at 0.3 and 0.5 kHz. The raw significance estimate at these frequencies is p ~0.05. Taking into account the Bonferroni correction reduces the significance to chance levels.

A study that did find significant correlations between measures of middle-ear mobility and audiometry in a normal hearing population was that of Ellison and Keefe (2005). While their analysis showed no significant correlations between power reflectance and hearing thresholds at frequencies of 6 kHz and less, they did describe a significant relationship between the power absorbed at 8 kHz and hearing thresholds at 0.25, 0.5, 1 and 2 kHz. They also observed correlations between ear-canal volume and hearing thresholds at 0.5 and 1 kHz, and between static compliance and 4 kHz thresholds.

The lack of significant correlations between our objective measurements of middle-ear acoustical and mechanical events and auditory thresholds suggests that the middle ear does not play a large role in the 20 dB variations in threshold that we observed in our normal ears. Though this conclusion is weakened by the results of Ellison and Keefe (2005), who did report some correlation between reflectance 8 kHz (above the range of our study) and hearing at lower frequencies. Factors that may limit our ability to find such correlations include the necessarily small range of thresholds in the normal ears (−10 to 20 dB), and the relatively large variations seen in repeated measurements of threshold and umbo velocity (+/− 5 dB), and in reflectance (+/− 0.1).

Effect of TM abnormalities on Power Reflectance and Umbo Velocity

Mechanical measurements recorded from the ear canal can be influenced by the mechanical properties of the TM. Reflectance measurements can be greatly influenced, and possibly dominated by unusual or pathological mechanical characteristics of the TM, that mask the contributions of ossicular or inner-ear mechanical processes to TM mobility. Umbo velocity measurements can also be influenced by TM mechanics even though the measurement is made directly on the umbo or very close to it. Tympanometry can sometimes provide additional information on the state of the eardrum, and we provide examples from normal hearing subjects excluded from our study by abnormal tympanometry or otoscopic exams.

NIH-PA Author Manuscript

NIH-PA Author Manuscript

NIH-PA Author Manuscript

In fig. 12a, we compare the ± 1 standard deviation range of our normal $|ECR|^2$ measurements with measurements in four ears with normal audiometry but where tympanometry suggested a hypermobile TM (a static compliance well above the normal range). Two of these hypermobile ears are from this study, and two are taken from the report of Feeney et al. (2003). The power reflectance measured in the hypermobile ears had significant notches at frequencies between 0.5 kHz and 1.2 kHz, indicative of large absorption of energy at those frequencies. The two ears from our subject with hypermobile TMs also showed somewhat higher umbo velocity as compared to the mean of our normal population with normal hearing and normal tympanometry (Fig. 12c), but the measured V_U varied by only about 1 standard deviation from the mean. The power reflectance and tympanometric measurements in these ears are all consistent with a hypermobile TM; the umbo velocity measurements seem to be less affected by this condition.

In Fig 12b & d, we plot examples of power reflectance and umbo velocity measurements on the ears of a volunteer subject and a clinic patient (neither of which were included in our normal group) with normal audiograms but with tympanosclerosis over a majority of the TM area. The left ear of Subject 24 (the black solid line) had a normal tympanogram with a static compliance of 0.3 cc. The $|ECR|^2$ measured in this ear was quite high in the mid frequencies where the V_U magnitude was low relative to normal. The right ear of Subject 44 (the dot-dashed line) had a nearly flat tympanogram with a small peak at 0 daPa and a static compliance of 0.05 cc. The $|ECR|^2$ and V_U magnitudes measured in this ear are consistent with a significant decreased mobility at low frequencies. The left ear of Patient 76 (the dotted lines) had a sharp peaked tympanogram with normal static compliance (0.7 cc), near normal V_U, and an $|ECR|^2$suggestive of a decreased mobility of the TM. These examples demonstrate that tympanosclerosis (maybe coupled with other undescribed abnormalities) can produce significant variations in power reflectance and umbo velocity, even in ears with normal hearing. Therefore, TM abnormalities, like tympanosclerosis, may mask the contribution of other pathologies to reflectance and umbo velocity measurements.

Practical Issues

Umbo velocity measurements have been made and studied in our laboratory for over 10 years, and have been shown to aid in the diagnosis of various middle and inner ear pathologies in our institution (Rosowski et al., 2003, 2008; Merchant, Rosowski and McKenna 2007; Merchant, Nakajima et al. 2007). Otologists at our institution often refer their patients for our measurements to aid in diagnosing conductive hearing loss. There is no question that an objective non-invasive diagnostic method such as umbo velocity measurements prior to surgery contributes to the understanding of pathology before surgery. These improvements in pre-surgical diagnosis lead to improved pre-surgical preparation, better counseling of patients as to surgical risks and benefits, as well as the prevention of unnecessary surgeries.

However, there are some practical issues with our umbo velocity measurement measurements. Our technique requires two professionals to make measurements – a trained clinician to operate the microscope-laser device and aim the laser on the umbo, and a trained computer operator to gather and evaluate the data. The measurements depend greatly on the ability to focus the laser on a sufficiently bright spot on the TM to ensure enough light is reflected back to the vibrometer’s sensor. Thus a dull eardrum, a poor light reflex or umbo obscured by anatomic issues (such as exostosis) can greatly complicate these measurements. Finally, while the Polytec’s HLV device has FDA approval for research purposes, it does not appear that Polytec is interested in applying for FDA approval for clinical use in the near future.

NIH-PA Author Manuscript NIH-PA Author Manuscript NIH-PA Author Manuscript

Ear-canal reflectance measurements have been a subject of research for many years (e.g. Stinson et al. 1982; Keefe et al. 1993; Voss and Allen 1994). In this study we used the only FDA approved device (Mimosa) that is generally available for use in clinics to measure acoustic reflectance. This Mimosa device is considerably less expensive than the laser Doppler vibrometer and requires minimal training. The primary practical difficulty we faced with the Mimosa device was calibrating the foam inserts manufactured by Etymotic. It was a challenge sometimes to get a tip to pass the calibration criteria, even after multiple attempts. Successful calibration required very specific positioning of the ear tips in the calibration device, and minimization of environmental acoustical noise as well as electrical noise. Many tips were discarded due to repeated poor calibrations. Generally, once calibration was successful, the measurements in patients were simple to perform, though it was crucial to establish a complete seal of the ear canal with the foam tip in order to make repeatable measurements.

Acknowledgments

Work supported by NIH/NIDCD grant R01-DC004798

We appreciate the generous assistance from Susan Voss and her analysis software. Data for comparison were generously supplied by Navid Shahnaz and Pat Feeney. Pat Jeng provided information regarding the Mimosa device. Melissa Wood and Dominic Pisano provided technical support. We’d also like to acknowledge the cooperation of all of our subjects. This work was funded by an NIH/NIDCD grant R01-DC004798.

References

Aibara R, Welsh JT, Puria S, Goode RL. Human middle-ear sound transfer function and cochlear input impedance. Hear Res. 2001; 152:100–109. [PubMed: 11223285]

Alberti PW, Jerger JF. Probe-tone frequency and the diagnostic value of tympanometry. Arch Otolaryngol. 1974; 99:206–210. [PubMed: 4853778]

Allen, JB. Measurements of eardrum acoustic impedance. In: Allen, JB.; Hall, JH.; Hubbard, A.; Neely, ST.; Tubis, A., editors. Peripheral Auditory Mechanisms. New York, NY: Springer-Verlag; 1986. p. 44-51.

Allen J, Jeng P, Levitt H. Evaluation of human middle ear function via an acoustic power assessment. J Rehabil Res Dev. 2005; 42:63–78. [PubMed: 16470465]

ANSI S1.1-1994. Acoustical Terminology; R2004.

Arechvo I, Lasurashvili N, Bornitz M, et al. Laser-Doppler vibrometry of the middle ear in humans: derivation dependence, variability, and bilateral differences. Medicina (Kaunas). 2009; 45(11):878–886. [PubMed: 20051720]

Blauert J, Platte H-J. Impulse measurements of human eardrum impedance. Proc Eighth Int Cong Acoust. 1974:1.

Cheng JT, Aarnisalo AA, Harrington E, et al. Motion of the surface of the human tympanic membrane measured with stroboscopic holography. Hear Res. 2010; 263:66–77. [PubMed: 20034549]

de La Rochefoucauld O, Olson ES. A sum of simple and complex motions on the eardrum and manubrium in gerbil. Hear Res. 2010; 263:9–15. [PubMed: 19878713]

Ellison JC, Keefe DH. Audiometric predictions using stimulus-frequency otoacoustic emissions and middle ear measurements. Ear Hear. 2005; 26:487–503. [PubMed: 16230898]

Feldman, AS. Tympanometry - procedures, interpretations and variables. In: Feldman, AS.; Wilbur, LA., editors. Acoustic Impedance and Admittance: The Measurement of Middle Ear Function. Baltimore, MD: Williams & Wilkins; 1976. p. 103-155.

Feeney MP, Grant IL, Marryott LP. Wideband energy reflectance in adults with middle-ear disorders. J Speech Lang Hear Res. 2003; 46:901–911. [PubMed: 12959468]

Feeney MP, Keefe DH. Acoustic reflex detection using wide-band acoustic reflectance, admittance, and power measurements. J Speech Lang Hear Res. 1999; 42:1029–1041. [PubMed: 10515503]

NIH-PA Author Manuscript

NIH-PA Author Manuscript

NIH-PA Author Manuscript

Feeney MP, Keefe DH. Estimating the acoustic reflex threshold from wideband measures of reflectance, admittance and power. Ear Hear. 2001; 22:316–332. [PubMed: 11527038]

Feeney MP, Sanford CA. Age effects in the human middle ear: Wideband acoustical measures. J Acoust Soc Am. 2004; 116:3546–3558. [PubMed: 15658706]

Goode RL. Middle ear function, biologic variation and otosurgical alchemy: Can we turn tin ears into gold? Arch Otolaryng/Head & Neck Surg. 1986; 112:923–924.

Gulya, AJ.; Minor, LB.; Poe, DS. Glasscock-Shambaugh Surgery of the Ear. 6. Shelton, CT: People's Medical Publishing House USA; 2010. p. 49-72.p. 465-500.

Huang GT, Rosowski JJ, Puria S, Peake WT. A non-invasive method for estimating acoustic admittance at the tympanic membrane. J Acoust Soc Am. 2000a; 108:1128–1146. [PubMed: 11008815]

Huang GT, Rosowski JJ, Puria S, Peake WT. Test of some common assumptions of ear-canal acoustics in cats. J Acoust Soc Am. 2000b; 108:1147–1161. [PubMed: 11008816]

Huber AM, Schwab C, Linder T, et al. Evaluation of eardrum laser-doppler interferometry as a diagnostic tool. Laryngoscope. 2001; 111:501–507. [PubMed: 11224783]

Hudde H. Measurement of the eardrum impedance of human ears. J Acoust Soc Am. 1983; 73:242–247. [PubMed: 6826891]

Hunter LL, Feeney MP, Lapsley Miller JA, et al. Wideband reflectance in newborns: normative regions and relationship to hearing-screening results. Ear Hear. 2010; 31:599–610. [PubMed: 20520553]

Jerger, J. Diagnostic use of impedance measures. In: Jerger, J., editor. Clinical Impedance Audiometry. New York, NY: Americam Electromedics Corporation; 1975. p. 149-174.

Keefe, DH. Influence of Middle-Ear Function and Pathology on Otoacoustic Emissions. In: Robinette, MS.; Glattke, TJ., editors. Otoacoustic Emissions: Clinical Applications. New York, NY: Thieme; 2007. p. 163-196.

Keefe DH, Levi EC. Maturation of the middle and external ears: Acoustic power-based responses and reflectance tympanometry. Ear Hear. 1996; 17:361–373. [PubMed: 8909884]

Keefe D, Ling R, Bulen J. Method to measure acoustic impedance and reflection coefficient. J Acoust Soc Am. 1992; 91(1):470–485. [PubMed: 1737890]

Keefe D, Bulen J, Arehart K, Burns E. Ear-canal impedance and reflection coefficient in human infants and adults. J Acoust Soc Am. 1993; 94(5):2617–2638. [PubMed: 8270739]

Keefe D, Bulen J, Campbell S, Burns E. Pressure transfer function and absorption cross-section from the diffuse field to the human infant ear canal. J Acoust Soc Am. 1994; 95(1):355–371. [PubMed: 8120247]

Lilly DJ. Multiple frequency, multiple component tympanometry: New approaches to an old diagnostic problem. Ear Hear. 1984; 5:300–308. [PubMed: 6389239]

Liu YW, Sanford CA, Ellison JC, Fitzpatrick DF, Gorga MP, Keefe DH. Wideband absorbance tympanometry using pressure sweeps: system development and results on adults with normal hearing. J Acoust Soc Am. 2008; 124:3708–19. [PubMed: 19206798]

Lynch TJI, Peake WT, Rosowski JJ. Measurements of the acoustic input-impedance of cat ears: 10 Hz to 20 kHz. J Acoust Soc Am. 1994; 96(4):2184–2209. [PubMed: 7963032]

Margolis, RH.; Hunter, LL. Tympanometry. In: Musiek, F.; Rintlemeann, WF., editors. Contemporary Perspectives on Hearing Assessment. Boston, MA: Allyn and Bacon; 1999. p. 89-130.

Margolis RH, Goycoolea HG. Multifrequency tympanometry in normal adults. Ear Hear. 1993; 14(6): 408–413. [PubMed: 8307245]

Margolis RH, Osguthorpe JD, Popelka GR. The effects of experimentally-produced middle ear lesions on tympanometry in cats. Acta Otolaryngologica. 1978; 86:428–436.

Margolis R, Saly G, Keefe D. Wideband reflectance tympanometry in normal adults. J Acoust Soc Am. 1999; 106(1):265–280. [PubMed: 10420621]

Margolis, R.; Shanks, J. Tympanometry. In: Katz, J., editor. Handbook of Clinical Audiology. Baltimore, MD: Williams & Wilkens; 1985. p. 438-475.

Merchant SN, McKenna MJ, Rosowski JJ. Current status and future challenges of tympanoplasty. Eur Arch Otorhinolaryngol. 1998; 255:221–228. [PubMed: 9638462]

NIH-PA Author Manuscript NIH-PA Author Manuscript NIH-PA Author Manuscript

Merchant SN, Ravicz ME, Voss SE, Peake WT, Rosowski JJ. Toynbee Memorial Lecture 1997: Middle-ear mechanics in normal, diseased and reconstructed ears. J Laryngol Otol. 1998; 112:715–731. [PubMed: 9850313]

Merchant SN, Rosowski JJ, McKenna MJ. Superior semicircular canal dehiscence mimicking otosclerotic hearing loss. Adv Otorhinolaryngol. 2007; 65:137–145. [PubMed: 17245035]

Merchant SN, Nakajima HH, Halpin C, et al. Clinical investigation and mechanism of air-bone gaps in large vestibular aqueduct syndrome. Ann Otol Rhinol Laryngol. 2007; 116:531–541.

Mehrgardt S, Mellert V. Transformation characteristics of the external human ear. J Acoust Soc Am. 1977; 61:1567–1576. [PubMed: 893803]

Nadol, JB.; McKenna, MJ. Surgery of the Ear and Temporal Bone. 2. Philadelphia, PA: Lippincott, Williams & Wilkins; 2004. p. 273-324.

Nakajima HH, Ravicz ME, Merchant SN, Peake WT, Rosowski JJ. Experimental ossicular fixations and the middle-ear's response to sound: Evidence for a flexible ossicular chain. Hear Res. 2005; 204:60–77. [PubMed: 15925192]

Nakajima HH, Ravicz ME, Rosowski JJ, et al. Experimental and clinical studies of malleus fixation. Laryngoscope. 2005; 115:147–154. [PubMed: 15630384]

Nakajima HH, Dong W, Olson ES, et al. Differential intracochlear sound pressure measurements in normal human temporal bones. J Assoc Res Otolaryngol. 2009; 10:23–36. [PubMed: 19067078]

Nakajima HH, Pisano DV, Roosli C, Hamade MA, Merchant GR, Mafoud L, Halpin CF, Rosowski JJ, Merchant SN. Comparison of ear-canal reflectance and umbo velocity in patients with conductive hearing loss: A preliminary study. Ear Hear. Submitted.

Norman, GR.; Streiner, DL. Biostatistics: The bare essentials. Hamilton, Ontario: B.C.Decker; 2000.

Rabinowitz WM. Measurement of the acoustic input immittance of the human ear. J Acoust Soc Am. 1981; 70:1025–1035. [PubMed: 7288039]

Rosowski JJ, Mehta RP, Merchant SN. Diagnostic utility of laser-doppler vibrometry in conductive hearing loss with normal tympanic membrane. Otol Neurotol. 2003; 24(2):165–175. [PubMed: 12621328]

Rosowski JJ, Nakajima HH, Merchant SN. Clinical utility of laser-doppler vibrometer measurements in live normal and pathologic human ears. Ear Hear. 2008; 29:3–19. [PubMed: 18091103]

Shahnaz N, Polka L. Standard and multifrequency tympanometry in normal and otosclerotic ears. Ear Hear. 1997; 18(4):326–341. [PubMed: 9288478]

Shahnaz N, Polka L. Distinguishing healthy from otosclerotic ears: effect of probe-tone frequency on static immittance. J Am Acad Audiol. 2002; 13(7):345–355. [PubMed: 12199511]

Shahnaz N, Bork K. Wideband reflectance norms for Caucasian and Chinese young adults. Ear Hear. 2006; 27:774–788. [PubMed: 17086086]

Shahnaz N, Bork K, Polka L, Longridge N, Bell D, Westerberg BD. Energy reflectance and tympanometry in normal and otosclerotic ears. Ear Hear. 2009; 30:219–233. [PubMed: 19194289]

Shahnaz, N.; Shaw, J. Unpublished data received from N. Shahnaz included in the poster for the American Auditory Society. 2010. Comparison of wideband energy reflectance obtained with Reflwin Interacoustics & Mimosa Acoustics.

Shaw, EAG.; Stinson, MR. The human external and middle ear: Models and concepts. In: deBoer, E.; Viergever, MA., editors. Mechanics of Hearing. Delft, The Netherlands: Delft University Press; 1983. p. 3-10.

Stepp CE, Voss SE. Acoustics of the human middle-ear air space. J Acoust Soc Am. 2005; 118:861–871. [PubMed: 16158643]

Stinson M. The spatial distribution of sound pressure within scaled replicas of the human ear. J Acoust Soc Am. 1985; 78:1596–1602. [PubMed: 4067075]

Stinson MR, Shaw EAG, Lawton BW. Estimation of acoustical energy reflectance at the eardrum from measurements of pressure distribution in the ear canal. J Acoust Soc Am. 1982; 72:766–773. [PubMed: 7130535]

Tonndorf J, Khanna SM. The role of the tympanic membrane in middle ear transmission. Ann Otol. 1970; 79:743–753.

NIH-PA Author Manuscript

NIH-PA Author Manuscript

NIH-PA Author Manuscript

Vander Werff KR, Prieve BA, Georgantas LM. Test-retest reliability of wideband reflectance measures in infants under screening and diagnostic test conditions. Ear Hear. 2007; 28:669–81. [PubMed: 17804981]

Voss SE, Allen JB. Measurement of acoustic impedance and reflectance in the human ear canal. J Acoust Soc Am. 1994; 95(5):372–384. [PubMed: 8120248]

Voss S, Horton NJ, Woodbury RR, Sheffield KN. Sources of variability in reflectance measurements on normal cadaver ears. Ear Hear. 2008; 29:651–665. [PubMed: 18600136]

Wada H, Kobayashi T, Suetake M, et al. Dynamic behavior of the middle ear based on sweep frequency tympanometry. Audiology. 1989; 28:127–134. [PubMed: 2735847]

Werner LA, Levi EC, Keefe DH. Ear-canal wideband acoustic transfer functions of adults and two- to nine-month-old infants. Ear Hear. 2010; 31(5):587–598. [PubMed: 20517155]

Whittemore KR, Merchant SN, Poon BB, Rosowski JJ. A normative study of tympanic-membrane motion in humans using a laser-Doppler vibrometer. Hear Res. 2004; 187:85–104. [PubMed: 14698090]

Withnell RH, Jeng PS, Waldvogel K, Morgenstein K, Allen JB. An in situ calibration for hearing thresholds. J Acoust Soc Am. 2009; 125:1605–11. [PubMed: 19275318]

Zhao F, Wada H, Koike T, et al. Middle ear dynamic characteristics in patients with otosclerosis. Ear Hear. 2002; 23(2):150–158. [PubMed: 11951850]

Zwislocki J. Analysis of the middle-ear function. Part I: Input impedance. J Acoust Soc Am. 1962; 34:1514–1523.

Zwislocki J, Feldman A. Acoustic impedance in pathological ears. Am Speech and Hear Assoc Monograph. 1970; 15:1–42.

NIH-PA Author Manuscript
NIH-PA Author Manuscript
NIH-PA Author Manuscript

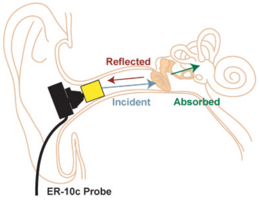

Figure 1.
Cross-section of the ear illustrating the probe in the ear canal. The probe emits a sound pressure wave that is incident on the tympanic membrane. Some of the incident sound pressure is reflected back and measured by the probe. The rest of the incident sound pressure is absorbed by the TM and the structures behind it.

NIH-PA Author Manuscript
NIH-PA Author Manuscript
NIH-PA Author Manuscript

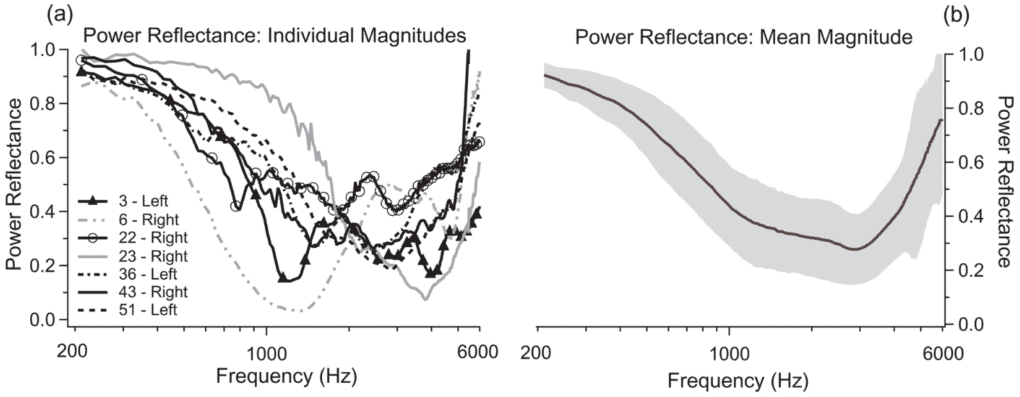

Figure 2.

Magnitude of power reflectance $|ECR|^2$. (a) Seven representative ears selected to display the variety of frequency-response curves that can be obtained. The 2 gray lines (subjects 6R and 23R) show the largest and smallest reflectance at frequencies below 2 kHz of all the normal ears measured. (b) Average and ± 1 standard deviation of $|ECR|^2$ for the 58 normal ears.

NIH-PA Author Manuscript
NIH-PA Author Manuscript
NIH-PA Author Manuscript

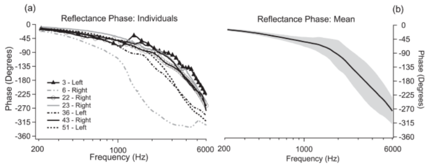

Figure 3.

Phase of the pressure reflectance $\angle ECR$ (a) Seven representative ears (same ears as in Fig. 2a). The 2 gray lines (subjects 6R and 23R) are the two most extreme outliers in power reflectance in our normal population (Fig. 2a). (b) Average ± 1 standard deviation of $\angle ECR$ for the 58 normal ears.

NIH-PA Author Manuscript NIH-PA Author Manuscript NIH-PA Author Manuscript

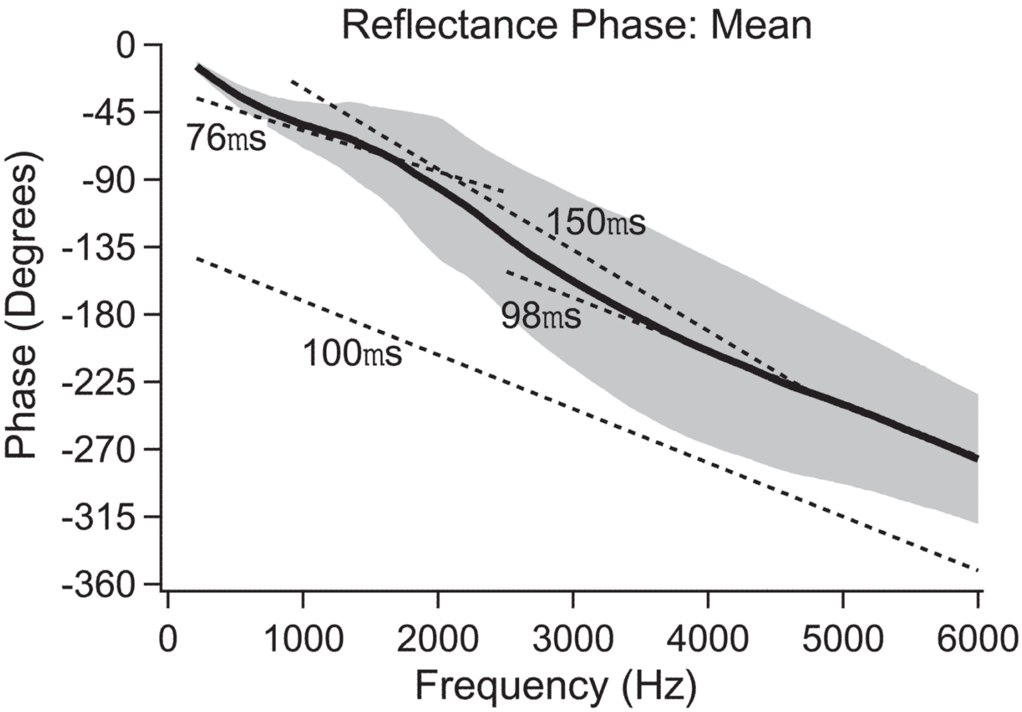

Figure 4.

Mean (thick black solid line) ± 1 standard deviation (shaded region) of the phase of the pressure reflectance, ∠*ECR*, plotted on a linear frequency scale. Lines are drawn to display different phase gradients consistent with local group delays of 76 to 150 μs. The group delay estimated from the entire frequency range is approximately 100 μs, illustrated by the line below the mean and standard deviation.

NIH-PA Author Manuscript

NIH-PA Author Manuscript

NIH-PA Author Manuscript

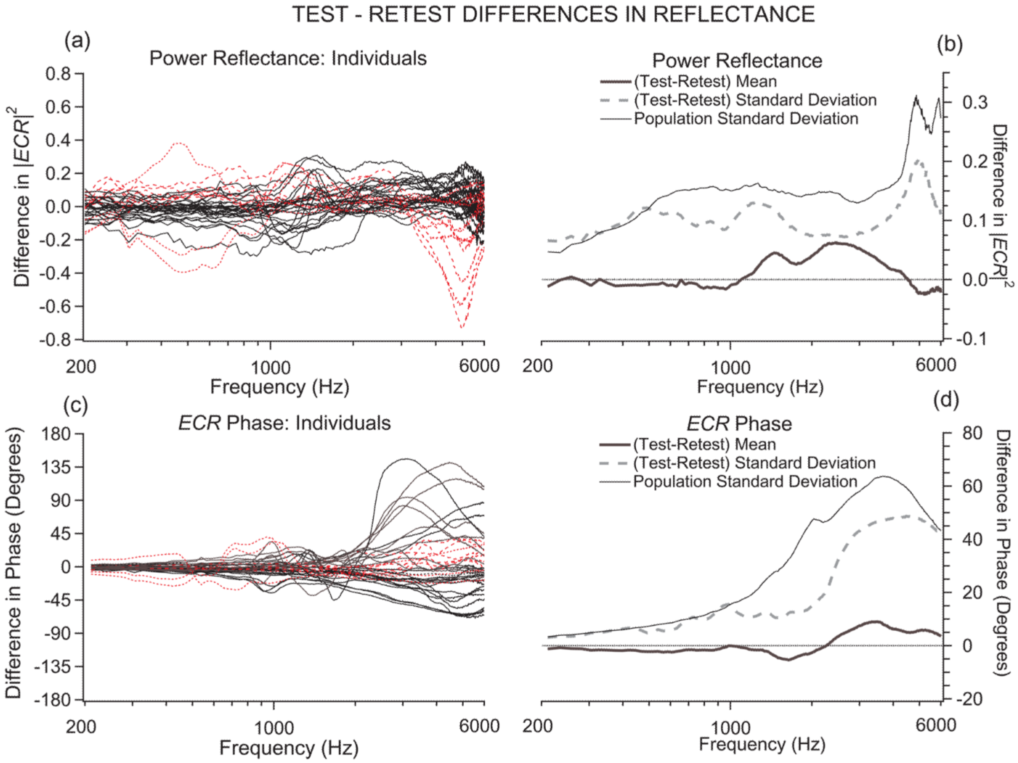

Figure 5.

Reflectance measurements were made 1, 2, and 3weeks after the initial recording for both ears in 7 subjects. The difference with respect to the initial recording of the three later measurements is plotted for power reflectance, $|ECR|^2$, in (a), and reflectance phase, $\angle ECR$, in (c). The gray lines represent subjects that had normal audiograms but did not meet our strict “normal hearing” criteria. The dotted gray had a suprathreshold low-frequency bone curve resulting in a small air-bone gap. The dashed gray had tympanograms consistent with a hypercompliant eardrum. (b) & (d) Plots of the average and standard deviation of these Test-Retest differences, as well as the standard deviation of the power reflectance measured in the 58 ears of the ‘normal’ population (Figs 2 & 3).

NIH-PA Author Manuscript

NIH-PA Author Manuscript

NIH-PA Author Manuscript

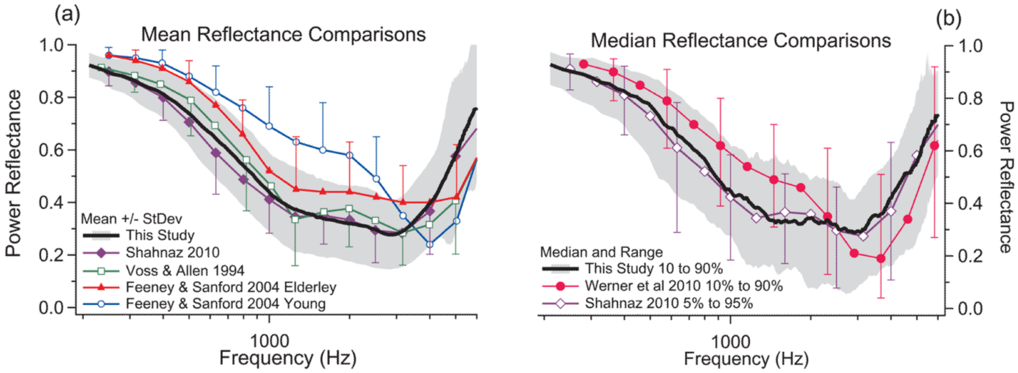

Figure 6.

Comparisons with other power reflectance measurements. (a) Comparison of the mean (black solid line) ± 1 standard deviation (shaded area) for the present study to the means (colored lines and symbols) and +1 or −1 standard deviation (vertical error bars) of previously published data, including Voss and Allen 1994; Feeney & Sanford 2004 and Shahnaz & Shaw (2010). (b) Comparison of the median (black solid line) and 10–90% range (shaded area) for the present study to median and 10 to 90% of Shanaz & Shaw (2010) and the 5–95% range of Werner et al. (2010)

NIH-PA Author Manuscript
NIH-PA Author Manuscript
NIH-PA Author Manuscript

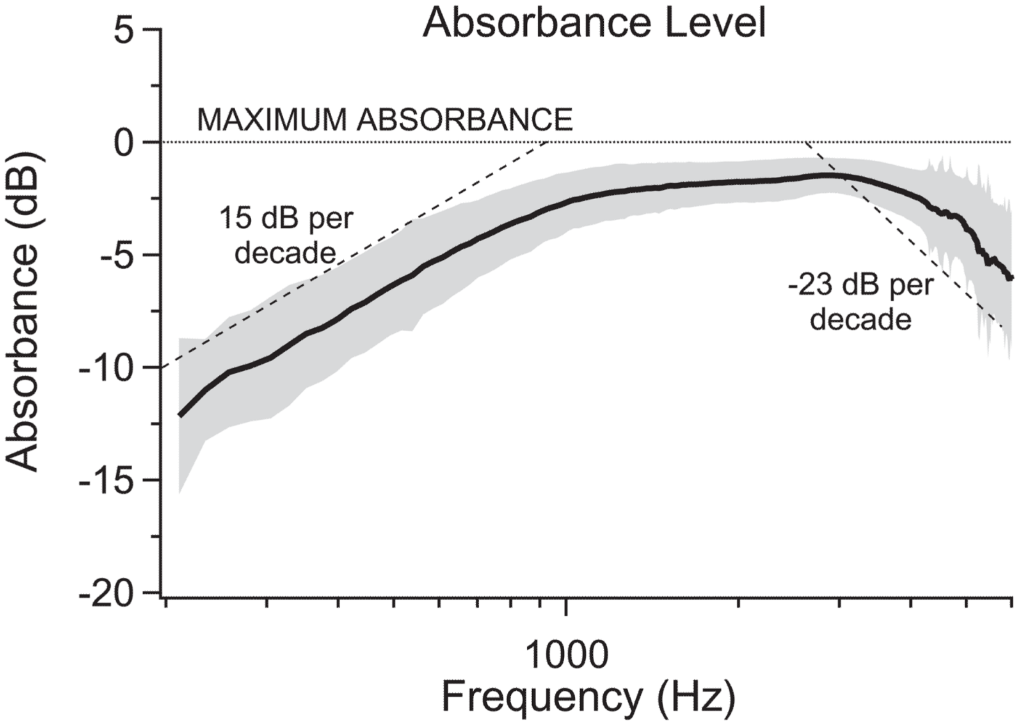

Figure 7.

Mean and standard deviation of the absorbance level ($10 \times log_{10} [1-|ECR|^2]$) is plotted for our 58 normal ears.

NIH-PA Author Manuscript NIH-PA Author Manuscript NIH-PA Author Manuscript

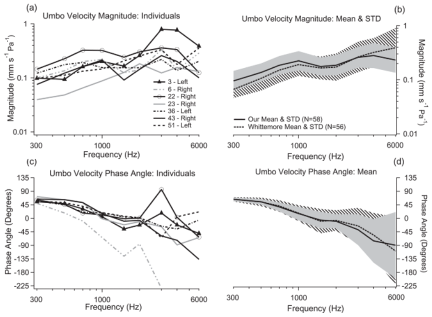

Figure 8.

Magnitude and phase of normalized umbo velocity V_U. (a & c) These measurements are from the same seven representative ears shown in Fig. 2(a) and 3(a). The 2 gray lines are from subjects (6R and 23R) with the highest and lowest $|ECR|^2$ at frequencies less than 2 kHz in the 58 ears measured. (c & d) Average and standard deviation of V_U, for 58 ears (29 subjects) in this study are shown in black and gray. A geometric average was taken of the magnitude data. The average and standard deviation from Whittemore et al. (2004) are shown in dashed lines and darker background.

NIH-PA Author Manuscript

NIH-PA Author Manuscript

NIH-PA Author Manuscript

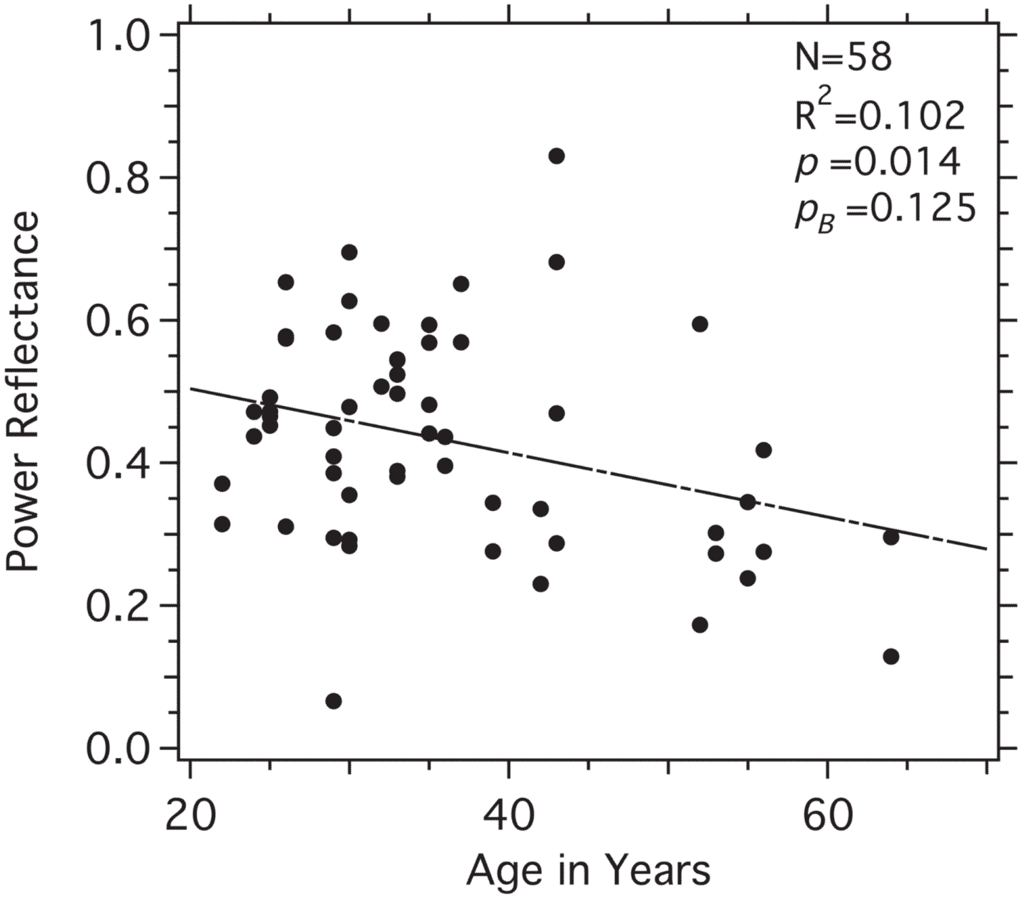

Figure 9.

Power reflectance at 1 kHz vs age. The regression line shown has a negative slope suggesting that the reflectance at 1 kHz tends to decrease with age. The line is the result of a least-squares regression analysis, where: Power Reflectance = 0.594 – 0.0045 the age in years. The probability p is the calculated probability that the regression slope equals zero based on a single regression calculation done at 1 kHz. The probability p_B is the calculated probability after applying a Bonferonni correction for the use of repeated regression/ correlation calculations.

NIH-PA Author Manuscript NIH-PA Author Manuscript NIH-PA Author Manuscript

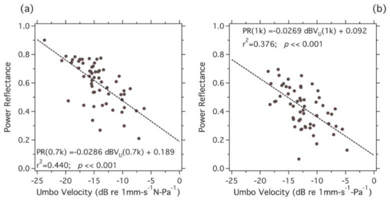

Figure 10.

Least-squares linear regression analyses between the power reflectance $|ECR|^2$ and normalized umbo velocity V_U: (a) at 0.7 kHz and (b) at 1 kHz. The probability that either of the pictured regression slopes equals 0 is much less than 0.1%, even *after Bonferonni correction.*

NIH-PA Author Manuscript

NIH-PA Author Manuscript

NIH-PA Author Manuscript

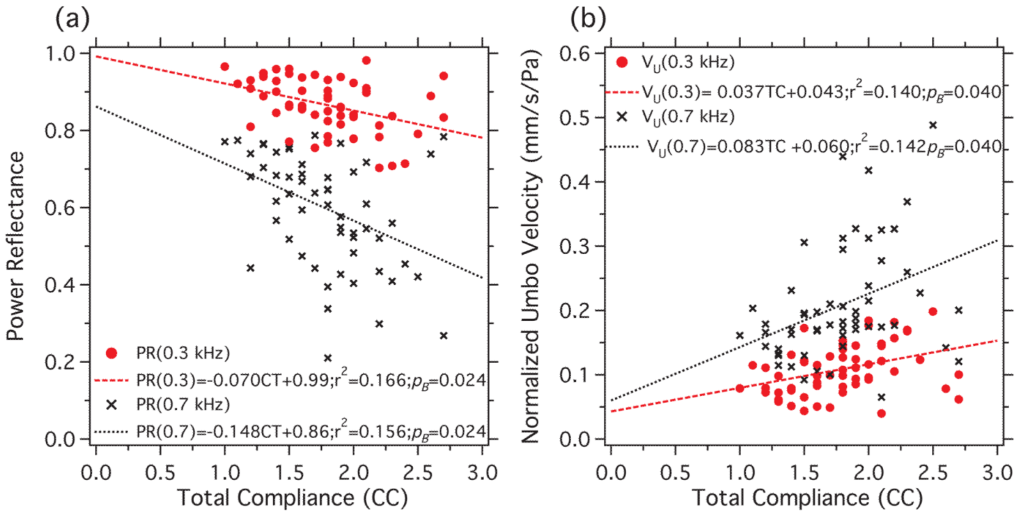

Figure 11.

(a) Correlations and linear regression analyses of power reflectance and normalized umbo velocity vs. the peak total compliance (measured by tympanometry). Each panel contains data measured at 2 frequencies: 0.3 kHz, the filled circles, and 0.7 kHz the x's. The results of least-squares linear regression analyses are also plotted and noted in the figure legends. The significance of fit, p_B, is the probability that the slope is zero corrected for the number of regression calculations performed between total compliance and either reflectance or umbo velocity.

NIH-PA Author Manuscript

NIH-PA Author Manuscript

NIH-PA Author Manuscript

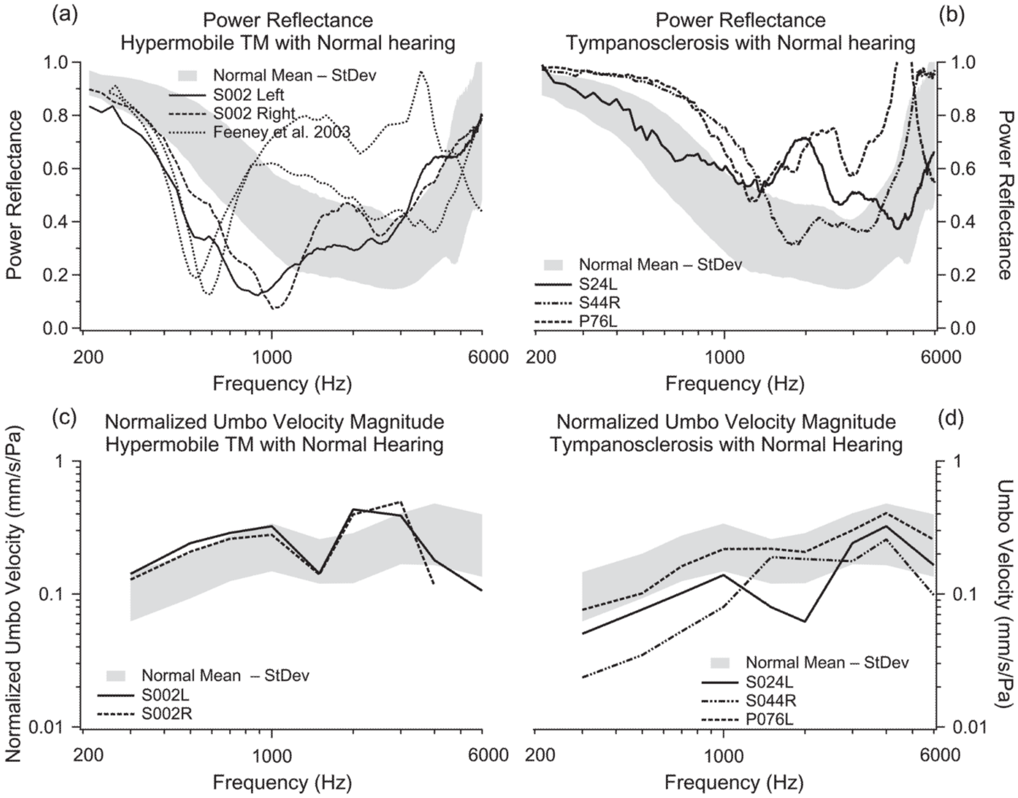

Figure 12.

Examples of power reflectance and umbo velocity for subjects with normal audiograms but with tympanometric or anatomical abnormalities: (a & c) hypermobile TM with static compliances of 4 cc (S002 Left) and 3.4 cc (S002 Right), plus 2 measurements from Feeney et al. (2003); (b & d) Three ears with tympanosclerosis and normal hearing.

NIH-PA Author Manuscript

NIH-PA Author Manuscript

NIH-PA Author Manuscript

Table 1

Age distribution of normal subjects

Age distribution	**All Normal Subjects**	**Male Subjects**	**Female Subjects**
N	**29**	**13**	**16**
Mean age (years)	36.6	30.7	41.3
Standard deviation	11.1	8.5	9.7
Median age (years)	33	29	37
Minimum age (years)	22	22	26
Maximum age (years)	64	53	64

NIH-PA Author Manuscript NIH-PA Author Manuscript NIH-PA Author Manuscript

Table 2

Audiometric Data from Both Ears of 29 Normal Hearing Subjects

Statistics	Air Conduction Frequency (Hz)						Bone Conduction Frequency (Hz)				
	250	**500**	**1000**	**2000**	**4000**	**8000**	**250**	**500**	**1000**	**2000**	**4000**
Average	6.8	6.3	4.1	5.1	8.2	9.3	4.2	7.3	2.9	8.6	8.2
St. Dev.	4.0	3.3	3.8	5.1	4.8	6.0	4.8	5.1	5.9	5.2	4.7
Median	5	5	5	5	10	10	5	5	5	10	10
Maximum	15	15	10	15	20	20	10	20	20	20	20
Minimum	−5	0	−5	−5	0	−5	−10	0	−5	0	−5

NIH-PA Author Manuscript NIH-PA Author Manuscript NIH-PA Author Manuscript

Table 3

Ten Best Correlations Between Power Reflectance and Umbo Velocity Magnitude in dB **Umbo Velocity (the independent variable) is scaled in terms of 20×log10(Vu/(1mm/s-1/Pa-1))**

Variables		**Statistics**			
Power Reflectance	**Umbo Velocity**	**r^2**	**Significance**[*]	**Slope**	**Int**
700 Hz	700 Hz	0.440	p ~2X10^{-8}	−0.0286	0.189
300 Hz	300 Hz	0.415	p ~5X10^{-8}	−0.1327	0.602
500 Hz	500 Hz	0.402	$p \sim 2\times10^{-10}$	−0.0242	0.314
700 Hz	500 Hz	0.394	$p \sim 2\times10^{-7}$	−0.0282	0.118
300 Hz	500 Hz	0.391	$p \sim 2\times10^{-7}$	−0.0129	0.646
1000 Hz	1000 Hz	0.376	$p \sim 2\times10^{-8}$	−0.0269	0.092
500 Hz	700 Hz	0.372	$p \sim 4\times10^{-7}$	−0.0223	0.406
500 Hz	300 Hz	0.364	$p \sim 6\times10^{-7}$	−0.0229	0.270
700 Hz	300 Hz	0.343	$p \sim 2\times10^{-6}$	−0.0262	0.075
300 Hz	700 Hz	0.335	$p \sim 2\times10^{-6}$	−0.0115	0.702

[*] These significance scores are not corrected by any Bonferroni-type adjustment. Since they are the result of 81 separate correlation/regression estimates, a simple Bonferroni adjustment would multiply each of the significance scores by 81, with little practical result on the estimation of significance.

NIH-PA Author Manuscript NIH-PA Author Manuscript NIH-PA Author Manuscript

Table 4

Regression Analyses Between Tympanometric Compliance and Power Reflectance or Umbo Velocity Magnitude

Dependent	Independent	r^2	Raw Significance	Adjusted Significance	Slope	Int
V_U 0.3 kHz	Static Compliance	0.080	p=0.032	p_B=0.32	0.0435	0.078
V_U 0.5 kHz	Static Compliance	0.091	p =0.021	p_B=0.231	0.0685	0.104
V_U 0.7 kHz	Static Compliance	0.100	p =0.016	p_B=0.192	0.1092	0.133
V_U 0.3 kHz	Total Compliance	0.140	p =0.004	p_B=0.040	0.0367	0.043
V_U 0.5 kHz	Total Compliance	0.122	p =0.007	p_B=0.049	0.0504	0.062
V_U 0.7 kHz	Total Compliance	0.142	p =0.004	p_B=0.040	0.0830	0.060
$\|ECR\|^2$ 0.3 kHz	Total Compliance	0.166	p =0.002	p_B=0.024	−0.0703	0.992
$\|ECR\|^2$ 0.5 kHz	Total Compliance	0.141	p =0.004	p_B=0.040	−0.1197	0.940
$\|ECR\|^2$ 0.7 kHz	Total Compliance	0.156	p =0.002	p_B=0.024	−0.1480	0.862