Introduction
A diamond has many facets, each providing a reflective glimpse of the inner jewel. Similarly, there are many facets to the functioning of the middle ear. This paper is concerned with eight of the most revealing facets and what they tell us about the transmission of sound in the middle ear. The eight facets of interest are:
1) Power reflectance 2) Transmittance, 3) Reflectance phase, 4) Acoustic length, 5) Normalized impedance magnitude, 6) Normalized resistance, 7) Normalized reactance, and 8) Impedance phase. The goal of this paper is to describe and discuss these measures of middle-ear function and demonstrate how these measures might provide informative clues for interpreting the transmission status of an impaired ear. Acoustic power measurements obtained from a hard-wall cavity, artificial ear coupler (B&K 4157), “normal” and pathological ears of adults, children, and infant will be used for discussion. The word “normal” is in quotes since there are still many uncertainties regarding the specification of normal middle ear function. Reflectance and other relevant measurements have all shown large variations between ears. There is also some evidence that more than one definition of normal middle ear function may be necessary (eg., some subjects with normal audiometric thresholds show a single minimum in the reflectance-vs-frequency curve while other subjects with normal audiometric thresholds show more than one minimum.)

Terminology and Definition of Terms
In delivering acoustic power into the ear canal, some power is reflected, some dissipated by the mechanical process of the middle ear structure, and the rest transmitted into the middle ear structure and then into cochlea. In this paper we consider four reflectance-based measurements and four impedance-based measurements, in order to obtain a better understanding of acoustic power flow in the middle ear.

The reflectance based quantities are defined as follows:

Complex Pressure Reflectance, \( R \), is defined as the ratio of reflected pressure to incident pressure.

Power Reflectance, \( |R|^2 \), is defined as the ratio of the time average reflected power to incident power and is expressed as a percentage.
Transmittance, T, specifies the average power transmitted into the middle ear on a decibel scale. 
T is defined as $10 \cdot \log_{10}(1-|R|^2)$ and is expressed in dB.

Reflectance Phase, angle($R$), is defined as the phase of $R$ expressed in radians or as fractions of cycles.

Acoustic Length is the group delay x speed of sound, where group delay = slope of angle($R$) vs frequency and is specified in mm.

The impedance-based quantities are defined as follows:

Normalized impedance magnitude, $|Z_{\text{norm}}|$, is defined as the ratio $|Z_{\text{load}} / Z_{\text{ear-canal}}|$ where $Z_{\text{load}}$ is the measure acoustic impedance and $Z_{\text{ear-canal}}$ is the characteristic impedance, $\rho c/A$, with $\rho$ for the density of air, $c$ for the speed of sound, and $A$ for the cross-sectional area of the ear canal estimated by the ear tip used.
Note that $Z$, measured in acoustic ohms, and has a magnitude $|Z|$ and phase $\angle Z$ (e.g. is complex) and $|Z_{\text{norm}}|$ is dimensionless.

Normalized Resistance is the Real part of $Z_{\text{norm}}$.

Normalized Reactance is the Imaginary part of $Z_{\text{norm}}$ and is always positive.
Note that a stiffness-dominated reactance is negative and a mass-dominated reactance is positive.

Impedance Phase, angle($Z_{\text{norm}}$), is defined as the phase of $Z_{\text{norm}}$ and is specified in radians or fractions of cycles, on cycle being $2\pi$ radians (r.e. 360°).

**Experimental Results**
The clinical cases presented in this paper are obtained from three different studies. In these cases, the acoustic power measurement was performed during the patient’s clinical visit. All the reflectance and impedance measurements were obtained using Mimosa Acoustics’ HearID Middle Ear Power Analyzer (MEPA3) version R3.4 or version R4.0. Audiometric data and diagnosis information were retained from the patient’s clinical evaluation.

The acoustic power measurement requires a precision probe calibration and the pressure response measurement in the patient’s ear canal. The probe calibration is performed once a day prior to the pressure response measurement in the patient’s ear. The principle of the probe calibration procedure is similar to the one described by Allen, 1986 and by Voss and Allen, 1994. The pressure response measurement using chirp stimulus is
similar to the in-the-ear calibration in DPOAE measurement. The Thévinen equivalent parameters from the probe calibration, source pressure and source impedance, and the pressure response from the patient’s ear canal are then used to compute all the acoustic power measures of the patient’s ear. The total measurement time in a patient’s ear is typically between 1 to 4 seconds depending on the artifact rejection and stopping rule.

Data are presented first for a rigid cavity and an artificial ear (B&K 4157). These data serve as a reference for the measurements in human ears; adult, children, and infant, including both ‘normal’ and pathological ears. For adult and children, “normal” ears are defined as ears with normal otoscopic examination, audiometric thresholds, and tympanometric data, while for newborn infant, “normal” ears are defined with passing OAE screening. The pathological ears include OME and perforated TM in adult and children, and not passing OAE screening in infant.
Case 1: Rigid cavity and artificial ear coupler (B&K4157)

Figure 1 shows Power flow and impedance measurements in a rigid cylindrical cavity, compared against measurement in an artificial ear coupler, B&K 4157. Eight quantities are shown in the diagram as functions of frequency from 0.2 to 6 kHz. The four panels on the left show, respectively, power reflectance in percent, transmittance in dB, reflectance phase in radians/2π, and the reflectance group delay expressed as acoustic length in mm. The four panels on the right show normalized impedance quantities re the characteristic impedance in the ear canal, i.e., normalized impedance magnitude, normalized resistance, normalized reactance, and impedance phase, respectively.

In a rigid cavity, virtually all the acoustic power is reflected. The red curve showing power reflectance for a rigid cavity (top left panel) is a straight line close to 100 % across all frequencies, indicating near complete reflection. The yellow curve shows the power reflectance measured by Voss & Allen (1994) in an artificial ear coupler (B&K 4157). The curve shows high reflectance at low frequency, decreases to 40% reflectance between 1 to 4 kHz, and increases again above 4 kHz.

The red transmittance curve (second panel on left) shows the amount of acoustic power transmitted in the rigid cavity is very small, less than -15 dB below 1 kHz and -13 dB at 3 kHz. The transmittance of the B&K4157 artificial ear (yellow curve) resembles the middle ear transfer function, sloping downwards below 1 kHz at about 6 dB per octave.

The third panel on the left shows reflectance phase. The curve for the rigid cavity decreases monotonically while the absolute value of its slope increases linearly with frequency; i.e., the group delay is constant with frequency. A reflectance phase curve of this type is indicative of a single point reflection. In the rigid cavity, the acoustic power is reflected off the back plane of the cylinder. This point is further clarified in the next panel showing acoustic length (= group delay x speed of sound). The slope of the reflectance phase vs frequency curve for the artificial ear does not increase linearly with frequency indicating that the group delay varies with frequency. The curve has a slope of zero in the region of 1 kHz, indicating that the group delay has a null in this frequency region.

The lowest panel on the left shows the acoustic length in mm. The acoustic length of the rigid cavity is constant at about 23 mm across the complete frequency range (0.2 to 6 kHz) indicating that the acoustic power is reflected from the same site (the back plane of the cylinder). An acoustic length of 23 mm matches our a priori knowledge of this cavity. The acoustic length of the artificial ear shows a similar length below 500 Hz and a shorter acoustic length (approximately 10 mm) at frequencies above 1.5 kHz. Between 0.5 to 1.5 kHz, there is a null at 1 kHz, corresponding to the zero group delay noted above and matching the knee frequency of the transmittance curve for the artificial ear.
Figure 1. Rigid Cylindrical Cavity and Artificial Ear Coupler (B&K 4157)
Red curves = rigid cavity (several replications). Yellow curves = B&K 4157 artificial ear.
A filled in region indicates data obtained over a large number of replications.
The top panel on the left shows power reflectance in percent
The second panel on the left shows transmittance in dB
The third panel on the left shows reflectance phase in cycles (i.e. radians/2π)
The lowest panel on the left shows acoustic length in mm
The top panel on the right shows normalized impedance magnitude
The second panel on the right shows normalized acoustic resistance
The third panel on the right shows normalized acoustic reactance
The lowest panel on the right shows impedance phase in cycles (radians/2π).
The top panel on the right shows normalized impedance magnitude. The impedance of the rigid cavity is dominated by stiffness at low frequencies and by mass at high frequencies with a very small positive resistance. The normalized impedance magnitude of the rigid cavity decreases monotonically with increasing frequency until a null is reached at 3.7 kHz and increases monotonically at higher frequencies. The null occurs at the frequency at which the reactance crosses from stiffness dominance to mass dominance. It also defines the frequency of the standing wave in this cavity.

Unlike the rigid cavity, the impedance of the artificial ear is determined primarily by its resistance and stiffness. The normalized impedance magnitude of the artificial ear thus decreases monotonically with increasing frequency and does not show a minimum at the null frequency for the rigid cavity.

The second panel on the right shows normalized acoustic resistance. The normalized acoustic resistance of the rigid cavity is essentially zero. The normalized acoustic resistance of the artificial ear is approximately 1 at frequencies below 2 kHz indicating the impedance of the coupler in this frequency region matches the characteristic impedance of the air allowing maximal transmission of the acoustic power. Above 2 kHz, the coupler’s resistance diminishes toward 0 and hence diminishes its contribution to the impedance.

Panel 3 on the right shows that the normalized reactance of the rigid cavity is less than zero at frequencies below the null frequency of 3.7 kHz. Above 3.7 kHz, the reactance is positive, indicating that it is mass dominated. The normalized reactance of the artificial ear is similar to that of the rigid cavity at frequencies below 3.7 kHz, but it remains less than zero up to 6 kHz, indicating that it is stiffness dominated over this entire frequency range.

The impedance phase shown in the lowest panel on the right is close to -90 degrees for the rigid coupler up to the null frequency of 3.7 kHz switching rapidly to +90 degrees at higher frequencies. The impedance phase of the artificial ear, in contrast, varies by a comparatively small amount over the entire frequency range.

The reflectance and impedance measurements shown in Figure 1 for the two cavities serve as a useful reference for the measurements in human ears.
Case 2: Adult with OMR in right ear and “Normal” in left ear

Figure 2 shows reflectance and impedance measurements of an adult’s two ears, whose right ear (R) has otitis media with effusion (OME) and the left ear (L) is normal according to the audiometric measurements. The audiometric measurements show that the OME ear has mild conductive hearing loss with air-bone gap (ABG) and an equivalent volume of 1.1 cc, but no observable static acoustic admittance \([Y_0 \text{ from TYMP}]\). The “normal ear” has a normal ABG and TYMP. The power reflectance shows a very stiff OME right ear having a stiffness below 0.8 kHz of about 1.5 that of an average-normal adult ear.

The acoustic power measurements show the OME ear behaves like a rigid cavity: with high reflectance, reduced transmittance, monotonic sloping of the reflectance phase, less variations in the reflectance group delay and acoustic length, higher impedance with a sharp null at ~3.6 kHz, increased resistance below 0.4 kHz and nearly 0 resistance above, increased stiffness, and a sharp switching of the impedance phase from -90 to +90 degree.

As shown in Table I, the audiometric air-bone gaps (ABG) of this OME ear are 20, 15, 40, 15, and 35 dB at .25, .5, 1, 2, and 4 kHz. Using the transmittance of the artificial ear (B&K 4157) as a reference, the amount of the transmittance reduction in the OME ear is the largest between .6 and 1 kHz and at 4 kHz and is less in other frequency regions. This pattern seems to agree with the amount of the ABGs having the larger gaps, 40 dB and 35 dB at 1 kHz and 4 kHz respectively, and smaller gaps in other frequencies. The air conduction thresholds also seem to follow the same pattern. It is a qualitative match.

Comparing the power measurement of the normal ear (left ear in red lines) with those of the OME ear and of the artificial ear coupler, the normal ear behaves more like the artificial ear with variations. The reflectance slope in the range of 0.7 to 1 kHz is shallower (higher reflectance), due to the reduction of the resistance in this region, causing the stiffness to dominate the impedance. However the resistance in this region is close to 1 meaning a match between input impedance and the characteristic impedance allowing good transmission of the acoustic energy.

WHERE IS THE Z, Re Z, Im Z, angle Z, DISCUSSION FOR CASE 2?
**Figure 2. Adult With OME in Right Ear**

See captions of Figure 1 for description of panels.
Blue lines = data obtained on the right (OME) ear, 2 replications
Red = data obtained on the left (Normal) ear, 2 replications
Yellow = data obtained on artificial ear coupler (B&K 4157)

![Graphs showing data for different ears and conditions]

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The power reflectance of the normal ear is relatively small (less than 40%) in the region of 2 to 5 kHz. This implies that more acoustic power is being transmitted to the middle ear. Is all of this acoustic power being passed on to the cochlea or is a significant proportion being consumed by the middle ear structure? In this region, the impedance phase shows a slow progressive change from stiffness dominance at 2 kHz to resistance dominance at 4 kHz (the impedance phase crossing zero), then to mass dominance at 6 kHz. This is typical in most of the normal adults’ ears and in normal children’s ears.

At frequencies above 2 kHz, the measurements of this normal ear’s reflectance group delay varies substantially with frequency because of the small amount of reflected power. Consequently, the measured acoustic length of this normal ear shows a large numbers of peaks and dips compared to that for the OME and artificial ears. The envelope of the reflectance group delay (RGD) in the normal ear matches the reflectance group delay of the OME ear which seems to indicate the similarity due to the same middle ear structure, from where the reflection comes. The condition of the OME ear causes this structure to be rigid, and the condition of the normal ear allows this structure to be mobile. The maximal point of the RGD in the OME ear is at ~ 3.5 kHz, the same as the anti-resonant frequency where the impedance phase crosses 0 angle switching from stiffness to mass dominance. The estimated acoustic length is ~32.5 mm. The large number of peaks and dips with two large dips in the acoustic length of the normal ear might indicate the mobility and interactions of the ossicles. This is typical in the normal ears, except the frequency range is shifted from .7 to 2 kHz (see Voss & Allen, 1994) to 2 to 4 kHz. This shift might due to the effect of middle ear infection in a much lesser degree comparing to the right ear (OME ear).

Comparing the acoustic lengths in this frequency region, those in the region below 400 Hz are about 15 and 25 mm for the OME and normal ears respectively. Can these lengths be used to identify the sites of reflections? The equivalent volumes computed from the power measurements are 0.8 and 1.1 cc (tip A) respectively indicating small volumes between the probe tip and the TM. Based on the rigid cavity example, the acoustic length of the OME ear at the low frequency region indicates the ear drum is a reasonable site of reflection, while the acoustic length of the normal ear at this frequency region indicates the site of reflection to be further down the ossicular path.

Below 500 Hz, the acoustic length of the OME ear is about 15 mm comparing to 25 mm for the normal ear. We suspect the site of reflection in the frequency region is from the TM in the OME ear and from annular-ligament for the normal ear. This speculation needs further examination.
Case 3: Child with OM and Retracted TM in both ears.

Figure 3 compares the reflectance and impedance measurements of two OME ears in a 7-year-old child with normative data for a group of 44 children. The audiomeric measurements of this child show type B tympanograms with retracted TM, and air-bone gaps (ABGs) in both ears, however with no fluid in left ear and uncertain of fluid in the right ear.

The reflectance measurements show above-normal power reflectance in the frequency region below 4 kHz, the left ear showing a higher reflectance than the right. Similarly, the transmittance was below normal in this frequency region, transmittance being lower for the left ear. The transmittance gap (the mean of the normative data minus the transmittance of the OME ear) varied between 2 to 7 dB. The left and right ears had average ABGs of 34 and 38 db, respectively. These two measures indicate a stiffened TM below 4 kHz.

The reflectance group delays for the left and right ears show acoustic lengths of approximately 22 and 26 mm, respectively, corresponding to equivalent volumes of .62 and .73 cc. The data for the OME ears also show less frequency dependence than the normative data, as expected since the precision of this measurement depends on the strength of the reflected power which is lower above 1 kHz for the normative data. Although the equivalent volume of the children ears with OME was less than that of the two adult ears with OME, the acoustic length of the children’s ears was slightly greater. Perhaps the lack of the fluid in the children’s OME ears allows the site of reflection to be further down the conductive path from the TM.

The impedance measurements show results similar to those for a rigid cavity. The curves for impedance magnitude, for example, show sharp dips at the resonant frequencies. These dips, however, are not as extreme as the null obtained with a rigid cavity, as shown in the top left panel of Figure 1. The impedance phase for the OME ears also shows a sharp transition in the region of the resonant frequencies, although not as steep as that for a rigid cavity.
Figure 3. Seven Year Old Child with OM and Retracted TM in Both Ears. See captions of Figure 1 for description of panels. Blue lines = left ear, No fluid. Red = right ear, Uncertain of fluid is present. Yellow = Range of normative data on 44 children.

Table 2. Audiometric and Tympanometric Data. Child With OME, Retracted TM

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Case 4: Two-Day-Old Infant: One Ear Failed OAE Screen

Reflectance and impedance measurements are shown for a newborn infant who did not pass OAE screening on day 1 in both ears, then passed the screening in left ear but failed the OAE screen in the right ear on day 2. The data shown are for day 2.

Figure 4a shows the measurements for the left ear. The ear passed OAE screening with moderate occlusion from vernix and cerumen, but normal TM mobility. The power reflectance and transmittance data are just within the normative range in the frequency range from 0.5 to 2 kHz. Note that the normative data were obtained on young children and that these data provide a rough estimate of the normative range for infants. The deviation from the normal shape of the power reflectance and transmittance curves may be caused by the flabby canal wall typical of infant ears. The impedance measurements also show substantial deviation from the normative children’s data. The slope of the impedance magnitude curve is relatively shallow with a small minimum below 2 kHz. The normalized resistance is substantially greater than normal, especially below 0.5 kHz, indicating that a significant amount of power is being absorbed by the middle ear, presumably because of the flabby ear canal wall. The reflectance phase and group delay measurements are also indicative of early reflections from the ear canal wall.

Figure 4b shows the measurements for the right ear which failed the OAE screen. Both the reflectance and impedance measurements show substantial deviations from the children’s normative data. The impedance phase was close to $\pi/4$ (45 degrees). This would occur with a “lossy compliance having an impedance of $1/\text{sqrt}(j)$”, probably due to the viscosity of the vernix and cerumen in the ear canal. As in the case of the left ear, the reflectance phase and group delay measurements are indicative of early reflections from the ear canal wall.
Figure 4. Two-Day-Old Infant: One Ear Failed OAE Screen
See captions of Figure 1 for description of panels.
Two replications are shown for each measurement.
Yellow = Range of normative data on 44 children.

Figure 4a. Left Ear: Passed OAE Screen

Figure 4b. Right Ear: Failed OAE Screen
Case 5: Adult: One Normal Ear, One With Acute Otitis and Ruptured TM

Figure 5 shows reflectance and impedance measurements for an adult whose right ear shows normal audiometric and tympanometric measurement (blue lines) and whose left ear is diagnosed to have acute otitis with drum rupture (red lines). Two replications were obtained on the normal ear and three replications on the impaired ear. The audiometric and tympanometric data are in Table 3.

The reflectance and impedance measurements for the audiometrically normal right ear are very similar to the measurements obtained on the artificial ear which is nominally representative of a normal adult ear. The replications also show a relatively small between-test variance except for the measurements of acoustic length which show a high degree of variability. For the impaired ear, the power reflectance and transmittance measurements show substantial absorption of power in the frequency region below 3 kHz. This is presumably because of the leak into the middle ear cavity caused by the ruptured TM. The normalized resistance is also substantial in the frequency region below 3 kHz, indicative of high power absorption. The normalized reactance and impedance phase measurements are also deviant in this frequency region.
Figure 5. Adult: Right Ear Normal, Left Ear With Acute Otitis and Ruptured TM
See captions of Figure 1 for description of panels.
Blue = right ear, normal, Red = left ear, acute otitis with drum rupture
Yellow = data obtained on artificial ear coupler (B&K 4157)

Table 3.
Audiometric and Tympanometric Data: Right Ear Normal, Left Ear With Acute Otitis and Ruptured TM

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Discussion

The battery of measurements provides important information on middle ear from several perspectives. The following is a summary of the strengths and limitations of each of the eight measurements considered in this paper.

**Power reflectance**
Power reflectance as a function of frequency provides a concise representation of the percentage of power absorbed by the middle ear. The characteristic normal pattern of this function shows a monotonic decrease in reflected power with increasing frequency, reaching a minimum in the region of 4 kHz with a complex pattern of increased power reflection at higher frequencies. There is, however, substantial between-subject variation in the shape of the normal power reflectance curve which limits the sensitivity of the measurement as a diagnostic tool. Many pathologies block power flow into the middle ear resulting in increased power reflectance which is most easily detected in the frequency region where normal power reflectance is low, as in ears with OME. (Cases 2 and 3). Not all pathologies, however, show abnormal power reflectance in this frequency region. In the case of a ruptured eardrum, the power reflectance curve deviated from the norm in the low frequencies, where power reflection is normally high. Other factors, in combination with a blockage in the middle ear, can disguise the effect of the blockage on the power reflectance curve. In Case 4, the power reflectance curve for an ear with a blockage appears normal, except over a limited frequency range.

In short, the measurement of percent power reflectance is useful in providing a concise summary of power absorbed by the middle ear and that abnormal power flow is most easily detected when the power reflectance curve is close to one of its two extremes; eg., an obstruction in the middle ear is most easily detected at those frequencies where normal power reflectance is in the region of a minimum, and leakage (as in a ruptured eardrum) is most easily detected when power reflectance is normally very high, as in the low frequencies. The power reflectance curve does not provide useful information on the site of the pathology.

**Transmittance**
Transmittance as a function of frequency also provides a concise summary of power absorbed by the middle ear, but in a form that quantifies the sound transmission characteristics of the middle ear in decibels. In addition, the normal transmittance curve is relatively smooth in the frequency region of maximum interest when power absorption is at or near a maximum, thereby making it easier to detect abnormal deviations in power absorption due to an obstruction and it varies by a few dB. Further, the normal transmittance curve is linear on dB-log frequency coordinates, indicative of a response that is proportional to frequency, and has a known slope at low frequencies (just under 6 dB/octave) making it easier to detect abnormalities in this frequency region. Also, the reduction in transmittance due to a conductive impairment is predictive of an air-bone gap, thereby providing an objective means for identifying an air-bone gap without subjective threshold measurement. This could be
of substantial value in identifying conductive disorders in infants and others for whom behavioral measurements are difficult to obtain.

**Reflectance phase and acoustic length**

The measurement of reflectance phase is very helpful in determining the site of an obstruction in the middle ear. The group delay of the reflected signal is equal to the slope of reflectance phase vs frequency. Knowing the group delay allows for the acoustic length (predictive of the reflection point) to be determined which, in turn, allows for the site of the obstruction (pathology) to be determined. It is interesting to note that for a normal ear, the reflected power is relatively small and measurements of group delay and acoustic length show a high degree of variability. In contrast, if there is a blockage resulting in substantial reflected power, the measurement of group delay and acoustic length is much less variable, thereby providing a practical means for locating the site of the blockage causing the reflection. This point is well illustrated in the panels showing acoustic length.

The impedance measurements while not independent measures, are also of particular value in affecting sound transmission in the ear. The use of normalized impedance reduces the effect of between-subject differences in ear canal size in that the characteristic impedance of the ear canal, which is used in normalizing the acoustic impedance, resistance and reactance, is inversely proportional to the cross-sectional area of the ear canal. The normalized impedance magnitude is a sensitive indicator of the location of a minimum in power reflectance, as is the measurement of impedance phase which shows a180° transition in the region of a null. Figures 1, 2, and 3 provide examples of these sharp transitions.

The measurement of acoustic resistance provides a means for quantifying the power absorbed by the middle ear in terms of a circuit element, and the measurement of acoustic reactance provides a means for assessing, in terms of equivalent circuit elements, the power stored temporarily in either the stiffness or mass of the middle-ear components. The change, as frequency is increased, from a stiffness dominated impedance to a resistance dominated impedance to a mass-dominated impedance is particularly revealing regarding the physical factors responsible for the absorption and reflection of acoustic power by the middle ear.

**NOTE THAT Re(1/Z) IS AN EVEN MORE SENSITIVE MEASURE.**

This choice of variables thus depends on the pathology. The measurement of impedance (including its real and imaginary components) is of particular value in modeling and understanding the physics of sound transmission in the ear. In terms of developing a practical tool for assessing middle ear function, the measurement of transmittance and acoustic length (as derived from reflectance phase) is most promising.

**CONCLUSIONS COULD BE STRONGER?**