#31

Evaluating Ossicular Discontinuity and Repair Using Wideband Energy Reflectance in Human Cadaver Ears

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ABSTRACT

The purpose of this study was to examine the use of wideband energy reflectance (ER) to evaluate an ossicular disarticulation in human cadaver temporal bones. Measurements were obtained on 5 temporal bones at ambient pressure in three conditions: 1) intact ossicular chain; 2) with the ossicular chain cut using an argon laser; and 3) repaired ossicular chain. Laser Doppler vibrometry (LDV) of stapes footplate velocity was used to monitor the effect of the experimental conditions. Disarticulation resulted in a low-frequency drop in ER in a narrow notch below 1000 Hz. The average reduction in ER was 31% at a mean frequency of 630 Hz. The low-frequency notch in ER was eliminated following repair of the ossicular chain with dental cement. LDV measurements confirmed the effects of the disarticulation and repair. A simple series impedance model of the middle ear provided a good description of the response at frequencies below 2000 Hz.

It appears that a disarticulation of the ossicular chain produces a low-frequency notch in ER at the zero crossing of reactance that recovers after repair of the disarticulation. These results suggest that ER has potential for use in the diagnosis of ossicular discontinuity and may be useful to monitor the status of the post-surgical ear. Additional data are needed from patients undergoing surgery for ossicular discontinuity to further study the usefulness of ER in diagnosis and evaluate the simple series impedance model of the middle ear.

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INTRODUCTION

Energy reflectance (ER) is the ratio of the sound power reflected from the middle ear to the sound power presented to the ear by a sound source (Keefe et al 1992; Stinson, 1990; Voss et al., 2008). Unlike traditional admittance measurements, ER is relatively insensitive to probe location in the ear canal, and thus avoids the measurement complication of the combined admittance of the ear canal and middle ear (Stinson, 1990; Voss et al., 2008).

ER ranges from 1.0, indicating that all the sound power was reflected from the middle ear, to 0.0, indicating that all the sound power was absorbed by the middle ear. The data from several studies have suggested the utility of wideband energy reflectance (ER) for the evaluation of middle-ear disorders (Allen, et al., 2005; Feeney et al., 2003; Hunter et al. 2008; Hunter & Margolis, 1997; Keefe & Simmons, 2003; Margolis et al., 1999; Piskorski et al., 1999). Feeney et al. (2003) presented data from patients with otosclerosis, ossicular discontinuity, hypermobile tympanic membrane, perforation of the tympanic membrane, middle ear pressure, and otitis media. Characteristic patterns of ER were apparent for the various disorders. Ossicular discontinuity demonstrated a deep low-frequency notch in ER, while the ER pattern for two cases of otosclerosis showed higher-than-normal ER in the low frequencies. Similar results for otosclerosis were obtained by Allen et al. (2005) and Shahnaz and Bork (2006) supporting the potential for this technique in the differential diagnosis of an ossicular discontinuity and otosclerosis.

In the present study we were interested in exploring further the ER pattern obtained in the presence of an ossicular discontinuity and the use of ER to evaluate the repair of the defect. We used human temporal bones to examine changes in wideband ER resulting from the discontinuity of the ossicular chain by a defect in the region of the inducostapedial joint and its subsequent repair. Laser Doppler vibrometry (LDV) was used to quantify the reduction of sound transfer to the cochlea resulting from the discontinuity and the resultant restoration of sound transfer following repair by measuring stapes footplate velocity in the various conditions. LDV is used to compare an outgoing laser light source with the reflected light from an object, in this case the stapes footplate. The Doppler shift in the frequency of the light due to the stapes vibration is used to calculate its velocity. We know of no other study that has directly evaluated the effect of an ossicular lesion using both ER and LDV measurements in the same preparation. A comparison of the two measures was thought to be of interest, especially to evaluate the effect of the ossicular repair.

The data are modeled using a simple three-element series impedance model of the middle ear consisting of a stiffness, mass and resistance using parameter values derived from the data. The model is useful in helping to explain the changes in ER observed with a discontinuity and the effect of a repair.

METHOD

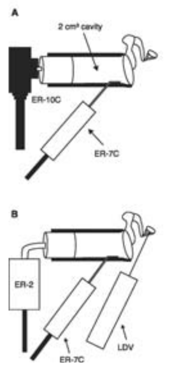


Figure 1. The experimental setup. A) ER measurements were obtained with an ER-10C microphone system with the probe tip inserted in a 2 cm³ coupler attached to the ear canal remnant. The ER-7C microphone was inserted in the coupler during reflectance data collection, but was not used for data collection. B) Laser Doppler vibrometry measurements consisted of a sound source (ER-2 earphone), an ER-7C microphone to monitor the sound level in the coupler, and a laser Doppler vibrometer to measure stapes footplate velocity through the mastoidectomy site.

Six sets of measurements were made on each temporal bone with the middle ear open at the mastoidectomy site for all measurements: 1) ER and LDV measurements with an intact ossicular chain; 2) ER and LDV measurements following the removal of the inferior portion of the long process of the incus; and 3) ER and LDV measurements following ossicular reconstruction with cement.

Prior to data collection, the method described by Keefe et al. (1992) was used to obtain the Thévenin source impedance and sound pressure of the ER-10C microphone system across frequency from 250 to 8000 Hz. ER is obtained by first calculating the pressure reflectance, *R*, using the equation:

$$R(f) = \frac{Z_{ec}(f) - Z_0}{Z_{ec}(f) + Z_0}$$

where *f* is frequency, Z_{ec} is the ear-canal impedance obtained from a pressure measurement in the ear canal using the Thévenin equivalent of the probe system (Allen, 1986; Keefe et al., 1992; Voss & Allen, 1994), and $Z_0=\rho c/A$, the characteristic impedance of the ear canal, where ρ equals the density of air, *c* is the speed of sound in air, and *A* is the cross-sectional area of the ear canal. ER is simply $|R|^2$. Wideband ER measurements were obtained in a sound-treated room using the system developed by Keefe et al. (1992). The probe signal was a 40-ms-duration chirp output from a digital-to-analog converter at a 24 kHz sample rate, and sent to a receiver in an Etymotic Research model ER-10C microphone system. For each measurement, the digitized response to eight chirps was averaged across one-twelfth-octave frequency from 250 to 8000 Hz and stored for data analysis. Three sets of stored responses in each experimental condition were averaged to arrive at the wideband impedance and ER in each of the three experimental conditions.

The LDV measurement system consisting of a Polytec CLV (Compact Laser Vibrometer) was used to measure stapes footplate velocity and phase in response to a swept sinusoid. Temporal bone specimens were mounted in a bone holder and placed under the laser on a vibration isolation table. A glass bead reflector measuring 0.25 x 0.25 mm was placed on the stapes footplate under the operating microscope. An Etymotic Research model ER-2 insert earphone was placed into the 2 cm³ coupler using a standard foam cuff. A swept sinusoidal signal (100-10,000 Hz) generated by a Hewlett Packard 35670 Dynamic Signal Analyzer (HP 35670) was used to drive the ER-2 phone at a nominal level of 100 dB SPL measured at the tympanic membrane with the ER-7C probe microphone. Measurements were captured and digitized using the HP 35670 under software control.

RESULTS

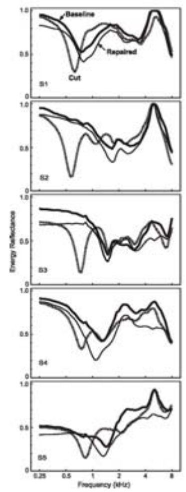
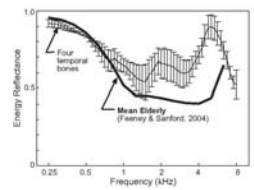


Figure 2. Measured one-twelfth octave ER for all temporal bones. In all panels, the heavy solid line represents the baseline response, the dashed line is the response measured in the cut condition, and the light solid line is the response after the repair. The same frequency axis applies to all panels; note that it is a logarithmic scale

Figure 3. Mean one-twelfth-octave ER for specimens 1-4 (gray line). The error bars represent ±1 standard error. Also shown is the mean one-third-octave ER for one ear each of 30 elderly subjects from Feeney and Sanford (2004) (black line).



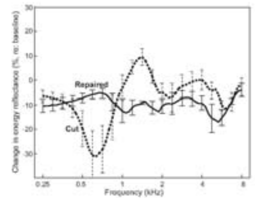


Figure 4. Average percent change in one-twelfth octave ER from the baseline measurement to the cut and repaired ossicular chain conditions. The error bars represent ±1 standard error with every third data point plotted for clarity.

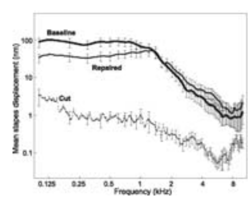


Figure 5. Mean one-sixtieth octave peak-to-peak stapes footplate displacement from 100 to 10,000 Hz in three conditions: the heavy solid line represents the baseline response, the dashed line is the response measured in the cut condition, and the light solid line is the response after the repair. The error bars represent ±1 standard error. Error bars are placed every 100 Hz from 100 to 1000 Hz and then every 200 Hz above 1000 Hz for clarity.

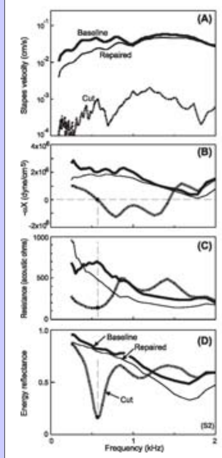


Figure 6. Example of a typical observed response at low frequencies (to 2000Hz) for a single temporal bone (S2).

Panel (A) presents the one-sixtieth-octave stapes velocity as measured by LDV at frequencies from 100 to 2000 Hz.

The middle two panels contain information on the one-twelfth-octave acoustic impedance *after* the impedance is transformed from probe tip to TM location.

Panel (B) presents the negative of the product of the angular frequency times the input reactance, or $-\omega X$, which gives an estimate of the acoustic stiffness, *K*, in dyne/cm⁵.

Panel (C) presents the real part of the input impedance, the resistance, in acoustic ohms (cgs).

Panel (D) re-plots the one-twelfth octave ER from Figure 2.

The vertical dashed line located at about 550 Hz emphasizes that the reactance in (B) in the cut condition crosses the zero line (resonance) exactly at the point where there is a sharp minimum in the ER in (D).

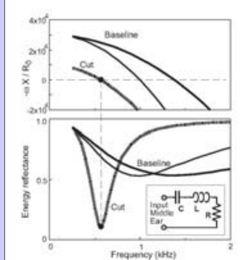


Figure 7. Results from a simple 3-element model of the middle ear for the changes observed in the low-frequency response when the stapes connection is severed. Axes are similar to those for panels B and D in Figure 6. The inset indicates the electrical circuit equivalent of the model, which is a series circuit with capacitance, C, inductance, L, and resistance, R. Physically, the inductance value is equal to the equivalent mass, M, while the capacitance is equal to the inverse of the spring constant, K.

Clinical Application

Combined with previous reports suggesting that a distinctive pattern of ER occurs for otosclerosis that is higher than normal in the low frequencies (Allen et al., 2005; Feeney et al., 2003; Shahnaz & Bork, 2006), the current results suggest that ER may be useful as a quick non-invasive test for distinguishing between ossicular discontinuity and otosclerosis. Moreover, the present study also suggests that ER may be useful as a surgical outcome measure to assess the function of an ossicular repair. Further research is needed to evaluate both pre- and post-operative middle-ear function using ER in ossicular discontinuity and other ossicular disorders such as otosclerosis.

Model Parameters: The reactance of the model seen at the input to the middle ear is given by $X = \omega M - K/\omega$. Normalized to the characteristic impedance of the ear canal, $Z_0 = R_0 \cong 100\ \Omega$, values in the cut condition are: resistance $R_c/R_0 = 0.5$; stiffness $K_c/R_0 = 1\text{x}10^4$; and mass $M_c/R_0 = 8\text{x}10^{-4}$. There are two cases shown for the baseline or normal condition, for both cases the resistance $R_b/R_0 = 6.5$ and the total stiffness $K_b/R_0 = 3\text{x}10^4$. For the thinner solid line, the effective mass $M_b/R_0 = 8\text{x}10^{-4}$ and for the thicker solid line the mass $M_b/R_0 = 4\text{x}10^{-4}$.