

Measurements of acoustic impedance at the input to the occluded ear canal

Vernon D. Larson, PhD; John A. Nelson, MAud; William A. Cooper, Jr., PhD; David P. Egolf, PhD
Audiology and Speech Pathology Service, Department of Veterans Affairs Medical Center, Augusta, GA 30910; Department of Speech-Language Pathology and Audiology, University of South Carolina, Columbia, SC 29208

Abstract—Multi-frequency (multi-component) acoustic impedance measurements may evolve into a sensitive technique for the remote detection of aural pathologies. Such data are also relevant to models used in hearing aid design and could be an asset to the hearing aid prescription and fitting process. This report describes the development and use of a broad-band procedure which acquires impedance data in 20 Hz intervals and describes a comparison of data collected at two sites by different investigators. Mean data were in excellent agreement, and an explanation for a single case of extreme normal variability is presented.

Key words: *acoustic impedance tests, electroacoustic impedance tests, hearing aids, middle ear, tympanometry.*

INTRODUCTION

There are several important clinical uses of acoustic impedance data. First, a clinical procedure known generically as “tympanometry” is commonly employed for the remote detection of middle-ear pathologies. In this discrete, low-frequency proce-

dures, which often yields only an estimate of the compliance component of the ear canal and eardrum, sound is monitored by a microphone in the ear canal at different levels of static air pressure. More recently, discrete, multi-frequency, multi-impedance component (i.e., reactance and resistance or susceptance and conductance) instrumentation has become commercially available. A more definitive estimate of middle-ear function should result from multi-frequency measurements. In fact, it is possible that the fine structure of acoustic impedance curves (i.e., at closely spaced frequency intervals) may yield a much more exacting and definitive appraisal of the status of the middle ear (1,2).

Second, shaping of the audio spectrum is an important focus of hearing aid prescription and fitting. Aural acoustic impedance data could be used as an integral part of a comprehensive, computer-based model (3,4,5) to select hearing-aid components for the individual patient, or, alternatively, acoustic impedance data could be used to “correct” hearing aid gain-by-frequency prescriptions. Unfortunately, even if manufacturers were able to obtain a precise gain-by-frequency specification (6) those protocols have inherent sources of error because they are based on audiometric measurements using supra-aural earphones and couplers representing the acoustic characteristics of the average ear (7). The specification of sound pressure level (SPL) in the individual ear canal (developed by a hearing aid) is fundamental to the realization of a precise frequen-

Address all correspondence and requests for reprints to: Vernon D. Larson, PhD, Audiology & Speech Pathology Service (126), VA Medical Center, 1 Freedom Way, Augusta, GA 30910.

Vernon D. Larson, PhD, and John A. Nelson, MAud, are with the Audiology and Speech Pathology Service, VA Medical Center in Augusta, GA. William A. Cooper, Jr., PhD, is with the Department of Speech-Language Pathology & Audiology at the University of South Carolina, Columbia, SC. David Egolf, PhD, is with AERG Consultants, in Schaumburg, IL.

cy-gain prescription. A principal determinant of SPL is the acoustic impedance of the ear canal itself. Objective evaluation of the effect of eardrum impedance on the SPL in the ear canals of normal and pathologic subjects has been lacking, perhaps due to the difficulties associated with making accurate measurements at higher frequencies, as well as with obtaining accurate estimates of ear canal dimensions.

Purpose

The purposes of this article are: 1) to describe the development of an automated, broad-band aural-acoustic impedance measurement system; 2) to report data, in fine structure, on a larger sample of normal subjects than has been heretofore reported in the literature; and, 3) to compare data collected on normal ears at two different laboratories by two different investigators using identical systems.

METHODS

Subject Selection

Data were acquired from 35 subjects in this study at two laboratories. The sample from Site 1 included 20 subjects, and the sample from Site 2 included 15 subjects. Subjects ranged in age from 20 years to 35 years. Each had normal hearing thresholds (equal to or better than 15 db hearing threshold level), normal ear canals, normal-appearing eardrums, no history of middle ear pathology, and normal otoadmittance findings (8).

Procedures

Following preselection measures, estimates of ear canal volume, diameter, and length were made on one ear of each subject. Measurements of aural acoustic impedance were made at a mid-location in the occluded canal on one ear of each subject. All ears were studied under a condition in which efforts were made to ensure that atmospheric pressure existed in the ear canal, after having checked for an hermetic seal. The details of the measurement procedures are described below.

Estimates of Ear-Canal Volume, Diameter, and Length

The computations for deriving acoustic impedance at the tympanic membrane require a knowledge

of the length and diameter of the ear canal. After a pilot study in which a high degree of inter- and intra-examiner reliability was observed, the diameter, d , was measured directly using a calibrated and graduated set (0.1 cm intervals) of ear probes which were inserted deeply into the ear canal. The examiner rotated the probe in the ear canal and judged which probe best made contact without distending the ear canal.

An estimate of ear canal length was derived from the diameter measurement and a tympanometric estimate of the volume between the impedance probe tip and the eardrum by the equation

$$L = \frac{\pi d^2}{4v} \quad [1]$$

where L is the length, v is the volume, and d is the diameter of the ear canal.

In conventional, low-frequency tympanometric measurements, the eardrum is "stiffened" by a high positive or negative static (dc) pressure (9). The assumptions underlying these measurements are that: 1) the impedance at the eardrum is driven to infinity by the static pressure; and, 2) an appreciable change in the length of the ear canal does not result from the dc pressure change. Shanks and Lilly (10) reported data which refute these assumptions, but they also provide data which can be used to correct tympanometric estimates to values obtained using a more rigorous measurement technique. Hence, in this study the eardrum was pressurized to -400 daPa; the volume was recorded in units of acoustic admittance ($|Y|$) using the conventional technique for a 220 Hz probe signal. This value was corrected by 13 percent, the error reported by Shanks and Lilly (10) to result from a 220 Hz measurement of $|Y|$ at -400 daPa, and entered into Equation [1].

Estimate of Ear-Canal Input Impedance (Z_L)

The method by which the magnitude $|Z_L|$, the reactance X_L , and the resistance R_L at the driving point (i.e., at a position 2 mm past the tip of an ear-insert sealed in the ear canal) is computed is based on a two-cavity or two-load method. This method, described by Beranek (11), is a variation of Thevinen's theorem which states that any one-port network of resistance elements and energy sources can be replaced by a series combination of an ideal voltage source, E_t , and a resistance, R_t , where E_t is

the open-circuit voltage of the one-port, and R_t is the ratio of the open-circuit voltage to the short-circuit current.

The method has been used to determine either the source impedance of a transducer (12,13) or the input impedance of a load connected to a transducer (14,15). While the equation has many incarnations, Egolf and Leonard (13) presented it as:

$$Z_s = \frac{E' - E}{E/Z_1 - E'/Z_2}, \quad [2]$$

where E and E' are the voltages (magnitude and phase) developed across each load, with the loads having known or calculable impedances of Z_1 and Z_2 . Z_s is the impedance of the source transducer. While Arslan, Canavesio, and Ceruti (14) and Rabinowitz (15) used source impedance as a term in their equations, Egolf¹ demonstrated mathematically that this requirement can be bypassed and, hence, the real and imaginary parts of acoustic impedance at the input to the ear canal can be computed using the following equation:

$$Z_L = j \left\{ \rho c (E_o/E_i) [(E_o''/E_i'') - (E_o'/E_i')] \right. \\ \left. \{ S'' (E_o''/E_i'') [(E_o'/E_i') - (E_o/E_i)] \tan(kL'') \right. \\ \left. - S' (E_o'/E_i') [(E_o''/E_i'') - (E_o/E_i)] \tan(kL') \right\} \quad [3]$$

where, as illustrated in **Figure 1**, E_o''/E_i'' , E_o'/E_i' , and E_o/E_i are the measured probe-assembly transfer functions when the assembly is coupled to the 2.0 cc cavity, the 0.5 cc cavity, and the outer ear canal, respectively. The quantities S'' , L'' , S' , and L' are the cross-sectional areas and lengths of the larger and smaller cavities, respectively. The term, k , is the wavenumber $2\pi f/c$, where f is frequency and c is the speed of sound. Air density is represented by the symbol ρ , and j is the imaginary operator $\sqrt{-1}$. Some errors in acoustic measurements occur because, rather than attempting to reproduce the open- and short-circuit conditions, the method uses two cavities with impedances sufficiently different to allow stable calculation of the desired parameter.

Calculation of Acoustic Impedance at the Tympanic Membrane (Z_T)

The ear canal's diameter and length were estimated as discussed above. Calculation of imped

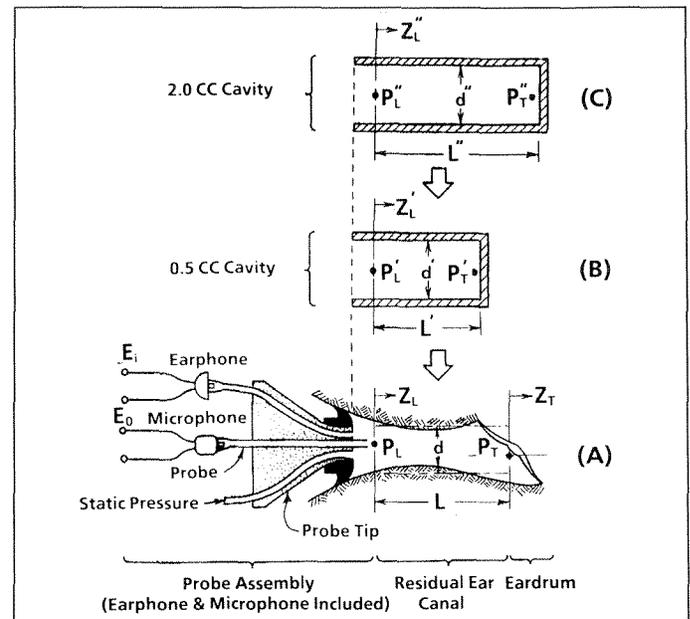


Figure 1.

Probe-tube assembly as sealed or mounted on *A* the ear canal, *B* a 0.5 cc cavity, and *C* a 2.0 cc cavity. (Reprinted, by permission, from *The Vanderbilt Hearing Aid Report II*, GA Studebaker, FH Bess, and LB Beck, editors. Parkland (MD): York Press, 1991.)

ance of the ear canal itself was accomplished in software using a distributed-parameter model described by Larson, Egolf, and Cooper (16) which treats the dimensions of the canal by a method similar to that of Kuhn (17). The algorithm calls for the residual ear canal to be sectioned via n hypothetical sagittal cuts as shown in **Figure 2a**, where each n th slice has a measured cross-sectional area S_n and thickness L_n , as shown in **Figure 2b**. In order to compute eardrum impedance (Z_T), the multiple-slice characterization of **Figure 2b** is represented by a serial connection of two-port electrical analog networks (see **Figure 2c**), each corresponding to one cylinder. Impedance at the tympanic membrane (Z_T) is then calculated by the equation

$$Z_T = \frac{Z_L D_S - B_S}{A_S - Z_L C_S}, \quad [4]$$

where the terms in Equation [4] are

$$\begin{bmatrix} A_S B_S \\ C_S D_S \end{bmatrix} = \begin{bmatrix} A_1 B_1 \\ C_1 D_1 \end{bmatrix} \begin{bmatrix} A_2 B_2 \\ C_2 D_2 \end{bmatrix} \cdots \begin{bmatrix} A_n B_n \\ C_n D_n \end{bmatrix} \quad [5]$$

and

¹ Egolf DP. A review of current technology dealing with the measurement of eardrum impedance/admittance. Unpublished lab report to V. Larson, VA Medical Center, Augusta, GA, March 1, 1988.

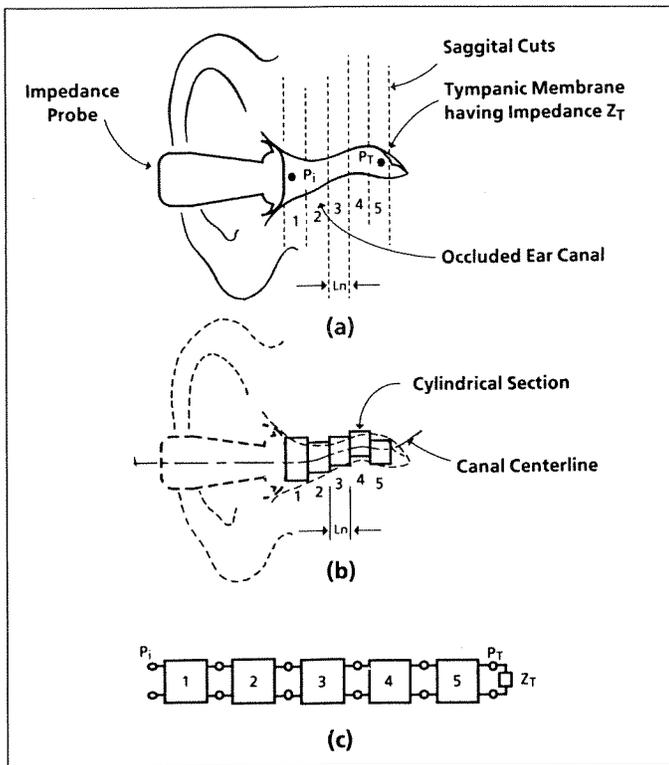


Figure 2. Diagram and illustration of a distributed parameter model for estimating the acoustic impedance of the ear canal. (Reprinted, by permission, from *The Vanderbilt Hearing Aid Report II*, GA Studebaker, FH Bess, and LB Beck, editors. Parkland (MD): York Press, 1991.)

$$\begin{aligned} A_n &= D_n = \cos(kL_n), \\ B_n &= j(\rho c/S_n) \sin(kL_n), \text{ and} \\ C_n &= j(S_n/\rho c) \sin(kL_n). \end{aligned} \quad [6]$$

In this study, because of the lack of a method for estimating the dimensions of the ear canal, the dimensions for two equal slices were entered into Equation [5], essentially treating the ear canal as a circular cylinder terminated at right angles by the eardrum.

Instrumentation

Details of the measurement system and the technique on which it is based were reported previously (16). Briefly, however, the system used to make the impedance measurements uses a two-channel spectrum analyzer (Rapid Systems, Inc., Model 1200 with a Texas Instruments 320-10 signal processor) which is bidirectionally interfaced with an IBM-compatible computer. Locally developed soft-

ware routines (Microsoft C, v. 1) pass parameters to assembly language routines in residence in the signal processor.

For all measurements, as illustrated in **Figure 1**, an impedance probe (Grason-Stadler, Model 1733 probe tip) was used to couple an earphone (Etymotic Research, Inc., Model ER-3A), a microphone (Etymotic Research, Inc., Model ER-7C), and a static air pressure pump and manometer to the ear canal or to either of the calibration cavities. The output of a waveform synthesizer (Quatech, Model WSB-10), a train of 100 μ s clicks, drove the earphone. The electrical input to the earphone (E_i) and the output (E_o) from the probe microphone were routed through low-pass filters to the two inputs of the spectrum analyzer. At each site, preliminary measurements were made to insure that an overpressure of 400 daPa had no effect on the response of either the earphone or the probe microphone.

The data acquired from the two channels were used to compute cross- and auto-spectra which, in turn, were used to compute magnitude and phase transfer functions (E_o/E_i) for each of the three cavity measurements. These transfer functions, estimates of the magnitude squared coherence function, and calculations of Z_L (Equation [3]) are made in software by locally developed routines.

RESULTS OF IMPEDANCE MEASUREMENTS

Studies of Cylindrical Cavities

As reported by Larson, Egolf, and Cooper (16), a series of studies were conducted to validate measurements and computations with the system described herein. First, input impedance measurements were made on cylindrical tubes having rigid terminations which ranged in size from 0.8 cc volume to a tube having a length of 19.8 cm. Transfer function measurements were made as described in the previous sections and only data which approximated a 1.0 coherence function were accepted and passed to impedance calculation routines (Equation [3]). Comparisons were made of input impedance measurements of the tubes with data calculated using the following expression (11) for calculating the input impedance of a circular tube with a rigid termination:

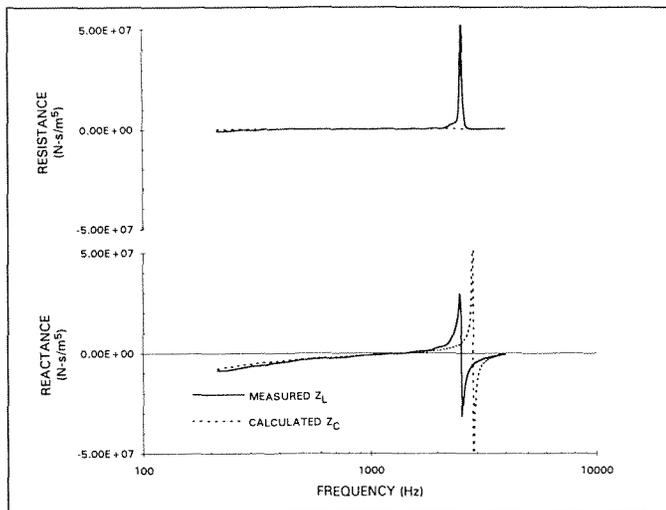


Figure 3.

Resistance (upper curves) and reactance (lower curves) for measured and calculated values of a 1.65 inside diameter (i.d.) tube. (Redrawn, by permission, from *The Vanderbilt Hearing Aid Report II*, GA Studebaker, FH Bess, and LB Beck, editors. Parkland (MD): York Press, 1991.)

$$\begin{aligned} Z_c &= R_c + jX_c, \\ R_c &= 0, \\ X_c &= -j(\rho c/S_c) \cot kL_c, \end{aligned} \quad [7]$$

where S_c is cross-sectional area and L_c is length. **Figure 3** shows one such comparison for a tube having the dimensions 6.0 cm (length) and 1.65 cm (diameter). Good agreement between the measured (i.e., using Equation [3]) and the computed data (i.e., via Equation [7]) was observed except for frequencies in the region of resonance. Note that the zero-crossing of the measured reactance curve occurs at a frequency which corresponds approximately to one-quarter wavelength: about 1,450 Hz for a 6.0 cm long tube. Note also a peak in the measured resistance (R_L) data at the frequency corresponding approximately to one-half wavelength. Ross (18) attributed such resistance peaks to mathematical anomalies (i.e., poles) that originate in Equation [3] when measurements are made on rigidly terminated cylindrical tubes, and hence provided sufficient justification to neglect them (16).

Acoustic Impedance Data and Interlaboratory Comparisons

Figure 4 presents mean Z_L data (i.e., from Equation [3]) measured on normal-hearing subjects

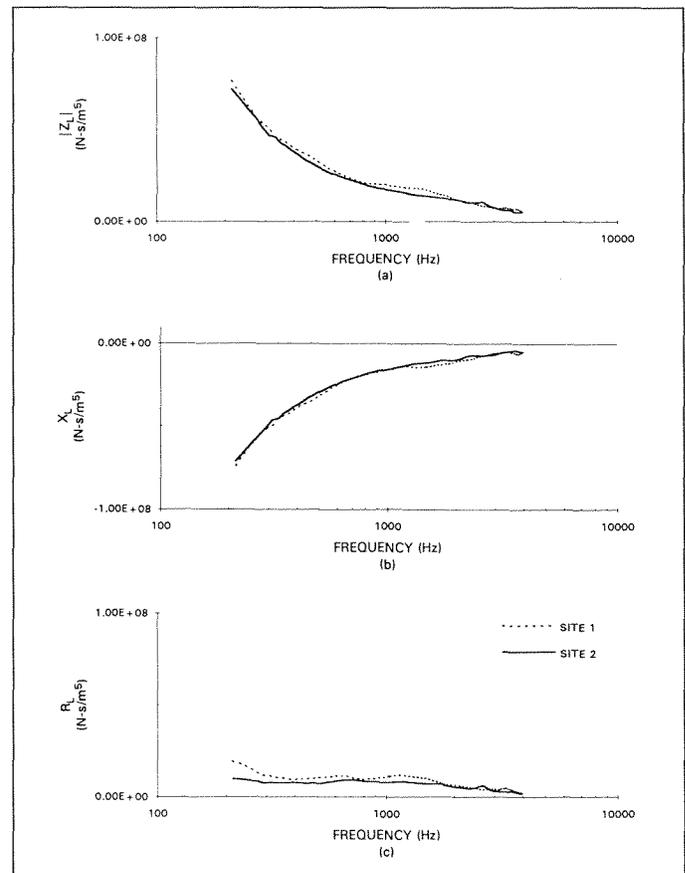


Figure 4.

Mean acoustic impedance (a) $|Z_L|$, (b) X_L , and (c) R_L for two sites.

at two sites. Illustrated in **Figures 4a**, **4b**, and **4c** are data for $|Z_L|$, X_L , and R_L , respectively, at the input to the occluded ear canal. Experimenters at the two sites used different IBM-compatible computers, signal processing hardware, probe microphones, earphones, and calibration cavities. Transfer function measurements as well as the estimates of ear canal dimensions were made as described previously, and $|Z_L|$, X_L , and R_L were computed for the mid-canal measurement location using Equation [3]. Excellent agreement is apparent between the mean data for Z_L for the two sites.

Shown in **Figures 5a**, **5b**, and **5c** are standard deviations associated with the means appearing in **Figure 4**. The standard deviations for the two sites are almost identical for frequencies below 1,500 Hz, but differences between the two sites emerge and reach large values in the 2,700 Hz region. In fact, a variance-ratio test in this frequency region

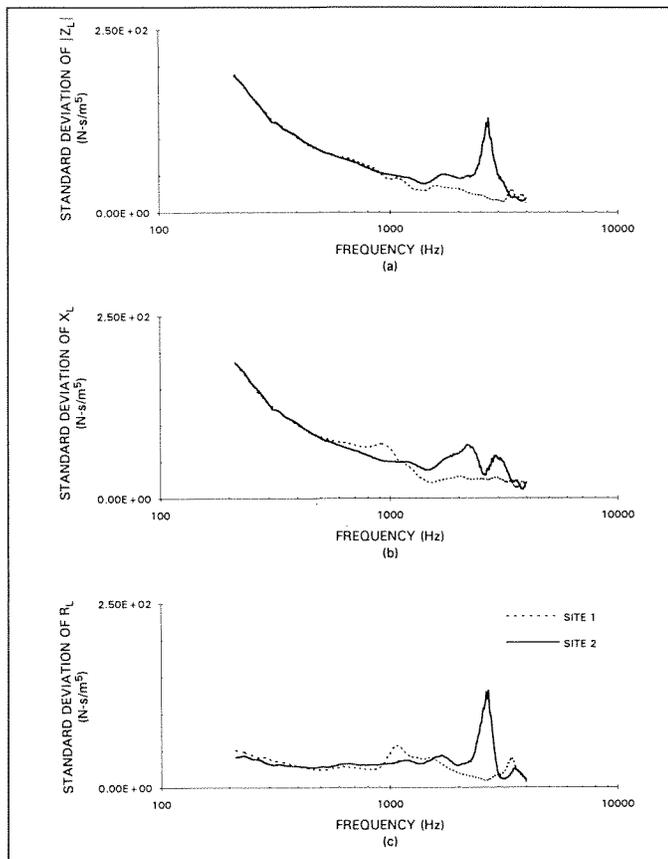


Figure 5. Standard deviations for acoustic impedance (a) $|Z_L|$, (b) X_L , and (c) R_L for two sites.

($p = 0.05$) did not support pooling the mean data obtained from the two samples. An inspection of individual data, however, determined that the data for just one subject inflated the standard deviations of Site 2. **Figure 6a** shows $|Z_L|$ for this subject plotted with the mean data for Site 2. The peak in the 2,700 Hz region led us to question whether the data were in error in some regard or the subject was representative of a normal outlier.

Figures 6b and **6c** compare the data for the subject with the mean data for X_L and R_L , respectively. An inspection of the data suggests that the subject's data contain a resonance such as that observed in **Figure 3** for the 1.65 cm diameter by 6.0 cm long tube. The reactance curve of **Figure 6b** shows a typical resonance pattern in the 2,000 Hz to 3,000 Hz region. The subject's data also contained a resistive peak for the frequencies near resonance (see dashed curve of **Figure 6c**) similar to the peak in

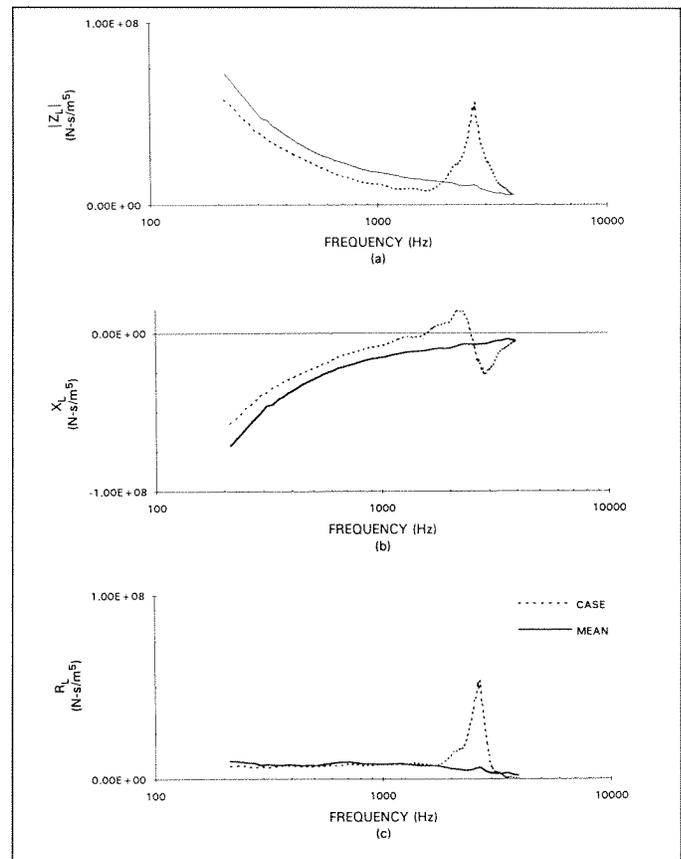


Figure 6. Comparison of mean and case acoustic impedance (a) $|Z_L|$, (b) X_L , and (c) R_L for two sites.

Figure 3. Recall that Ross (18) discussed the resistive peak as being a mathematical anomaly when measurements are made in a cylindrical tube with a rigid termination, and hence provided a justification for ignoring the resistive data in the frequency region of resonance.

DISCUSSION

A knowledge of the acoustic conditions which produce "normal outliers" would be important to the interpretation of diagnostic acoustic impedance findings and clinical probe-tube measurements of ear canal sound-pressure levels, as well as to the application of acoustic impedance data to hearing aid design and fitting protocols.

Acoustically, ear canal resonances in the higher frequencies are related to the length of the ear canal

and/or to the plane of measurement relative to the eardrum. Specifically, the frequencies corresponding to one-quarter and the first one-half wavelength, such as observed in the data of **Figure 3**, are predicted by

$$f = c/4L \quad \text{and by} \quad [8]$$

$$f = c/2L \quad [9]$$

where L is length of the occluded ear canal. Gilman and Dirks (19) demonstrated, in a mechanical simulation of eardrum impedance, that this location-dependent minimum in sound pressure predicted by Equations [8] and [9] is accurate for a purely resistive termination of the ear canal, but a correction to L must be made for terminations which are reactive, as is shown by

$$L = \lambda/4 + L_T \quad \text{where} \quad [10]$$

$$L_T = A/\pi(\lambda/4). \quad [11]$$

where A is the phase of the reflected wave relative to the incident and λ is wavelength. Equation [10] shows, then, that for L with a termination with no reactance, the quarter-wave minimum (and frequency location thereof) is predicted by Equations [8] and [9] but would be greater (longer effective distance from the eardrum) for a positive reactance and less (shorter effective distance from the eardrum) for a negative reactance. **Figure 7** shows a comparison of eardrum reactance X_T and resistance R_T (computed using Equation [4]) for the subject with the mean data. With reference to **Figure 7b**, the reactance for the individual case is clearly positive in the frequency region of resonance and, as shown in **Figure 7a**, resistance falls to zero. Apparently, the combination of ear-canal geometry and eardrum impedance are such that the frequencies of the one-quarter and one-half wavelengths fall within the bandwidth of measurements presented herein. For the other subjects, this phenomenon occurred at frequencies above 4,000 Hz.

SUMMARY

Aural acoustic impedance measurements made at two sites by different investigators were in excellent agreement. An inspection of the intersubject variability suggested, however, that an occasional outlier may be expected when either the

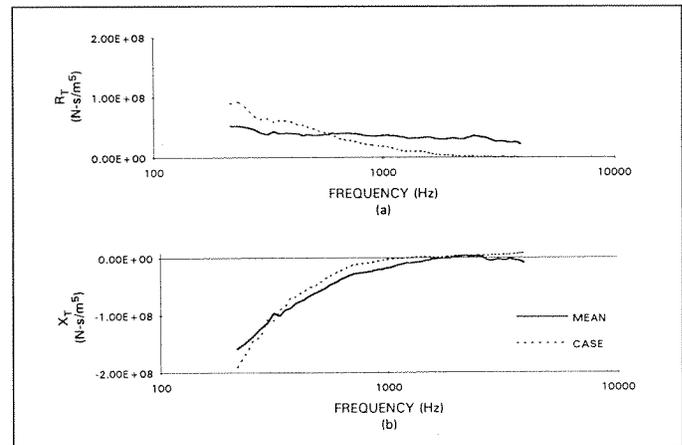


Figure 7.

Comparison of mean and case acoustic impedance (a) resistance, R_T , and (b) reactance, X_T , at the tympanic membrane.

actual distance between the plane of measurement and the eardrum or the effective length of the residual ear canal is such that the frequencies corresponding to one-quarter and one-half wave lengths are shifted downward to a frequency below 4,000 Hz. Studies of pathologic ears and studies in which aural pathologies are simulated are under way.

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