Wideband acoustic immittance: Concepts and clinical utility

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Harry Levitt

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Abstract

Measurements of middle ear (ME) acoustic power flow and related measures (e.g., reflectance, absorbance, normalized impedance, acoustic resistance, and acoustic reactance) have several important advantages over other measures of acoustic impedance, such as the clinical “gold standard” measure, tympanometry. In addition to its wide bandwidth, ease of use, the absorbance curve, on a dB scale, has a shape that is similar to the ME transfer function, and is easily codified by three audiollogically relevant parameters. The wideband acoustic impedance measures (resistance and reactance) can provide additional important information about ME status. Alone, or together with other audiological tests such as otoacoustic emission tests and audiometry, acoustical tympanic membrane (TM) measurements can help identify many abnormal conditions, including degrees of otitis media, TM perforations, otosclerosis and ossicular disarticulation. In addition, the problem of ear canal standing waves may be solved by the introduction of the Forward Pressure level (FPL) calibration, Reference Equivalent Forward Pressure Level (RETFPL) as an alternative to the present “gold standard” Reference Equivalent Sound Pressure Level (RETSPL). Reflectance/absorbance also provides new ways of measuring the middle-ear reflex (MER) that may be more sensitive, thus allowing lower stimulus levels. Normative data from several studies, are summarized.

Abbreviations: DPOAE = distortion product otoacoustic emission; HL = hearing level; ME = middle ear; MER = middle ear reflex; OME = otitis media with effusion; RETSPL = Reference equivalent sound pressure level; RETFPL = Reference equivalent forward pressure level; SPL = sound pressure level; FPL = Forward pressure level; Tympanic membrane = TM.

Key words: acoustic impedance, acoustic power reflectance, characteristic impedance, conductive disorders, middle ear pathologies, otitis media, otoacoustic emissions, otosclerosis, transmittance.

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A  Intensity and reflectance definitions

The intensity for a pure tone at frequency $f$ is given by

$$I(f) = \frac{1}{2} |P(f)U(f)| = 0.5|P(f)|^2/407,$$  \hspace{1cm} (A.1)

where the complex pressure $P(f) = \rho c U(f)$ at frequency $f$ and $|P(f)|^2$ is its square-magnitude. As an example, if the pressure is 1 [Pascal] (i.e., 94 [dB-SPL]) and the diameter of the ear canal is 7.5 [mm], then the power in the canal is

$$P \equiv I_A = 0.5 \cdot 1^2 \pi (3.75 \times 10^{-3})^2 / 407 = 54.3 \text{[nW]}.$$  \hspace{1cm} (A.2)

Once a reflection occurs, e.g., at the tympanic membrane (TM), the power is split into three parts, the total power $P_{\text{canal}}$, the power absorbed by the middle ear (ME) $P_{\text{absorbed}}$ and the reflected power $P_{\text{reflected}}$. Thus

$$P_{\text{canal}} = P_{\text{absorbed}} - P_{\text{reflected}} = P_a \left(1 - \frac{P_r}{P_a}\right) \hspace{1cm} (A.2)$$

Henceforth we will use $P_c, P_a, P_r$ as a proxy for $P_{\text{canal}}, P_{\text{absorbed}}, P_{\text{reflected}}$.

The canal power reflectance is denoted

$$|\Gamma_c(f)|^2 = \frac{P_r(f)}{P_a(f)}.$$  \hspace{1cm} (A.3)

namely it is the ratio of the power reflected over the power absorbed. The complex pressure reflectance is

$$\Gamma_c(f) = \frac{P_r(f)}{P_a(f)} = |\Gamma(f)| e^{j\phi(f)}.$$  \hspace{1cm} (A.4)

The magnitude squared of the pressure reflectance gives the power reflectance. The power-latency, as a function of frequency, is coded in the phase reflectance phase, as the negative of the slope of the phase $\phi(f)$ with respect to frequency, i.e., $\tau(f) = -d\phi(f)/df$.  \hspace{1cm} (A.4)

B  Summary of Immittance Terminology

In Table 1 we summarize most of the terms used in immittance measurements. From the table it should be clear why the topic of immittance is confusing, simply due to the terminology. The use of reflectance, while yet one more term, obviates the need for much of the impedance language. Reflectance is a much more intuitive way of understanding the same physical properties, in an intuitive way.


<table>
<thead>
<tr>
<th>Term</th>
<th>Generic Name</th>
<th>Symbol</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sound Pressure</td>
<td>Pressure</td>
<td>$P(f)$</td>
<td>[Pa]</td>
</tr>
<tr>
<td>Sound Pressure Level</td>
<td>SPL</td>
<td>$\tau(f)$</td>
<td>[ms]</td>
</tr>
<tr>
<td>Sound Pressure Group Delay</td>
<td></td>
<td>$\tau(f)$</td>
<td>[ms]</td>
</tr>
<tr>
<td>Sound Intensity Level</td>
<td>SIL</td>
<td>$10\log_{10}|I(f)|^2$</td>
<td>[dB]</td>
</tr>
<tr>
<td>Complex Reflectance</td>
<td>Reflectance</td>
<td>$\Gamma(f)$</td>
<td>Normalized</td>
</tr>
<tr>
<td>Reflectance Phase</td>
<td></td>
<td>$\phi(f)$</td>
<td>[Rads]</td>
</tr>
<tr>
<td>Reflectance Group Delay</td>
<td></td>
<td>$\tau(f)$</td>
<td>[ms]</td>
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<tr>
<td>Power Reflectance</td>
<td>Reflectance</td>
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<td>\Gamma(f)</td>
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<tr>
<td>Power Absorption</td>
<td>Absorbance</td>
<td>$1 -</td>
<td>\Gamma(f)</td>
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<tr>
<td>Power Transmittance</td>
<td>Transmittance</td>
<td>$10\log_{10}(1 -</td>
<td>\Gamma</td>
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<tr>
<td>Admittance Magnitude</td>
<td>Admittance</td>
<td>$</td>
<td>Y(f)</td>
</tr>
<tr>
<td>Impedance Phase</td>
<td></td>
<td>$\phi(f)$</td>
<td>[Rads]</td>
</tr>
<tr>
<td>Admittance (Real Part)</td>
<td>Conductance</td>
<td>$G(f)$</td>
<td>Normalized</td>
</tr>
<tr>
<td>Admittance (imaginary Part)</td>
<td>Susceptance</td>
<td>$S(f)$</td>
<td>Normalized</td>
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<tr>
<td>Impedance Magnitude</td>
<td>Impedance</td>
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<td>Z(f)</td>
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<tr>
<td>Impedance Phase</td>
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<td>$\psi(f)$</td>
<td>[Rads]</td>
</tr>
<tr>
<td>Impedance (Real Part)</td>
<td>Resistance</td>
<td>$R(f)$</td>
<td>Normalized</td>
</tr>
<tr>
<td>Impedance (imaginary Part)</td>
<td>Reactance</td>
<td>$X(f)$</td>
<td>Normalized</td>
</tr>
</tbody>
</table>

Table 1: Quantities Relating to Immittance. This table makes clear the inherent complexity of the terminology related to acoustic immittance. This problem is largely historical, and may be largely avoided when working with the reflectance, which has a much simpler interpretation in terms of power, or in the case of complex reflectance, power and latency. The term immittance refers to all the flavors of these measures. It is intended to be nonspecific, perhaps like the generic word automobile vs. Ford. The impedances have all been normalized by the canal characteristic resistance $r_0 = \rho c / A$. When transforming the impedance into a reflectance, this normalization is necessary, and to reduce the possibility of error in using the wrong value, and in keeping track of the data, we have traditionally worked with the normalized impedance. There is a further advantage beyond computational in that working with the normalized values simplifies the interpretation of the values. This reduces the variability across subjects, since the area is best estimated at the time the data is taken, based on the size of the probe tip used for the measurement.


27. Hunter LL. Wideband reflectance of the middle ear: Implications for infant hearing assessment. The 5th Biennial Audiology Symposium. Innovations in Hearing. The Cleveland Clinic; 2004 Apr 67; Cleveland, OH.


These relations summarize pressure, velocity and power. Next we express the wideband TM admittance $Y_{TM}(f)$ and wideband TM reflectance $\Gamma_{TM}(f)$ in terms of these relationships.

While the acoustic power (intensity/area) is the product of the pressure and the velocity, the velocity to pressure ratio defines the complex acoustics admittance

$$Y(f) = \frac{U(f)}{P(f)} = |Y(f)|e^{j\phi(f)} \equiv G(f) + jS(f).$$

Here $G$ and $S$ are the real and imaginary parts of $Y$. These two components are best thought of in terms of admittance magnitude $|Y|$ and phase $\phi(f)$, rather than in terms of the real and imaginary parts. Typically $Y(f)$ is for single frequencies $f$. 