PRINCIPLES OF TYMPANOMETRY

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Preface

Tympanometry is a biophysical measurement of the acoustic properties of the ear. The fundamental principles upon which this measurement is based are quite different from those that gave rise to other audiologic tests. The physical principles underlying tympanometry can be traced to Oliver Heaviside's extension of Ohm's Electrical Law. Over one hundred years ago, Heaviside despaired of the "extraordinary jumbles" to which Ohm's Law was frequently subjected. This monograph is, in large measure, a response to a similar despair. The frequent misunderstanding of the physical principles of acoustic immittance has led to "extraordinary jumbles" in the clinical literature that have emerged as tympanometry developed from an experimental procedure to a routine audiologic test. Our attempts to resolve these jumbles in our own minds led to a four–year collaboration between physicists and audiologists who shared the conviction that the best clinical decisions are made when the design of a test is based on a solid understanding of the basic principles underlying the measurement. The monograph begins with a thorough presentation of those principles (Chapter 1) which are then applied to an analysis of normal tympanograms (Chapter 2) and to a discussion of the influences of measurement procedures on tympanometric results (Chapter 3). Basic design principles of the various types of clinical acoustic immittance instruments are described (Chapter 4) and the use of these instruments for determining the immittance characteristics at the tympanic membrane is discussed (Chapters 5 and 6). The clinical significance of abnormal tympanometric results is reviewed (Chapters 7, 8, and 9). Some further physical principles are presented in appendices along with a history of the development of tympanometry.

This work was made possible by grants from the Scientific Affairs Division of NATO. Additional support was received from BRSG Grant S07 RR077068–17 awarded to Syracuse University by the Biomedical Research Support Grant Program, Division of Research Resources, National Institutes of Health, from Merit Reviews, and a Career Development Award from the Medical Research Program of the Veterans Administration. We are grateful to P. van de Heyning for contributing previously unpublished data to this work and for his assistance in locating research subjects. We are indebted to S. Van Loo who prepared most of the figures in this volume.

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Chapter 1

Concept of Acoustic Immittance

1.1 INTRODUCTION

Clinical acoustic–immittance measurement is a method for describing the physical properties of the ear that is derived from a class of experimental techniques known as systems analysis. In this approach the behavior of the system under study is observed in response to simple, known input signals. Observations of this type can be used to develop simple descriptions of apparently complex behavior and, in clinical application, provide the basis for distinguishing normal from abnormal systems. Ideally, the approach leads to information that is useful in determining the nature of the process that transformed the normal system into an abnormal one. The concept of acoustic immittance is a very useful one which includes the physical quantities of acoustic impedance, acoustic admittance, and all of their polar and rectangular components. These quantities are developed in detail in this chapter.

The first mathematical relation between a physical cause and the resulting response (effect) was introduced by Newton in 1686. His famous second law relates the external driving force (F) (cause) to the subsequent change in state (effect), here the acceleration (a), by the expression

$$F = ma \qquad (1.1)$$

where m is the mass of the body on which the external force acts. From Newton's second law it is evident that by exerting a known force (F) and measuring the resulting acceleration (a) the mass of the system can be computed. This computation provides, in one quantity, a description of the responses to an infinite variety of input signals.

1.2 ACOUSTIC IMPEDANCE

Late in the 19th century, Heaviside (1886a) introduced a new concept to relate cause and effect in electrical circuits driven by continuous sinusoidal input signals. The driving force, here the voltage (V), was related to the resulting electrical current (I) through the concept of impedance (Z). Heaviside's principle, an extension of Ohm's (1827) electrical law, relates a force–like quantity, the voltage (V), and a velocity–like quantity, the current (I).[1] This concept proved to be so useful (see Appendix A) that it was soon applied to different fields such as mechanics, hydrodynamics, and also acoustics (Webster, 1919).

In acoustics, the force–like quantity is the sound pressure of a pure tone defined as a time–varying function:

$$p(t) = p_o \sin (2\pi f t + \varphi) \qquad (1.2)$$

where p_o is the peak sound pressure (also called amplitude) and f is the frequency of the tone in Hertz (Hz) (cycles per second) and t is time (seconds). The phase angle (φ) is introduced to account for the time shifts between cause and effect. The corresponding velocity–like quantity is now the volume velocity (U), which is defined as the volume of air passing through an imaginary surface per unit time. The acoustic impedance is thus defined at a "measurement plane." The system on which the sound pressure acts is said to be "linear" if the resulting volume velocity is also a sinusoidally–varying quantity with the same frequency f as the sound pressure waveform:

$$U(t) = U_o \sin 2\pi f t \qquad (1.3)$$

where U_o is the peak volume velocity or volume velocity amplitude. The two expressions for p(t) and U(t) can now be related to each other through the concept of impedance by application of Heaviside's principle to acoustic systems.

Equations 1.2 and 1.3 precisely define a sinusoidally varying sound pressure and the resulting sinusoidal velocity response of a linear system. An example of a pressure waveform and response are shown in Figure 1.1. The volume velocity response to a known sinusoidal pressure can be determined if two quantities are known: (a) the ratio of pressure to volume velocity, which is constant in a linear system for all input pressures, and (b) the time delay between the sound pressure and the response, expressed as a phase angle. These two quantities together constitute the definition of an acoustic impedance and can be expressed as

$$|Z_a| = \frac{p_o}{U_o} \qquad (1.4)$$

and

$$\varphi_z = \frac{360^\circ t_{p,U}}{T} \qquad (1.5)$$

[1] Current is defined as the amount of electrical charge (coulombs) passing through a cross–section of an electrical conductor per unit time (second).

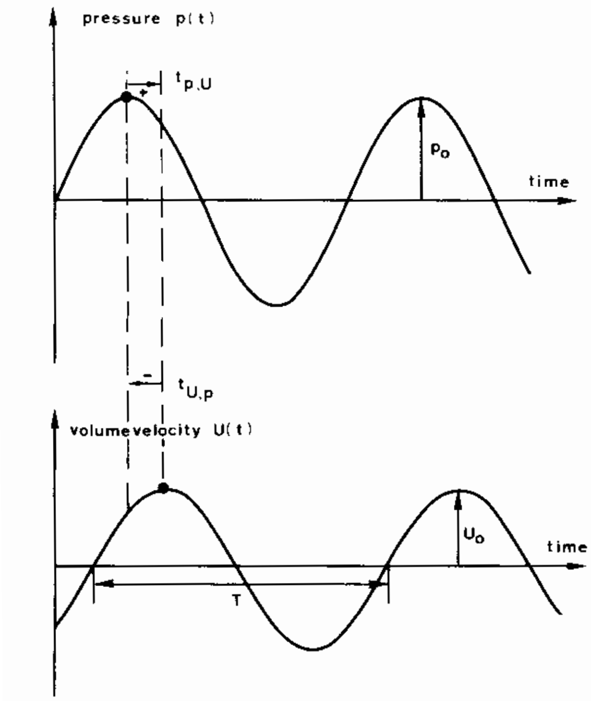


FIGURE 1.1. Sinusoidally varying sound pressure [p(t)] with period (T) and resulting volume velocity [U(t)] for a linear system.

where T (the period) is the time required to complete one cycle (T = 1/f) and $t_{p,U}$ is the time difference between a point on the p waveform with respect to the corresponding point on the U waveform. Note that $t_{p,U}$ can be either positive or negative. In Figure 1.1, p precedes (or leads) U, $t_{p,U}$ is positive, and therefore φ_z is positive. If p lags U, then $t_{p,U}$ would be negative and therefore the phase angle φ_z would be negative. This way of specifying an impedance by the pressure volume–velocity ratio (p_o/U_o) and the phase angle φ_z is referred to as polar notation. That is,

$$|Z_a| = \frac{p_o}{U_o} \angle \varphi_z. \tag{1.6}$$

$|Z_a|$ is also referred to as "impedance magnitude" or the "absolute value of impedance." When the acoustic impedance is assessed in the plane of the tympanic membrane, we speak of the *input impedance* of the middle–ear system.

Graphically, the impedance can be represented as a *phasor*, a quantity bearing some resemblance to a vector. In Figure 1.2a, the length of the phasor represents the impedance magnitude $|Z_a|$, whereas the angle between the horizontal reference axis and the phasor is the phase angle of the pressure with respect to the volume velocity.

1.3 ACOUSTIC ADMITTANCE

As will be demonstrated in Chapter 2, in tympanometry there are several important advantages to recording acous-

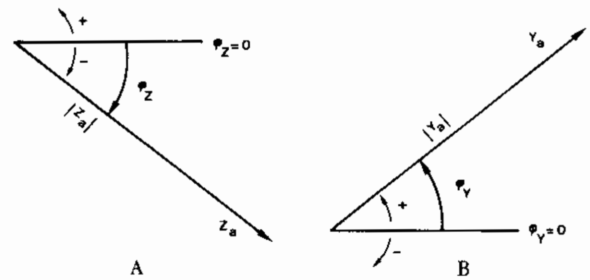


FIGURE 1.2. Impedance (A) and admittance (B) phasor diagrams.

tic admittance rather than acoustic impedance. Acoustic admittance, the reciprocal of impedance, can be defined as the ratio of volume velocity to sound pressure:

$$|Y_a| = \frac{1}{|Z_a|} = \frac{U_o}{p_o} \tag{1.7}$$

and

$$\varphi_y = \frac{360° t_{U,p}}{T}. \tag{1.8}$$

The time difference $t_{U,p}$ is now defined as the time difference of the volume velocity with respect to the sound pressure. It is clear from Figure 1.1 that if p precedes U, then U lags p and thus,

$$t_{U,p} = -t_{p,U} \tag{1.9}$$

and

$$\varphi_y = -\varphi_z. \tag{1.10}$$

By defining admittance as a ratio and phase angle (Equations 1.7 and 1.8), we have specified acoustic admittance in polar notation. That is,

$$|Y_a| = \frac{U_o}{p_o} \angle \varphi_y. \tag{1.11}$$

In Figure 1.2b the admittance is represented graphically by an admittance phasor. The length of the phasor represents $|Y_a|$ and the angle between the phasor and the horizontal axis is φ_y.

1.4 RECTANGULAR VERSUS POLAR NOTATION

The impedance of a system can be specified in polar notation, or, equivalently, in rectangular notation. In rectangular notation the tip of the impedance phasor is projected onto the $\varphi_z = 0°$ axis to obtain a value R_a, which is the in–phase component of impedance also called *resistance* or real component. Similarly, the tip of the phasor is projected onto the $\varphi_z = \pm 90°$ axis to obtain a value X_a, which is the 90° out–of–phase (quadrature) component also called *reactance* or imaginary component (see Figure 1.3). Similarly, the admittance phasor is projected onto the real and imaginary axes to obtain values of G_a, acoustic conductance, and B_a, acoustic susceptance. Thus, acoustic im-

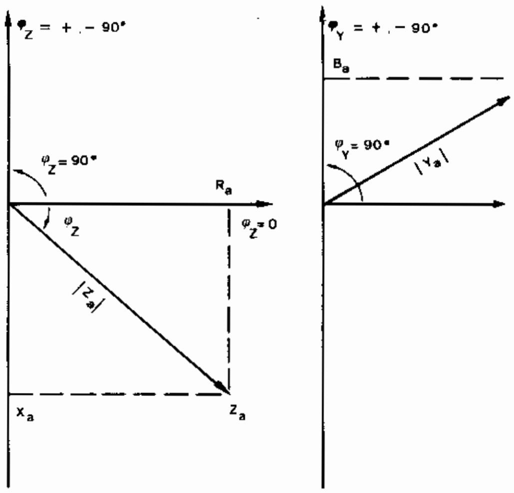


FIGURE 1.3. Phasor diagram showing the relative orientation and magnitude of the acoustical impedance $|Z_a|$ and its components R_a and X_a. Similar admittance phasor diagram showing the relative orientation and magnitude of the acoustical admittance $|Y_a|$ and its components G_a and B_a.

TABLE 1.1. Definitions and conversion formulas for immittances.

Impedance Z	*Admittance Y*
$\|Z\| \angle \varphi_z$	$\|Y\| \angle \varphi_y$
$R + jX$	$G + jB$
$R = \|Z\| \cos \varphi_z$	$G = \|Y\| \cos \varphi_y$
$X = \|Z\| \sin \varphi_z$	$B = \|Y\| \sin \varphi_y$
$\|Z\| = \sqrt{R^2 + X^2}$	$\|Y\| = \sqrt{G^2 + B^2}$
$\tan \varphi_z = \frac{X}{R}$	$\tan \varphi_y = \frac{B}{G}$
$\frac{p_o}{U_o} = \|Z\| = \frac{1}{\|Y\|}$	$\frac{U_o}{p_o} = \|Y\| = \frac{1}{\|Z\|}$
$\varphi_z = -\varphi_y$	$\varphi_y = -\varphi_z$
$X = \frac{-B}{G^2 + B^2}$	$B = \frac{-X}{R^2 + X^2}$
$R = \frac{G}{G^2 + B^2}$	$G = \frac{R}{R^2 + X^2}$

pedance and admittance in rectangular notation can be expressed as

$$Z_a = R_a + jX_a \tag{1.12}$$

and

$$Y_a = G_a + jB_a \tag{1.13}$$

where the j indicates that the components cannot be combined by simple addition.[2]

The resistive component for a complex system can be associated with an equivalent friction element, whereas the reactive component can be associated with equivalent spring and mass elements. The characteristics of these immittance elements are detailed in the following section.

Table 1.1 summarizes the specification of acoustic immittance in polar and rectangular notation and also provides computational formulas that relate the various quantities. While polar and rectangular notation are equivalent methods of expressing immittance, there may be definite advantages of certain components in clinical application. These are discussed in Chapter 7. See also Appendix A for a derivation of the relation between immittance and energy flow.

From the preceding discussion it is clear that an immittance must always be specified by two quantities in order to relate unambiguously the sound pressure (p) and the volume velocity (U). Most clinical instruments measure only $|Z_a|$ or $|Y_a|$ at a low probe–tone frequency (220 Hz). These instruments were not capable of measuring the immittance phase angle. This design was based on the observation that the impedance phase angle of the normal ear at 220 Hz is about −75° and is nearly independent of ear–canal air pressure (see Chapter 4). The clinical significance of phase–angle tympanograms at higher probe–tone frequencies will be discussed in Chapters 2 and 7.

[2]Using the mathematics of complex numbers, it can be proven that impedance can be fully specified by the complex quantity $Z = R + jX$ where $j = \sqrt{-1}$. Admittance can be similarly derived as the complex quantity $Y = G + jB$ (Heaviside, 1886a).

1.5 ACOUSTIC IMMITTANCE OF "IDEAL" ELEMENTS

There are three types of elements that offer impedance. In mechanics, these are mass, spring, and friction elements. Analogous quantities exist in acoustics. An acoustic spring is an enclosed volume of air that, when compressed, tends to "spring back" to its original volume. An acoustic mass exists when a quantity of air is moved as a unit as in a constriction or narrow tube. Friction resulting from collisions among the molecules in the medium represents the resistive component of impedance. An *ideal* element, which does not really exist, is one that has only a mass, spring, or friction characteristic, and not a combination of effects that occurs in real elements. The ear, an acoustico–mechanical system, contains both acoustical and mechanical elements. The eardrum is a mechanical spring, whereas the volumes of air on either side of the tympanic membrane are acoustic springs. The ossicles are mechanical masses, whereas the narrow lumens connecting the tympanic air cells offer an acoustic mass element. There is acoustic resistance due to the viscosity of air and mechanical resistance due to friction within the membranes, tendons, and ligaments in the middle ear. These acoustical and mechanical elements, which are illustrated in the model depicted in Figure 1.4, together determine the acoustic impedance of the ear. The following discussion outlines the characteristics of ideal elements.

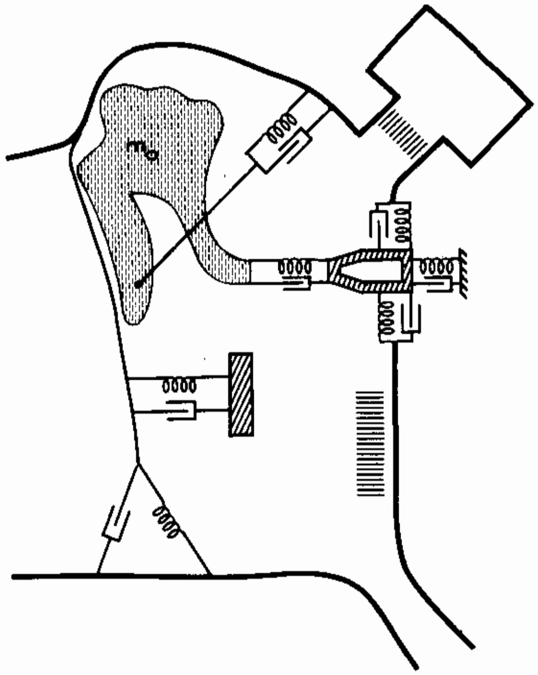


FIGURE 1.4. Mechanoacoustical model of the ear, containing masses, springs and friction elements as mechanical elements, together with open and closed air–filled volumes as acoustical elements. From Marquet, Van Camp, Creten, Decraemer, Wolff, & Schepens, 1973. Reprinted by permission.

1.5.1 The Mass Component

The pars flacida of the tympanic membrane, the ossicles, and the perilymph in the cochlea are the mass components that contribute to the overall input impedance of the middle–ear system. A simple experiment can be performed to help understand the relationship between pressure (p) and volume velocity (U) for a mass. Hold an object (e.g., a bottle of beer) in the air and move it back and forth rapidly. Experience the relation between the force (F) you exert to move the bottle and the resulting linear velocity (v). When the direction of the motion is changed, you will experience the need to exert the maximum force in order to reverse the direction. Figure 1.5 illustrates the force (upper graph) and the velocity (lower graph) functions that correspond to a sinusoidal motion of the mass. Positive values of force and velocity represent motion in one direction, whereas negative values represent motion in the other direction. When the motion changes direction, there is an instantaneous point (A) at which the force is maximum and the velocity is zero. Just after the change in direction occurs (Point B), both the force and the velocity are in the same direction, that is, both move to the right. In the middle of the oscillation (Point C), the mass moves by itself (due to inertia) and no force, therefore, is needed (i.e., the force is zero). At Point C, the velocity, as you can experience, is maximum.

The force and velocity functions in Figure 1.5, differ in time by a quarter of a period (T/4). That is, there is a 90° phase lead of force relative to velocity for an ideal mass. For an acoustic mass, the same phase relationship applies to the time courses of pressure (p) and volume velocity (U). Accordingly, the impedance phase angle for a mass is φ_z = 90° and the admittance phase angle is therefore $\varphi_y = -90°$.

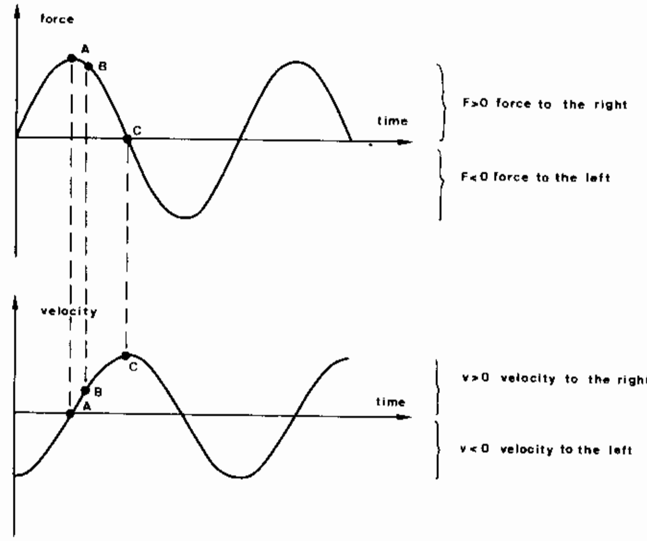


FIGURE 1.5. Force (F) and velocity (v) as functions of time for a sinusoidally oscillating mass.

Now empty the bottle and repeat the experiment maintaining the same amplitude and velocity of motion as in the first experiment. You should observe that in order to maintain the same amplitude and velocity with the smaller mass, less force must be exerted on the object. The relationship among force (F), velocity (v), and mass (M) can be expressed as:

$$F_o/v_o \propto M \qquad \varphi_z = +90°, \tag{1.14}$$

that means force amplitude F_o is proportional to mass for the same velocity amplitude v_o of sinusoidal oscillation.

In acoustics the force–like quantity is the sound pressure (p) and the velocity–like quantity is the volume velocity (U), so from the experiment and Equation 1.14 we can write

$$|Z_a| = p_o/U_o \propto M, \quad \varphi_z = +90°. \tag{1.15}$$

The exact computations result in

$$|Z_a| = 2\pi f M/S^2 \qquad \varphi_z = +90° \tag{1.16}$$

or

$$|Y_a| = S^2/2\pi f M \qquad \varphi_y = -90° \tag{1.17}$$

where S is the surface upon which the sound pressure acts and f is the frequency of the sinusoidal sound pressure (Van Camp & Creten, 1976). Figure 1.6 summarizes the characteristics of an ideal mass. The impedance of a mass can also be specified in rectangular components:

$$X_a = 2\pi f M/S^2 \quad \text{and} \quad R_a = 0, \tag{1.18}$$

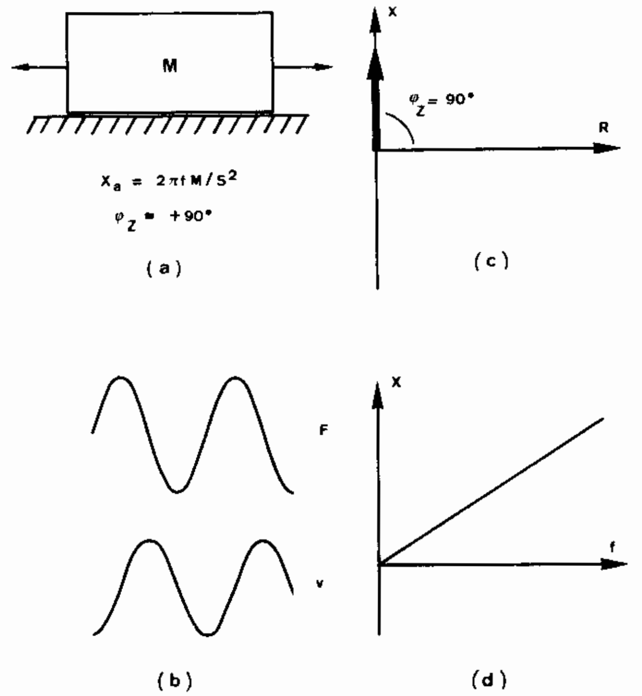


FIGURE 1.6. Summary of the impedance characteristics of an ideal mass: expressions for the impedance components (a), force and velocity as functions of time (b), impedance phasor representation (c) and the reactance (X) as a function of the frequency (f) (d).

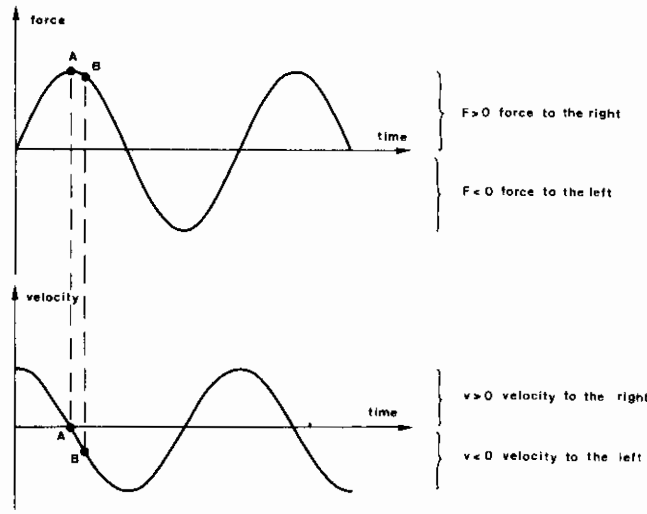


FIGURE 1.7. Force (F) and velocity (v) as functions of time for a sinusoidally oscillating spring.

because $\varphi_z = +90°$ for an ideal mass. A mass has a pure positive reactance that is proportional to the frequency (f) (see Figure 1.6d). The admittance of a mass in rectangular notation is given by:

$$B_a = -S^2/2\pi f M \qquad \text{and} \qquad G_a = 0. \qquad (1.19)$$

1.5.2 The Spring Component

In the middle–ear system, ligaments, tendons, the tympanic membrane, and the air enclosed in the ear canal and middle ear behave like spring elements. Again, a simple experiment can demonstrate the relationship between force and velocity as they apply to the action of a spring. Take a stiff spring that is fixed at one end and alternately pull and push the free end in a slow sinusoidal motion. Relate the force (F) exerted on the spring to the resulting velocity (v). The force will be maximum when the spring is either maximally compressed or maximally extended. Figure 1.7 illustrates the force and velocity functions as they relate to the motion of a spring. As the spring reverses from extension to compression or vice versa, the force is maximum and the velocity is zero (Point A). As in the case of mass, there is a 90° phase relationship between the force and velocity functions. There is, however, something different about the phase relations depicted in Figure 1.7. After the change from extension to compression (Point B), the spring (velocity) is retracting (to the left), whereas the force is still pulling (to the right). Force and velocity have opposite phase signs at Point B.

The stiffer the spring, the larger the force that is required to act upon the spring. This may be expressed as

$$F_o/v_o \propto k, \qquad \varphi_z = -90° \qquad (1.20)$$

where F_o and v_o are the force and velocity amplitudes, respectively, and k represents the spring constant (which is a quantity that is directly proportional to the stiffness of the spring[3]).

Often springs are described by the inverse of the spring constant, the compliance (C):

$$C = 1/k. \qquad (1.21)$$

The greater the compliance of a spring, the easier it is to extend or compress.

The acoustic impedance of a compliant element may be expressed in terms of its compliance in polar notation:

$$|Z_a| = 1/2\pi f C S^2 \qquad \varphi_z = -90° \qquad (1.22)$$

or in rectangular components as:

$$X_a = -1/2\pi f C S^2 \qquad \text{and} \qquad R_a = 0, \qquad (1.23)$$

because $\varphi_z = -90°$ for an ideal spring (Van Camp & Creten, 1976). The acoustic admittance in polar notation is given by:

$$|Y_a| = 2\pi f C S^2 \qquad \varphi_y = +90° \qquad (1.24)$$

or in rectangular components:

$$B_a = 2\pi f C S^2 \qquad \text{and} \qquad G_a = 0. \qquad (1.25)$$

Note from Equation 1.23 that an acoustic compliance has a pure negative reactance that is inversely proportional to

[3]If static force (F) is applied, then the extension (x) is related to the force by F = kx or F = x/C.

the frequency. This means that the higher the frequency, the smaller the absolute value of reactance (see Figure 1.8d).

Let us perform another experiment. Take a large syringe and seal the needle end. By pulling and pushing the plunger of the syringe, the enclosed volume of air will react in exactly the same way as a spring. The impedance of this "acoustic spring" in polar notation is

$$|Z_a| = \rho c^2/2\pi f V \qquad \varphi_z = -90° \qquad (1.26)$$

where ρ is the density of air, c is the speed of sound, and V is the volume. The impedance of a spring can also be expressed in rectangular components:

$$X_a = -\rho c^2/2\pi f V \quad \text{and} \quad R_a = 0. \qquad (1.27)$$

The admittance in polar notation is given by:

$$|Y_a| = 2\pi f V/\rho c^2 \qquad \varphi_y = +90° \qquad (1.28)$$

or in rectangular components:

$$B_a = 2\pi f V/\rho c^2 \quad \text{and} \quad G_a = 0. \qquad (1.29)$$

This means that an enclosed volume of air (e.g., the middle–ear cavity) contributes to the acoustic impedance in the same way that a spring does, provided the cavity has certain constraints on its dimensions (see also Section 4.7). The essential features of spring elements are summarized in Figure 1.8.

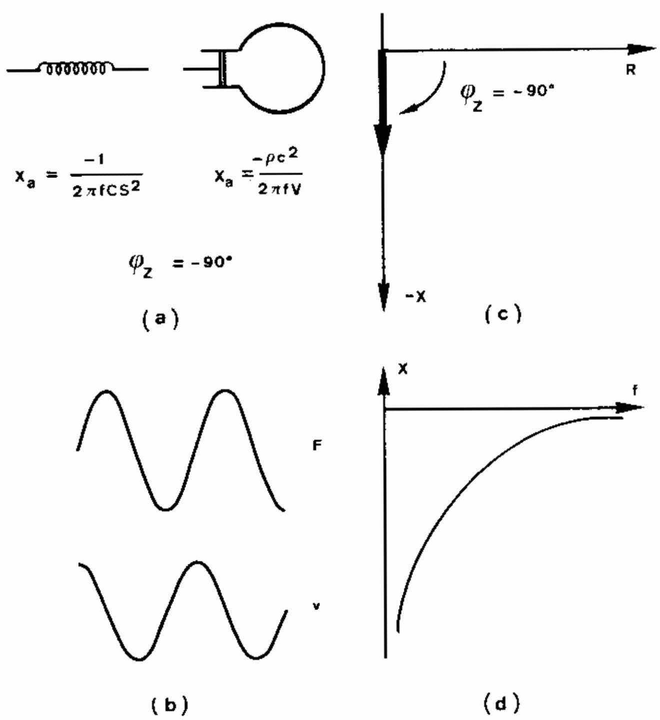


FIGURE 1.8. Summary of the impedance characteristics of an ideal spring or a closed cavity: expressions for the impedance components (a), force and velocity as functions of time (b), impedance phasor representation (c) and the reactance (X) as a function of the frequency (f) (d).

1.5.3 The Friction Component

The tympanic membrane and the tendons and ligaments in the middle ear are not pure compliance elements. Soft biological materials are visco–elastic elements that are characterized by a combination of spring and friction effects. The viscosity of the perilymph also introduces a friction component into the acoustic impedance of the ear. The viscosity of the mucous lining of the middle–ear cavity contributes to the friction element of the system. The narrow passages between the middle–ear cavity and the mastoid also contribute to the acoustic–friction element.

A simple experiment is instructive in the understanding of the friction component. Using a syringe with a long thin needle with the tip submerged in water, alternately flush water back and forth through the needle. The viscosity of the water is the physical quantity that provides the internal friction in the water flow. The force on the plunger and the velocity of the plunger are at any time directly proportional to each other. For example at Point A in Figure 1.9, when the plunger has been pushed completely from the out position to the in position, the velocity of the water through the needle is zero and the force on the plunger is zero. In this example, force and velocity are always in–phase ($\varphi_z = \varphi_y = 0°$). The impedance in polar notation of an ideal resistive element is (Van Camp & Creten, 1976):

$$|Z_a| = b/S^2 \qquad \varphi_z = 0° \qquad (1.30)$$

where S is the surface area and b is the friction coefficient relating the external force and the resulting velocity in a friction element (F = bv). The resistance can also be expressed in rectangular components:

$$R_a = b/S^2 \quad \text{and} \quad X_a = 0 \qquad (1.31)$$

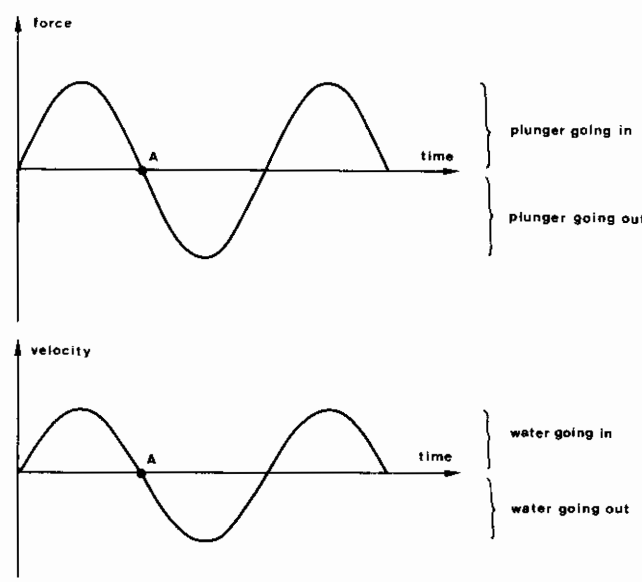


FIGURE 1.9. Force (F) and velocity (v) as functions of time for a sinusoidally oscillating friction element.

because $\varphi_z = 0°$ in an ideal friction element. The admittance in polar notation is given by:

$$|Y_a| = S^2/b \qquad \varphi_y = 0° \tag{1.32}$$

or in rectangular components:

$$G_a = S^2/b \quad \text{and} \quad B_a = 0. \tag{1.33}$$

For flowing water b is directly proportional to the viscosity of the medium. A friction element is thus a *pure acoustic resistance* and its impedance is independent of the frequency (see Figure 1.10d). The characteristics of resistive elements are summarized in Figure 1.10.

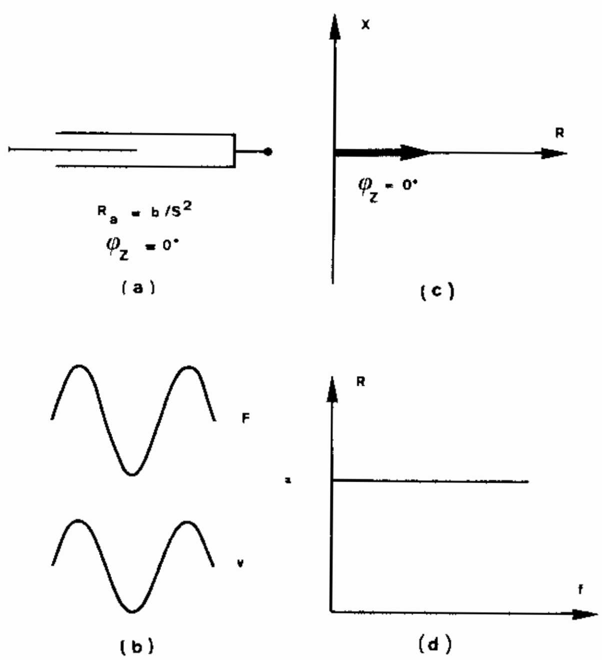


FIGURE 1.10. Summary of the impedance characteristics of an ideal friction element: expressions for the impedance components (a), force and velocity as functions of time (b), impedance phasor representation (c) and the resistance (R) as a function of the frequency (f) (d).

1.6 ADDITION OF IMMITTANCE COMPONENTS

In a complex system containing mass, spring, and resistive elements, the total immittance is determined by the combined effects of all the elements. Complex systems can be analyzed using a set of techniques collectively referred to as network analysis. In this section we will present two simple rules of network analysis to illustrate the combined effects of immittance components. These rules will be referred to as the admittance rule and the impedance rule (Table 1.2).

1.6.1 Admittance Rule

If the same sound pressure acts on a system consisting of two components (e.g., a mass and a spring), then the total immittance offered by the system is determined by the admittance rule. By analogy to electrical systems, components on which the same sound pressure acts are said to be configured *in parallel.* If the sound pressure acting on the elements is the same, then we can see by the definition of admittance that the admittance of parallel elements can be added. Recall that

TABLE 1.2. Admittance and impedance rules.

Admittance Rule: The total admittance of a system consisting of elements on which identical sound pressures act is determined by addition of admittance components.

Impedance Rule: The total impedance of a system consisting of elements that are driven to identical volume velocity is determined by addition of impedance components.

$$|Y| = \frac{U_o}{p_o} \angle \varphi_y \tag{1.34}$$

and that

$$Y = G + jB, \tag{1.35}$$

where G (conductance) represents the in-phase component of admittance, and B (susceptance) represents the 90° (quadrature) component.[4]

Since B is positive for a spring element and negative for a mass element we can write

$$Y = G + j(B_c + B_m), \tag{1.36}$$

where B_c is the positive susceptance of the spring elements and B_m is the negative susceptance of the mass elements. Because admittance is defined as the complex ratio of volume velocity to sound pressure, each component can be represented by its own ratio:

$$G = \frac{U_o(0°)}{p_o} \tag{1.37}$$

$$B_c = \frac{U_o(+90°)}{p_o} \tag{1.38}$$

$$B_c = \frac{U_o(-90°)}{p_o} \tag{1.39}$$

where $U_o(0°)$ represents the in-phase component of the volume velocity, and so forth. If the sound pressure (p_o) acting on n conductance elements is the same, then the ratios have the same denominators and the conductances can be combined by simple addition. That is,

$$G_{total} = \frac{U_{o_1}}{p_o} + \frac{U_{o_2}}{p_o} + \ldots + \frac{U_{o_n}}{p_o} \tag{1.40}$$

which can be simplified as

[4]In this and subsequent sections, the subscript a will be dropped from all immittance symbols.

$$G_{total} = G_1 + G_2 + \ldots + G_n. \quad (1.41)$$

Simply stated, the conductances of parallel elements combine by simple addition. Note that conductances are always positive. We can similarly show that the susceptances of parallel elements can be added:

$$B_{c_{total}} = B_{c_1} + B_{c_2} + \ldots + B_{c_n} \quad (1.42)$$

and

$$B_{m_{total}} = B_{m_1} + B_{m_2} + \ldots + B_{m_n}. \quad (1.43)$$

Because $B_{c_{total}}$ and $B_{m_{total}}$ act in opposite directions (i.e., they are 180° out–of–phase), spring elements have positive susceptances and mass elements have negative susceptances. Thus they can be combined algebraically so that:

$$B_{total} = B_{c_{total}} + B_{m_{total}}, \quad (1.44)$$

which is what was stated in Equation 1.36, and illustrates that all parallel susceptances can be added provided that the sign of each susceptance component is respected.

The admittance rule can be illustrated by the addition of phasors. Figure 1.11 depicts a system in which the total admittance consists of two conductance elements (G_1 and G_2) and two susceptance elements (B_1 and B_2). Note that the susceptance elements have different signs. That is, one is a spring element (positive susceptance) and one is a mass element (negative susceptance). The total conductance G_{total} is obtained by simple addition of the component conductances. Similarly, the total susceptance B_{total} is obtained by algebraic addition of the component susceptances, in this case resulting in a positive B_{total}. G_{total} and B_{total} can now be combined to produce the admittance of the system Y. Because conductance and susceptance elements represent volume velocities that are out–of–phase with each other, they cannot be added by simple addition. However, in Figure 1.11 it is evident that B_{total} and G_{total} represent two sides of a right triangle, and therefore $|Y|$ can be calculated by the Pythagorean Theorem:

$$|Y| = \sqrt{G^2 + B^2}. \quad (1.45)$$

A derivation of Equation 1.45 is in Appendix B.

In this section we have demonstrated that the conductances of elements configured in parallel, that is, on which the same sound pressure acts, can be combined by simple addition. Similarly, the susceptances of parallel elements can be added (with due respect for the sign of each component value). The admittance magnitudes of parallel elements cannot be combined by simple addition, except in rare cases. Parallel admittance magnitudes are combined by the addition of phasors, which are discussed in the next section.

1.6.2 Addition of Admittance Phasors

Suppose we now have a system that consists of two subsystems, each of which consists of a total conductance (G_1 and G_2) and a total susceptance (B_1 and B_2), each of which, therefore, has an admittance (Y_1 and Y_2). If Y_1 and Y_2 are configured in parallel, that is, the same sound pressure acts on the two subsystems, then the total admittance Y_{total} can be determined by the addition of phasors, illustrated in Figure 1.12. Y_{total} can be determined graphically by the line from the origin to the tip of Y_2. Alternatively, Y_{total} can be determined from the sum of the B components (B_{total}) and the sum of the G components (G_{total}) as was illustrated in the previous section. Because the two subsystems are in parallel, the total susceptance B_{total} is $B_1 + B_2$ and the total conductance G_{total} is $G_1 + G_2$. The

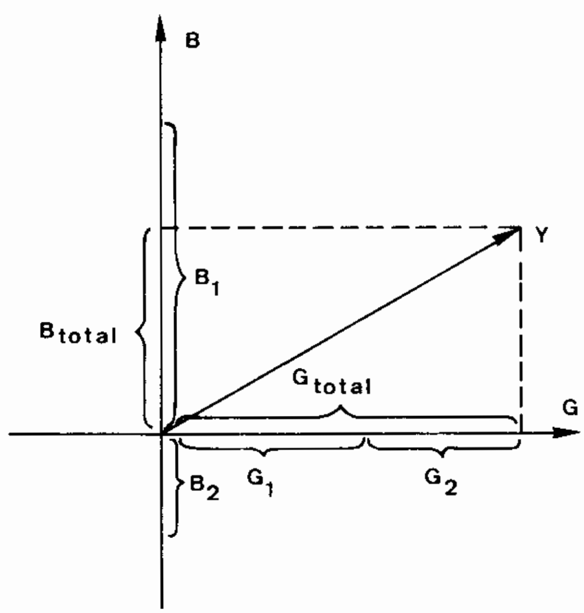


FIGURE 1.11. Admittance rule applied to two sets of susceptances and conductances.

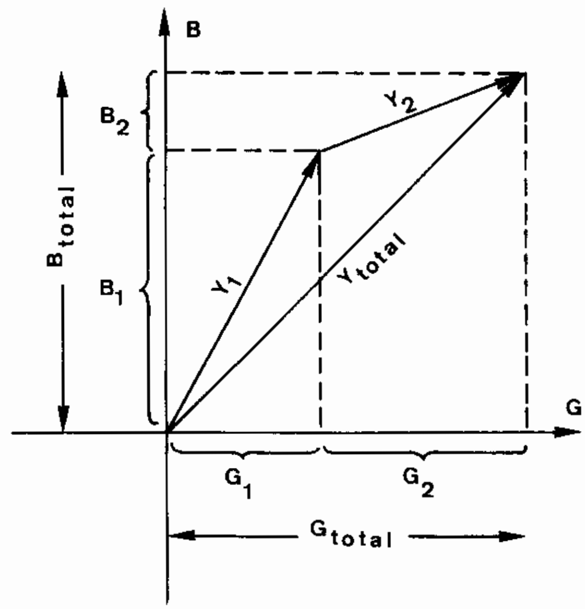


FIGURE 1.12. Parallelogram rule for adding two admittance phasors.

admittance Y_{total} is represented by the hypotenuse of the right triangle formed by B_{total} and G_{total} so that the total admittance magnitude can be calculated by Equation 1.45.

Thus, there are two methods for determining the admittance of complex systems: (a) Admittance phasors, one for each subsystem, may be added graphically as in Figure 1.12; or (b) a total conductance and total susceptance can be determined by addition of like components and the resulting total admittance magnitude can be calculated by the Pythagorean Theorem (Equation 1.45).

1.6.3 Impedance Rule

If two components in a system are driven to the same volume velocity, then the total acoustic immittance can be determined by the impedance rule (Table 1.2). Again, by analogy to electrical systems, if the volume velocity of two components is the same, then they are said to be configured *in series*. Recall that we defined acoustic impedance as

$$|Z| = \frac{p_o}{U_o} \angle \varphi_z \tag{1.46}$$

and

$$Z = R + jX \tag{1.47}$$

where R (resistance) represents the in–phase component and X (reactance) represents the total 90° (quadrature) component. Because X is negative for a spring and positive for a mass we can write

$$Z = R + j(X_m + X_c), \tag{1.48}$$

where X_m is the reactance of the mass elements and has a positive sign and X_c is the reactance of the spring elements and has a negative sign. Because impedance is defined as the complex ratio of sound pressure to volume velocity, each component can be represented by a similar ratio:

$$R = \frac{p_o(0°)}{U_o} \tag{1.49}$$

$$X_c = \frac{p_o(-90°)}{U_o} \tag{1.50}$$

$$X_m = \frac{p_o(+90°)}{U_o} \tag{1.51}$$

where $p_o(0°)$ is the in–phase component of the peak sound pressure, and so forth.

Because the volume velocities and, therefore, the denominators of like elements are the same, we can derive the following in the same way that we derived Equations 1.40 through 1.42:

$$R_{total} = R_1 + R_2 + \ldots + R_n \tag{1.52}$$

$$X_{c_{total}} = X_{c_1} + X_{c_2} + \ldots + X_{c_n} \tag{1.53}$$

$$X_{m_{total}} = X_{m_1} + X_{m_2} + \ldots + X_{m_n} \tag{1.54}$$

and because $X_{m_{total}}$ and $X_{c_{total}}$ have opposite signs algebraic addition gives

$$X_{total} = X_{c_{total}} + X_{m_{total}}. \tag{1.55}$$

In Figure 1.13 we see that series resistances (R_1 and R_2) add to produce a total resistance R_{total}, and series reactances (X_1 and X_2) add to result in a total reactance X_{total}. The impedance magnitude |Z| can be determined by the Pythagorean Theorem:

$$|Z| = \sqrt{R^2 + X^2}. \tag{1.56}$$

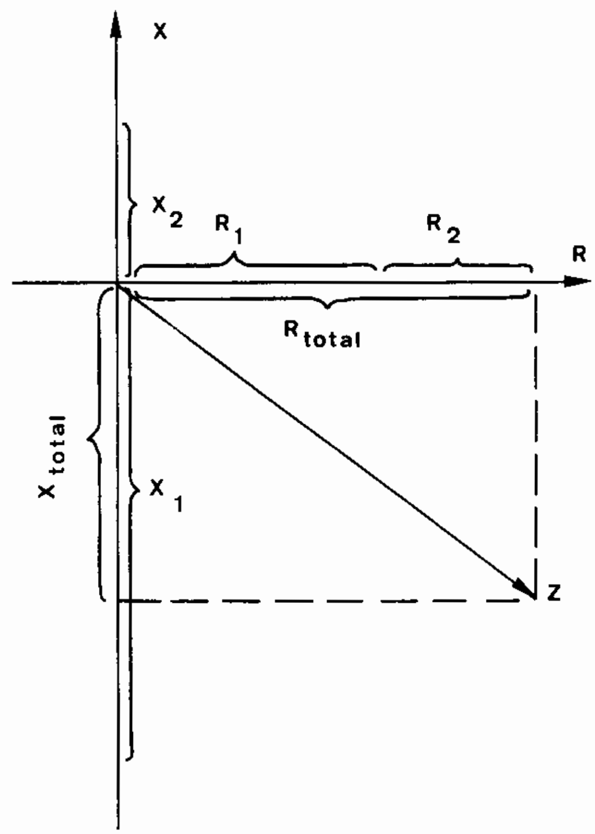


FIGURE 1.13. Impedance rule applied to two sets of resistances and reactances.

1.6.4 Addition of Impedance Phasors

The impedance of a series system can be determined either graphically or by the Pythagorean Theorem, just as parallel admittances could be combined by both methods. Figure 1.14 illustrates that Z_{total} can be determined by (a) addition of phasors (Z_1 and Z_2), or (b) addition of resistances and reactances and calculating the Z_{total} by the Pythagorean Theorem.

1.6.5 Mechanical Analogies

The terms *series* and *parallel* are borrowed from electronics in which the physical arrangement of components

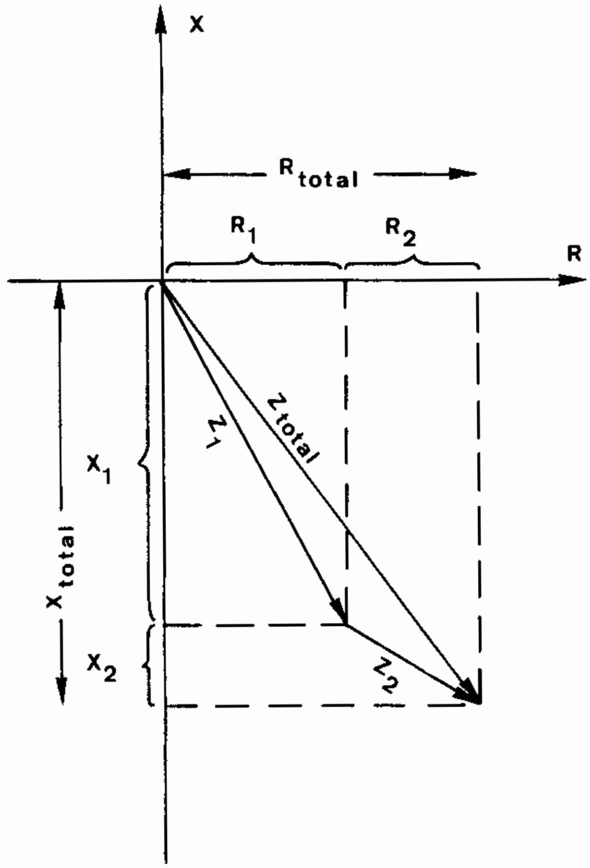


FIGURE 1.14. Parallelogram rule for adding two impedance phasors.

usually indicates unambiguously that they are, in fact, series or parallel elements. In mechanics and acoustics, it is not always obvious from the physical arrangement whether two components are in series or in parallel. Consider the examples given in Figure 1.15.

In Figure 1.15a, a force is exerted on a mass, behind which is a spring that is attached to an immovable wall. Any movement of the mass must be accompanied by an identical movement, in amplitude and phase, of the spring. The physical arrangement does not allow anything else. Because the velocity of the mass and spring are identical (analogous to identical volume velocities in an acoustic system), we know the impedance rule is applied. The elements, therefore, are configured in series. Now consider the system in Figure 1.15b, which looks quite similar to

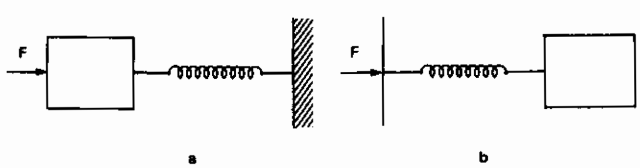


FIGURE 1.15. Mechanical system with mass and spring as series elements (a) and a similar mechanical system with mass and spring as parallel elements (b).

that in Figure 1.15a. The position of the mass and spring, however, are reversed and the system is no longer fixed to a rigid wall. Now the mass and spring will respond to the force with different velocities, depending on the characteristics of the components. If the spring is very compliant and the mass very large, then there will be a considerably greater velocity response of the spring than the mass. Analysis of the system would reveal that the pressures exerted on the two elements are identical; the admittance rule, therefore, must be applied and the elements must be in parallel.

These examples illustrate that in mechanical systems, the geometric arrangements of elements does not always reveal their functional relationship (Beranek, 1954; Olson, 1967; Van Camp & Creten, 1976). Similarly, in acoustics, it is not always obvious whether elements are in series or parallel. For example, the anatomy of the ear might suggest that the ear canal and middle ear are in series. In fact, for the purposes of clinical acoustic–immittance measurement, the ear canal and middle ear are functionally in parallel. This is developed in detail in Chapter 5.

1.7 UNITS

A complete understanding of a measurement is only possible if one understands the units with which the measurement is expressed. By clearly defining the measurement units, scientists and clinicians are able to compare results obtained with various apparatus and procedures. Ambiguous definition of units, such as the "arbitrary units" sometimes used to express tympanometry data, excludes quantitative comparisons and creates confusion. In this section we discuss the fundamental physical measurement units (Table 1.3), with emphasis on those necessary for tympanometry. A summary of tympanometric units can be found in Table 1.4.

1.7.1 Dimensional Analysis

A unit system is a set of quantities with which all physical measurements can be expressed. Rather simple unit systems are possible because all physical events can be quantified with a limited number of fundamental "concepts." These concepts include six quantities having spe-

TABLE 1.3. Fundamental concepts and unit systems.

Name	*Symbol*	*Unit c.g.s.*	*Unit SI*
Length	[L]	centimeter: cm	meter: m
Mass	[M]	gram: g	kilogram: kg
Time	[t]	second: s	second: s
Temperature	[T]	Kelvin: K	Kelvin: K
Electrical current	[I]	several	ampere: A
Luminous intensity	$[I_v]$		candela: cd
Plane angle	rad	radian	
Solid angle	sr	steradian	
Quantity of substance	mol	mole	

TABLE 1.4. Units used to express tympanometric measurements.

Quantity	Symbol	*cgs system* Name	Unit	Practical name	Practical unit	*Système International* Name	Unit	Practical name	Practical unit	*Conversion of c.g.s practical units to SI practical units*
Acoustic impedance	Z_a					Siemen				$\frac{10^3 \text{ dyne s}}{\text{cm}^5} = \frac{10^8 \text{ Pa s}}{\text{m}^3}$
Acoustic resistance	R_a	cgs acoustic ohm	$\frac{\text{dyne s}}{\text{cm}^5}$	cgs acoustic kilohm	$\frac{\text{dyne s} \times 10^3}{\text{cm}^5}$	mks acoustic ohm (see note)	$\frac{\text{Pa s}}{\text{m}^3}$	Gigasiemen acoustic ohm (see note)	$\frac{\text{Pa s} \times 10^9}{\text{m}^3}$	1 cgs acoustic kohm = 0.1 SI acoustic Gohm
Acoustic reactance	X_a									
Impedance phase angle	φ_z	degree	degree	degree	degree	radian	radian	radian	radian	1 degree $= \frac{\pi}{180}$ radians
Acoustic admittance	Y_a									
Acoustic conductance	G_a	cgs acoustic mho	$\frac{\text{cm}^5}{\text{dyne s}}$	cgs acoustic millimho	$\frac{\text{cm}^5 \times 10^{-3}}{\text{dyne s}}$	none	$\frac{\text{m}^3}{\text{Pa s}}$	none	$\frac{\text{m}^3 \times 10^{-9}}{\text{Pa s}}$	$\frac{10^{-3} \text{ cm}^5}{\text{dyne s}} = \frac{10^{-8} \text{ m}^3}{\text{Pa s}}$
Acoustic susceptance	B_a									
Admittance phase angle	φ_z	degree	degree	degree	degree	radian	radian	radian	radian	1 degree $= \frac{\pi}{180}$ radians
Acoustic mass (inertance)	M_a	none	$\frac{\text{dyne s}^2}{\text{cm}^5}$	none	$\frac{\text{dyne s}^2}{\text{cm}^5}$	none	$\frac{\text{Pa s}^2}{\text{m}^3}$	none	none	$\frac{\text{dyne s}^2}{\text{cm}^5} = \frac{10^5 \text{ Pa s}^2}{\text{m}^3}$
Acoustic compliance (capacitance)	C_a	none	$\frac{\text{cm}^5}{\text{dyne}}$	none	$\frac{\text{cm}^5}{\text{dyne}}$	none	$\frac{\text{m}^3}{\text{Pa}}$	none	none	$\frac{\text{cm}^5}{\text{dyne}} = \frac{10^{-5} \text{ m}^3}{\text{Pa}}$
Air pressure	P	none	$\frac{\text{dyne}}{\text{cm}^2}$	millimeters of water	$\frac{98.07 \text{ dyne}}{\text{cm}^2}$	Pascal	$\frac{\text{N}}{\text{m}^2}$	dekapascal	$\frac{\text{N} \times 10^{-1}}{\text{m}^2}$	1 millimeter of water = 0.98 daPa

Note: Système International (SI) did not adopt a unit for impedance, resistance, and reactance. The mks, ohm, and Siemen have been used by various investigators.

cific dimensions and three ratios or numbers that are referred to as dimensionless quantities. The nine concepts from which all unit systems are developed are listed in Table 1.3. Some of these concepts, specifically luminous intensity, solid angle, and quantity of substance are not relevant to tympanometric measurement and are omitted from the following discussion.

Remarkably, any physical quantity can be expressed in terms of the concepts in Table 1.3. Stated otherwise, one can prove the rather surprising fact that a force of any nature (such as nuclear interaction, mechanical friction, stapedial muscle contraction) can always be expressed in the same limited number of fundamental concepts in the same combination. Force is defined as mass times acceleration (Equation 1.1). Because acceleration is length/(time)^2, force can be expressed in terms of mass, length, and time, which are three of the concepts in Table 1.3. For the dimensional equation of any force one obtains:

$$[F] = [ML/t^2] \tag{1.57}$$

or equivalently,

$$[F] = [MLt^{-2}]. \tag{1.58}$$

Note that dimensional quantities are conventionally set in brackets. Dimensional equations, such as Equation 1.57 for a force, are independent of the unit system used. In general, any physical quantity can be expressed in terms of the nine concepts of Table 1.3.

1.7.2 SI and c.g.s. Unit Systems

The first unit system was proposed early in the 19th century by a group of French scientists. Because they chose the centimeter, gram, and second as the units of length, mass, and time, the system became known as the c.g.s. unit system. Since the nature of electricity was not understood at the time the c.g.s. system was first proposed, a basic electrical concept or unit was not introduced. Later, a variety of electrical units were used without consistent agreement. To eliminate the confusion, the Système International (SI) was proposed with new units for the nine fundamental concepts. The two systems are summarized in Table 1.3.

1.7.3 Units for Tympanometry

By defining units for the fundamental concepts, it is possible to derive units for all other quantities. For example, pressure is defined as force per unit area $[L^2]$. That is,

$$[P] = [F/L^2]. \qquad (1.59)$$

Using Equation 1.57 we obtain:

$$[P] = [ML/t^2]/[L^2] = [ML^{-1}\,t^{-2}]. \qquad (1.60)$$

Sometimes new names are introduced for units of nonfundamental quantities as a shorthand notation. In c.g.s. units for example, the name dyne is introduced as a unit for force; in the SI system we introduce units such as pascal for pressure and newton for force. The introduction of such special names does not mean that the above quantities cannot be expressed in combination of the fundamental concepts. We will continue now to derive dimensional equations for all the quantities we will need in tympanometry and fill in units afterwards.

A volume velocity (U) is defined as a volume $[L^3]$ per unit time, so that:

$$[U] = [L^3\,t^{-1}]. \qquad (1.61)$$

The dimensional equation for the acoustic impedance and its components can be derived starting from Equation 1.6, so that:

$$[Z] = [P]/[U] \qquad (1.62)$$

or

$$[Z] = [P]/[L^3t^{-1}] = [F]/[L^5t^{-1}]. \qquad (1.63)$$

Similarly, the dimensional equation for the acoustic admittance and its components can be derived from Equation 1.7, so that:

$$[Y] = [1/Z] = [L^3t^{-1}]/[P] = [L^5t^{-1}]/[F]. \qquad (1.64)$$

For frequency (f), having units of cycles per second we note:

$$[f] = [t^{-1}], \qquad (1.65)$$

while density (ρ) and velocity (c) which are used in Equation 1.26 are

$$[\rho] = [ML^{-3}] \qquad (1.66)$$

and

$$[c] = [Lt^{-1}]. \qquad (1.67)$$

If units are substituted in Equations 1.59 through 1.67, then we find units for all quantities used in tympanometry. They are summarized in Table 1.4. For specific names of the SI units for acoustic impedance and admittance we still await decisions of the I.E.C. Throughout this paper we will use nanosiemens (nS) as the name for the SI unit of acoustic admittance and its components

$$1\text{ nS} = 0.1\text{ mmho cgs}, \qquad (1.68)$$

although this unit has not been adopted by the I.E.C.

Chapter 2

The Normal Tympanogram

2.1 INTRODUCTION

Various definitions of "normal" have been used to define normal tympanograms. In the clinical literature, a normal tympanogram has sometimes referred to results from ears with normal hearing (with various definitions of normal hearing). Elsewhere, normal tympanograms have been viewed as those recorded from ears without medically or surgically correctable pathology, even though permanent mechanical abnormalities may exist. The difficulty in defining normal tympanometric results lies in the fact that disease–altered conditions of the middle ear occur without important changes in function. These conditions are permanent mechanical changes that do not progress and do not require medical attention. The most common example of this type of condition is the monomeric tympanic membrane. In other cases, normal tympanograms occur in the presence of substantial functional abnormalities. Tympanograms from otosclerotic ears, for example, frequently have been interpreted as normal, in the presence of a substantial conductive hearing loss. Due to the location of the otosclerotic lesion, the effect of stapedial fixation on the input impedance of the middle ear can be difficult to detect with tympanometry.

In this monograph, normal refers to the distribution of immittance characteristics obtained from normally developed ears that have not been altered by disease. Defined in this manner, abnormal tympanograms may occur in normal–hearing subjects whose pathological middle ears do not require medical attention. Normal tympanograms may occur in subjects with middle–ear pathologies that result in hearing loss and/or conditions that require medical or surgical treatment. Optimal clinical use of tympanometry requires that tympanometric results be evaluated in the context of other information to assess the probability of medically significant ear disease. The use of tympanometry for determining the need for medical referral is discussed further in Chapter 8.

The difficulty in defining the normal tympanogram is further complicated by the fact that commercially available acoustic–immittance instruments vary in the acoustic quantities that they measure. Most provide only one, low–frequency, probe signal, typically 220 or 226 Hz, although some provide other frequencies, most commonly 660 or 678 Hz. At low–probe tone frequencies, normal tympanograms are almost always bell–shaped for all acoustic–immittance quantities. At higher probe frequencies (e.g., 660 Hz) a variety of patterns occur that may display more than one peak. These multipeaked tympanograms were first described by Lidén (1969a,b), Lidén, Peterson, and Björkman (1970a,b), and Lidén, Harford, and Hallen (1974) and were called W–patterns because they plotted an inverted admittance tympanogram. In the more conventional form that will be used throughout this work, these tympanograms could be described as M–patterns. Before Vanhuyse, Creten, and Van Camp (1975) presented a mathematical analysis that accounted for these patterns, a multipeaked tympanogram was commonly interpreted as a reflection of a pathological middle ear. In this chapter and those that follow it will be shown that multipeaked tympanograms result from both normal and pathological ears, and that the differentiation of normal from abnormal tympanograms can be accomplished by a set of rather simple rules.

An understanding of the classification of multipeaked patterns is essential to the interpretation of tympanograms, especially when high–probe tone frequencies are used. At higher frequencies both normal and impaired ears display tympanometric patterns that are more complex than the patterns observed with a low–frequency probe. The more complex patterns provide clinically useful information that cannot be obtained with the more common low–probe frequency instruments. This is particularly true for pathological conditions that result in low impedance at the eardrum and for some pathologically high–impedance ears as well. This chapter is devoted to a description of the systematics of normal multipeaked tympanograms.

2.2 RESISTANCE AND REACTANCE TYMPANOGRAMS

Moller (1965) published the first reactance (X) and resistance (R) tympanograms that were obtained from cats. The shapes of these tympanograms were quite different from human impedance (Z) tympanograms obtained with commercial instruments that were introduced after the pioneering work of Terkildsen and Scott–Nielsen (1960). In the early 1970s Grason–Stadler, Inc. introduced a commercial instrument that was capable of measuring both components of acoustic admittance (susceptance and conductance) at two probe frequencies (220 and 660 Hz).

Tympanograms recorded with this instrument can be converted into reactance and resistance tympanograms after appropriate ear–canal volume corrections are made (see conversion formulas in Table 1.1). At both probe–tone frequencies investigators using this instrument obtained resistance and reactance tympanograms for normal human ears that were similar to those obtained by Moller on cats (Creten, Vanpeperstraete, & Van Camp, 1978; Lidén, Björkman, Nyman, & Kunov, 1977; Margolis & Popelka, 1977). Examples of resistance and reactance tympanograms for a normal adult human ear are shown in Figure 2.1.

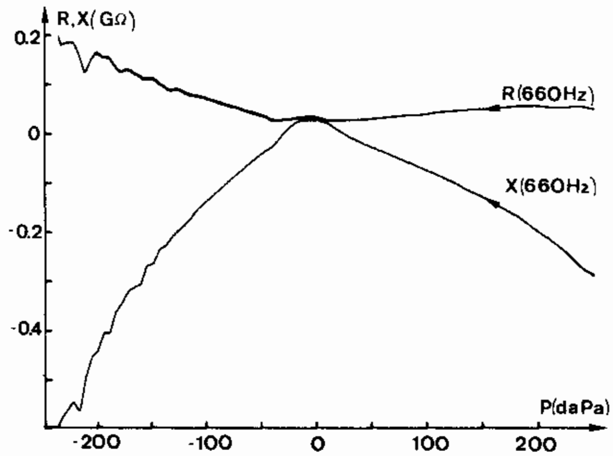


FIGURE 2.1. Resistance (R) and reactance (X) tympanograms (corrected to the tympanic membrane) calculated from 660–Hz susceptance (B_1) and conductance (G_1) tympanograms recorded with a Grason–Stadler, Model 1720 Otoadmittance meter from a normal adult human ear. (1 ac kohm c.g.s. = 0.1 ac Gohm SI)

2.2.1 Reactance Tympanogram

The reactance tympanogram at the eardrum for a normal human ear has the shape of an inverted *V* (Figure 2.1). From recordings obtained at 220 and 660 Hz, and from admittance tympanograms obtained by Colletti (1977) using high–frequency probe tones, one can deduce that if the probe frequency is increased, then the inverted V–shape of the reactance tympanogram, plotted on linear coordinates,[5] will broaden. The static acoustic impedance measurements reported by Zwislocki (1962) indicate that the peak of the reactance tympanogram (near ambient ear–canal pressure) shifts from large negative values toward positive values as the probe frequency is increased. The reactance tympanogram reported by Moller (1965) from cats is nearly symmetrical. In contrast, the reactance tympanograms obtained from humans often show a marked asymmetry. This asymmetry can be real, but it also can be introduced by an error in the correction for ear–canal volume. If precise tympanograms are to be obtained, the ear–canal volume and the change in ear–canal volume that occurs with changes in ear–canal pressure must be determined precisely and appropriate corrections must be employed.[6] The estimate of the residual eardrum admittance at high ear–canal pressures (see Section 5.3) also has an important influence on the shape of the reactance tympanogram at the eardrum (see Margolis & Popelka, 1977; Shanks & Lilly, 1981; Vanpeperstraete, Creten, & Van Camp, 1979 for discussions). In summary, the reactance tympanogram normally has an inverted V–shape that shifts from negative toward positive values and becomes broader (on linear coordinates) with increasing probe frequency. Precise determination of the magnitude of the reactance at the eardrum and the shape of the reactance tympanogram requires precision that is probably not feasible for clinical implementation.

2.2.2 Resistance Tympanogram

The resistance tympanogram at the eardrum for a normal human ear is a rather flat curve, often monotonically decreasing toward positive ear–canal pressures (see Figure 2.1). The shape and absolute value of the resistance tympanogram is rather independent of probe frequency. The frequency independence of the acoustic resistance near ambient ear–canal pressure is evident in the data of Zwislocki and others (see Rabinowitz, 1981; Zwislocki, 1962). At high ear–canal pressures it is very difficult to obtain reliable estimates of the acoustic resistance at the eardrum because ear–canal volume and residual eardrum admittance at high pressures have a major influence on the resistance tympanogram. These effects are difficult to estimate. For this reason resistance tympanograms are usually determined over a limited range of ear–canal pressures; for example, −200 to +200 daPa.[7] As with the reactance tympanogram, the accurate recording of the resistance tympanogram requires more precision than usually is available with clinical instrumentation.

2.3 ADMITTANCE TYMPANOGRAMS

As an alternative to the reactance and resistance tympanograms discussed above, tympanograms can be recorded in admittance quantities: susceptance (B_1), conductance (G_1), admittance magnitude (Y_1), and the admittance phase angle φ_{y_1}.[8] Admittance can be fully spec-

[5]When the logarithm of reactance is plotted against ear–canal air pressure, reactance tympanograms at different probe frequencies are nearly parallel (Margolis & Popelka, 1977).

[6]The changes in ear–canal volume that result from varying the ear–canal air pressure can be quantified with a flow–measuring device such as the one described by Vanpeperstraete, Creten, and Van Camp (1979) and in Chapter 5.

[7]In this monograph the dekapascal (daPa) will be used as the unit of air pressure. Because 1 daPa = 1.02 mm H_2O, for the purposes of tympanometry, 1 daPa can be considered equivalent to 1 mm H_2O.

[8]The subscript, $_o$, will denote the peak value (near ambient pressure); the subscript, $_1$, will indicate that the measurement plane is the tip of the probe, and an immittance quantity with no subscript (e.g., B, G, or Y) will indicate that the value is estimated at the tympanic membrane. All admittance, conductance, and susceptance tympanograms are plotted with units nanosiemens (nS) on the ordinate. 1 nS = 0.1 mmho cgs.

ified only when two components are given, either susceptance and conductance (B,G), or admittance magnitude and phase angle (Y,φ). In this section we will discuss the systematics of normal susceptance–conductance tympanograms. Then normal admittance–phase tympanograms will be described with special emphasis on the three different kinds of phase-angle tympanograms.

2.3.1 Normal Susceptance, Conductance Tympanograms

Type 1B1G

The simplest possible set of (B_1,G_1) tympanograms at the tip of the probe occurs when both the susceptance and conductance curves are bell-shaped (or single-peaked), displaying their maxima near ambient ear-canal pressure (Figure 2.2). As both tympanometric curves only show one extreme (in this case a maximum), this type is called 1B1G. It is encountered especially at lower probe-tone frequencies (e.g., 220 Hz) in normal adult ears. In the mathematical explanation of tympanometric patterns of Vanhuyse et al. (1975) it was shown that 1B1G tympanograms are obtained when the reactance is negative and the absolute value of reactance is greater than the value of the resistance ($X_o < -R_o$) for all ear-canal pressures. Because reactance is always negative in the 1B1G pattern, the middle-ear system is said to be stiffness controlled.

Type 3B1G

The 3B1G pattern is the most common multipeaked or W-pattern. The susceptance B_1 tympanogram has two maxima situated on either side of a central minimum (see Figure 2.3). The conductance tympanogram G_1 is single-peaked with its maximum very near the pressure value of the central minimum in the susceptance tympanogram. According to Vanhuyse et al. (1975) the 3B1G pattern is obtained if $-R_o < X_o < 0$ where X_o is the peak reactance near ambient ear-canal pressure and R_o is the corresponding value of resistance. That is, reactance is negative for all values of ear-canal pressure and the absolute value of reactance is less than resistance at low ear-canal pressures and greater than resistance at high pressures. Because reactance is always negative in the 3B1G pattern, the middle-ear system is stiffness controlled.

Type 3B3G

For a middle-ear system that becomes mass controlled near ambient ear-canal pressure, that is, $0 < X_o < R_o$, both the susceptance and the conductance tympanograms show two maxima located on either side of a central minimum (see Figure 2.4). The 3B3G pattern can be classified as normal only if the pressure interval between the maxima in susceptance is broader than the pressure interval between conductance maxima. During a tympanometric run, 3B3G tympanograms obtained from normal ears display maxima in the following symmetrical sequence:

1. B_1 maximum,
2. G_1 maximum,
3. central minima of B_1 and G_1 at similar pressures (near ambient pressure),

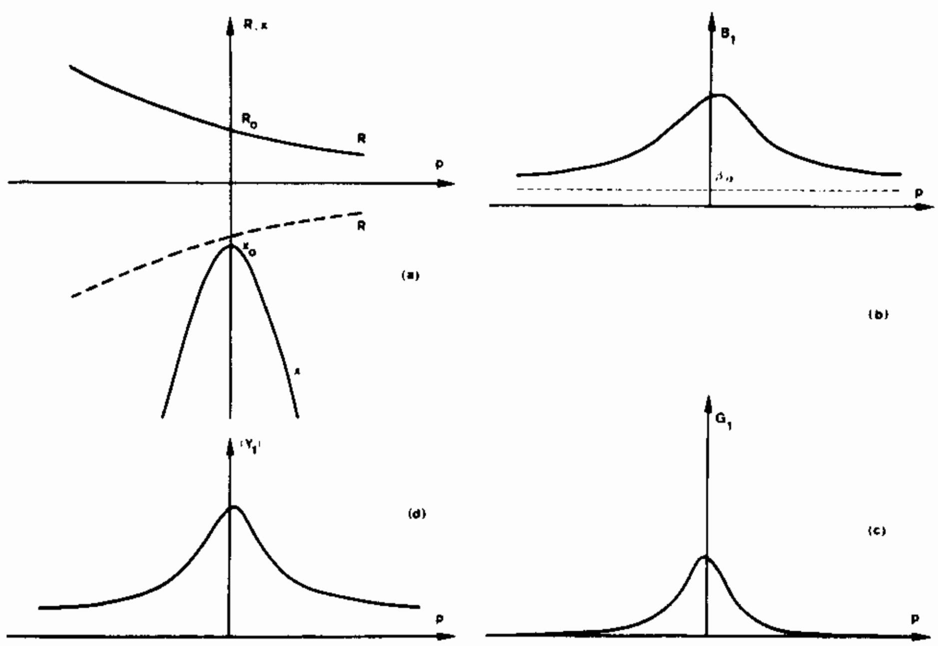


FIGURE 2.2. Type 1B1G. (a) Assumptions of R,X as functions of the ear-canal pressure (P). (b) Calculated susceptance (B_1), (c) conductance (G_1), and (d) admittance (Y_1) tympanograms. From Vanhuyse et al., 1975. Copyright 1975 by The Almqvist & Wiksell Periodical Company. Reprinted by permission.

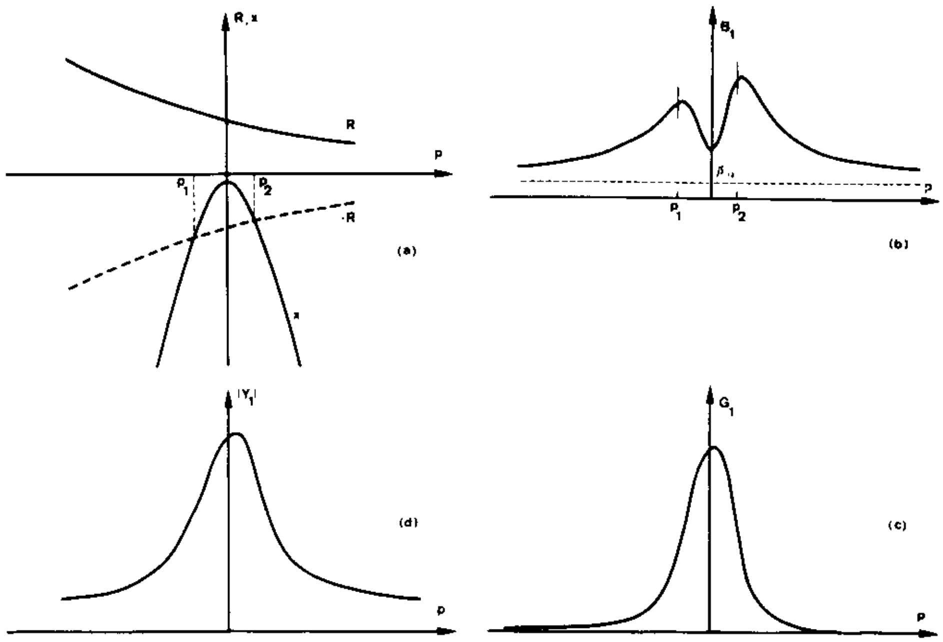


FIGURE 2.3. Type 3B1G. (a) Assumptions of R,X as functions of the ear–canal pressure (P). (b) Calculated susceptance (B_1), (c) conductance (G_1), and (d) admittance (Y_1) tympanograms. From Vanhuyse et al., 1975. Copyright 1975 by The Almqvist & Wiksell Periodical Company. Reprinted by permission.

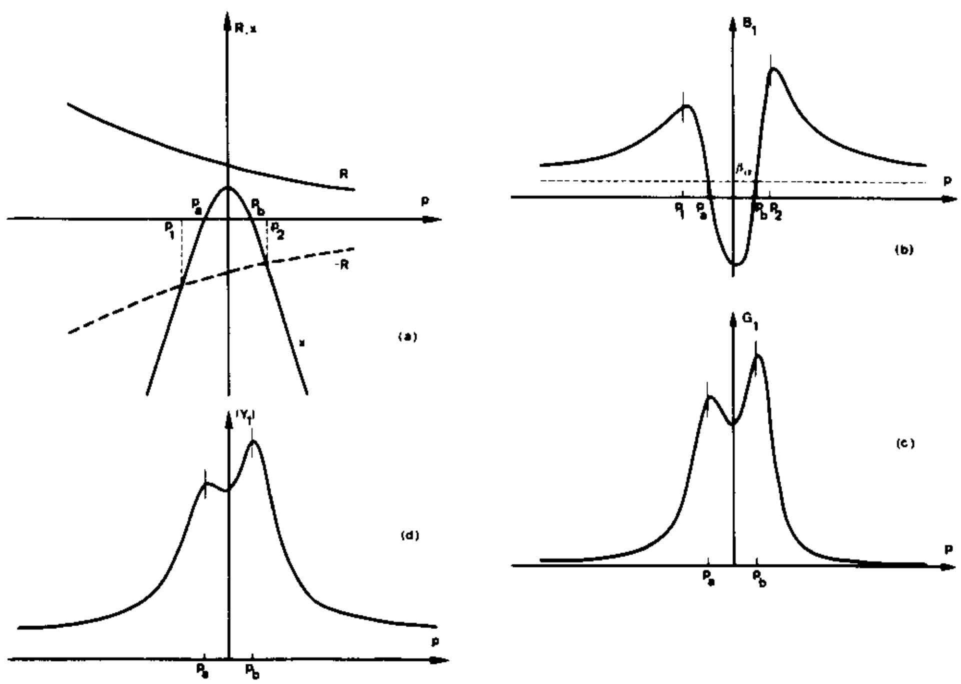


FIGURE 2.4. Type 3B3G. (a) Assumptions of R,X as functions of the ear–canal pressure (P). (b) Calculated susceptance (B_1), (c) conductance (G_1), and (d) admittance (Y_1) tympanograms. From Vanhuyse et al., 1975. Copyright 1975 by The Almqvist & Wiksell Periodical Company. Reprinted by permission.

4. G_1 maximum, and
5. B_1 maximum.

The results of Van de Heyning, Van Camp, Creten, and Vanpeperstraete (1982) suggest that the 3B3G pattern is normal at 660 Hz only if the two susceptance maxima occur within a pressure interval not exceeding 75 daPa.

Type 5B3G

For very mobile but normal middle–ear systems, the most complex B_1,G_1 pattern is the 5B3G; five extrema in susceptance and three in conductance (see Figure 2.5). As ear–canal pressure is changed in either direction, the following symmetrical sequence of extrema is observed:

1. B_1 maximum,
2. G_1 maximum,
3. B_1 minimum,
4. central extrema of B_1 and G_1 at similar pressures (near ambient pressure),
5. B_1 minimum,
6. G_1 maximum, and
7. B_1 maximum.

According to the Vanhuyse et al. (1975) model, the ear–canal pressure interval between the conductance maxima must be less than the pressure interval between the outer susceptance maxima. Furthermore, the height of the positive susceptance maxima of the susceptance B_1 may only slightly exceed the tail values of the B_1 tympanogram.

In addition, the results of Van de Heyning et al. (1982) suggest that the 5B3G pattern is normal at 660 Hz only if the outer susceptance maxima occur within a pressure interval not exceeding 100 daPa. While a small proportion of normal ears exhibit this pattern at 660 Hz, it is more commonly associated with slight eardrum abnormalities.

In order for a B_1,G_1 tympanogram to be classified as normal, the peaks must occur in the order discussed in this section. A summary of the essential characteristics of normal B_1,G_1 tympanograms appears in Table 2.1. Occasionally, irregular tympanometric patterns occur in ears with no identifiable pathology. An example of a 3B3G pattern in which the extrema do not occur in the normal order is shown in Figure 2.6. This subject had a normal–appearing eardrum on microscopic otoscopy and normal hearing.

2.3.2 Secondary Properties of Normal B,G Tympanograms

In this section some details of the normal B_1,G_1 patterns will be discussed in relation to the mathematical model of Vanhuyse et al. (1975) (see Figures 2.2–2.5). These details relate to the relative positions and magnitudes of the susceptance and conductance peaks and can be related to the relations between resistance and reactance tympanograms. Normal variations in the relations between resistance and reactance tympanograms result in some variability in these secondary characteristics. Accordingly, exceptions to these secondary properties are not necessarily evidence of a

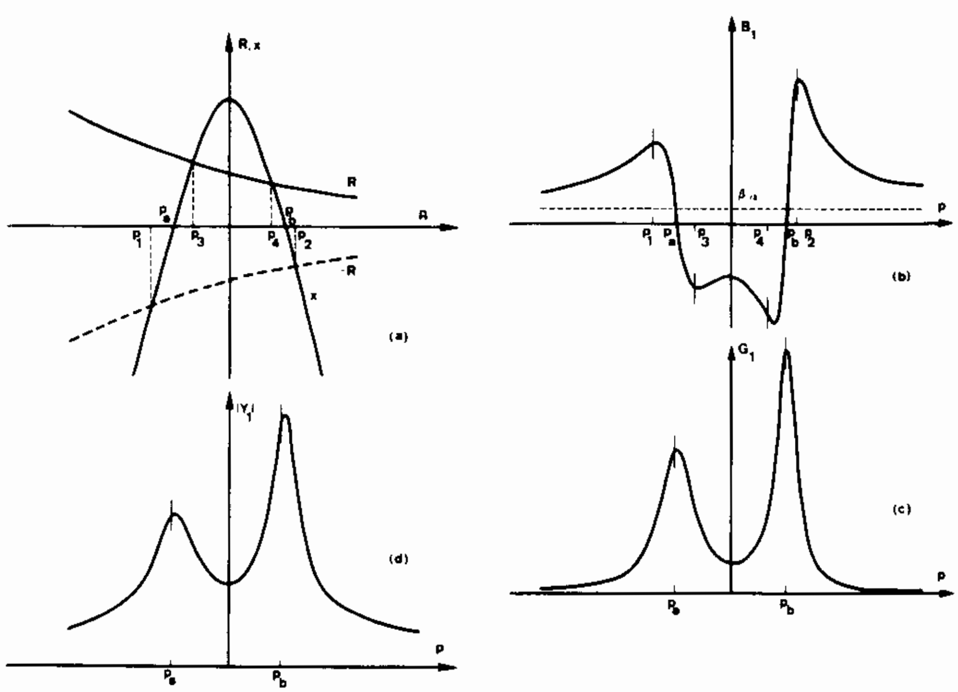


FIGURE 2.5. Type 5B3G. (a) Assumptions of R,X as functions of the ear–canal pressure (P). (b) Calculated susceptance (B_1), (c) conductance (G_1), and (d) admittance (Y_1) tympanograms. From Vanhuyse et al., 1975. Copyright by 1975 by The Almqvist & Wiksell Periodical Company. Reprinted by permission.

TABLE 2.1. Sequence of extrema occurring during a tympanometric run for normal susceptance–conductance recordings.

Type	Sequence of extrema			Condition
	Negative pressure	*Central extrema*	*Positive pressure*	
1B1G		B(max) G(max)		$X_o < -R$
3B1G	B(max)	B(min) G(max)	B(max)	$-R < X_o < 0$
3B3G	B(max) G(max)	B(min) G(min)	G(max) B(max)	$0 < X_o < R$
5B3G	B(max) G(max) B(min)	B(max) G(min)	B(min) G(max) B(max)	$R < X_o$

middle–ear abnormality. The secondary characteristics fall into three categories:

1. the sign of the reactance at the eardrum (mass controlled or stiffness controlled),
2. the asymmetry in the magnitudes of tympanometric peaks, and
3. the asymmetry of the pressure locations of the tympanometric peaks.

The Sign of the Reactance at the Eardrum. Multipeaked tympanograms at 660 Hz occur in normal ears that are stiffness controlled ($X_o < 0$) and also in normal ears that are mass controlled ($X_o > 0$). The following rules can be applied to determine from the susceptance tympanogram whether a tympanometric pattern reflects a stiffness–controlled or mass–controlled middle ear.

1. If the susceptance tympanogram has a single–peaked (inverted V–shape), then the ear is stiffness controlled (negative reactance) for all ear–canal pressures.
2. If the susceptance tympanogram is multipeaked, and if the minimum in the notch is higher than the tail values, then the ear is stiffness controlled (negative reactance) for all ear–canal pressures.
3. If the minimum in the susceptance notch is lower than the tail values, then the susceptance at the eardrum is negative, indicating a mass–controlled ear (positive reactance) in the pressure region near the susceptance minimum.

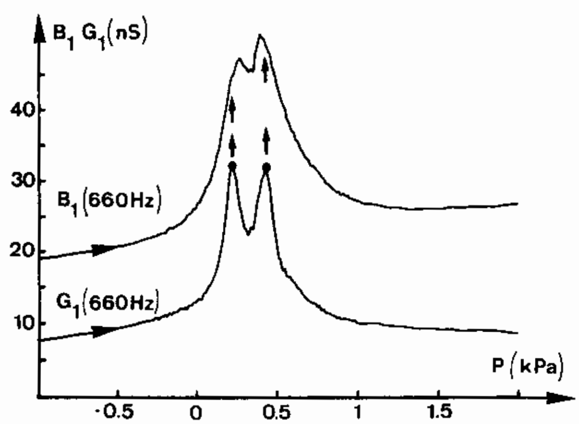


FIGURE 2.6. Simultaneous 660–Hz recordings of susceptance (B_1) and conductance (G_1) (1 nS = 0.1 acoustic mmho) as functions of the ear–canal pressure (P). Unique case of abnormal B_1G_1 tympanograms (scrambled sequence of extrema) found in an ear showing no marked pathology.

In the normal 3B1G pattern the central B_1 minimum is never below the tail values of the tympanogram; that is, the ear is stiffness controlled for all pressures. The Vanhuyse et al. (1975) model suggests that the 3B3G pattern occurs only for mass–controlled ears (see Figure 2.4). However, the 3B3G pattern has been observed in some stiffness–controlled normal ears (Margolis & Popelka, 1977; Van de Heyning et al., 1982), a finding that is consistent with the more elaborate mathematical model of Van Camp, Vanhuyse, Creten, and Vanpeperstraete (1978). Thus, the depth of the susceptance notch can be useful for distinguishing stiffness–controlled 3B3G patterns from those that are mass controlled. The 5B3G pattern (when obtained from normal ears) always reflects a mass–controlled ear. The minima in the susceptance tympanogram must be lower than the tail values of the curve. We should emphasize that the minimum in any conductance tympanogram theoretically cannot be the lowest point on the curve. When this occurs it is usually due to inaccurate calibration or inadequate probe characteristics (see Chapter 4).

Asymmetry of Tympanometric Peak Magnitudes. In the Vanhuyse et al. (1975) model and experimental results obtained from normal ears (Creten et al., 1978; Lidén et al., 1977; Margolis & Popelka, 1977), the resistance tympanogram is a monotonically decreasing function of ear–canal pressure (see Figure 2.1). The asymmetry of the resistance tympanogram results in higher maxima and deeper minima for the susceptance and conductance peaks located on the positive pressure side of the tympanogram compared to those located on the negative pressure side. These asymmetries in peak magnitudes are depicted in the bivariate plots shown in Figures 2.7 and 2.8.

Although the differences in the peak magnitudes both for notched susceptance and conductance tympanograms for a 678–Hz probe tone are influenced somewhat by the direction of the ear–canal pressure changes (Wilson, Shanks, & Kaplan, 1984), the bivariate plots illustrate that, as a rule, susceptance and conductance peaks that occur on the positive pressure side of multipeaked tympanograms are higher than those that occur on the negative pressure side. The dependence of this asymmetry on the direction of ear–canal pressure changes is particularly evident for the notched susceptance tympanograms analyzed in Figure 2.7. The asymmetry in peak magnitudes for multipeaked tympanograms is evident in the theoretical predictions of Vanhuyse et al. (1975; see Figures 2.2–2.5) and has been consistently reported in measured data (Lidén et al., 1977; Margolis, Osguthorpe, & Popelka, 1978; Margolis & Popelka, 1977; Van de Heyning et al., 1982; see also an exception to this finding in Creten et al., 1978, Figure 4).

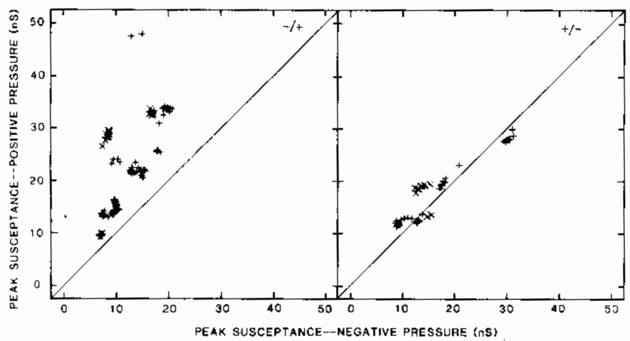


FIGURE 2.7. Bivariate plots of the peak susceptance values on the negative pressure side of the notch (abscissae) versus the peak susceptance values on the positive pressure side of the notch (ordinate) (1 nS = 0.1 acoustic mmho). The +s are from 3B1G tympanograms and the Xs are from 3B3G tympanograms. The data on the left panel were obtained with a negative to positive (−/+) pressure direction; right panel—positive to negative (+/−).

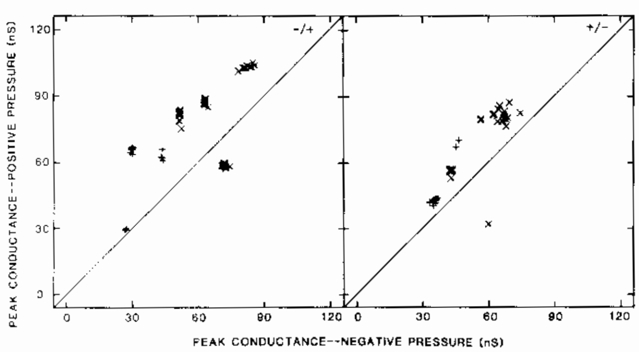


FIGURE 2.8. Bivariate plots of the peak conductance values on the negative pressure side of the notch (abscissae) versus the peak conductance values on the positive pressure side of the notch (ordinate) (1 nS = 0.1 acoustic mmho). The +s are from 3B3G tympanograms and the Xs are from 5B3G tympanograms. The data on the left panel were obtained with a negative to positive (−/+) pressure direction; right panel—positive to negative (+/−).

Asymmetry in the Pressure Locations of Tympanometric Peaks. The monotonically decreasing resistance tympanogram also causes an asymmetry in the positions of tympanometric peaks, even in simultaneously recorded B_1,G_1 tympanograms. Thus in the normal 1B1G pattern, the susceptance peak typically occurs at a more positive pressure than does the conductance peak (see Figure 2.2). The 3B1G pattern is similarly asymmetrical but the asymmetry is reversed relative to the 1B1G pattern. That is, in the 3B1G pattern, the susceptance minimum occurs at a more negative pressure than the conductance maximum (see Figure 2.3). These pressure relationships for 1B1G and 3B1G, 678–Hz tympanograms are illustrated in the bivariate plots in Figure 2.9 (Wilson et al., 1984). Note that the pressure relationships between peak conductance and susceptance vary somewhat with the direction of the ear–canal pressure changes. In the 1B1G tympanograms (upper panels), the susceptance peak pressures generally are more positive than the conductance peak pressures. This relationship was true for all individual tympanograms (N = 100) recorded with increasing ear–canal pressure changes (−/+) and was true for 78% of the tympanograms (N = 160) recorded with decreasing pressure changes (+/−).

In the 3B1G tympanograms (lower panels), the relationship between the conductance and susceptance peak pressures generally was reversed in comparison with the 1B1G patterns; that is, the conductance peak pressures generally are more positive than the susceptance peak pressures. This reversal was found for 82% (N = 85) of the tympanograms recorded with increasing pressure changes, whereas the remaining 18% showed no pressure difference in conductance and susceptance peak pressures. This relationship, however, was considerably weaker for the 3B1G tympanograms recorded with decreasing pressure changes; only 38% (N = 39) of the cases demonstrated this pressure relationship. However, 31% of the cases showed the reverse relationship with more positive susceptance than conductance peak pressures. The remaining 31% showed no peak pressure difference in conductance and susceptance. The 3B3G and 5B3G patterns also show asymmetries in their central extrema due to the asymmetrical resistance (see Figure 2.5). These differences, however, are very small, usually a few daPa.

2.3.3 Normal Admittance-Phase Tympanograms

In Sections 2.3.1 and 2.3.2 admittance was specified as a set of conductance–susceptance tympanograms. Admittance at the tip of the probe also can be fully specified by the admittance magnitude (Y_1) and the phase angle (φ_{y_1}) between the sound pressure (p) and volume velocity (U). Until recently the phase angle has not been used in plotting tympanograms, but Creten, Van Camp, Maes, and Vanpeperstraete (1981), Creten, Van Camp, Vanpeperstraete, and Van de Heyning (1981), and Van Camp, Creten, Van de Heyning, Decraemer, and Vanpeperstraete (1983) pointed out that the Y_1,φ_{y_1} approach has certain advantages compared with the B_1,G_1 tympanograms for detecting middle–ear pathologies. A knowledge of the systematics of normal Y_1,φ_{y_1} tympanograms is essential for clinical application of this tympanometric approach. As with the B_1,G_1 approach, the Y_1,φ_{y_1} tympanograms can be categorized according to the number of extrema in the admittance magnitude and phase–angle tympanograms. There is not, however, a one–to–one correspondence between the two classification schemes. Ears that produce a single B_1,G_1 type can produce more than one Y_1,φ_{y_1} category. The systematics of

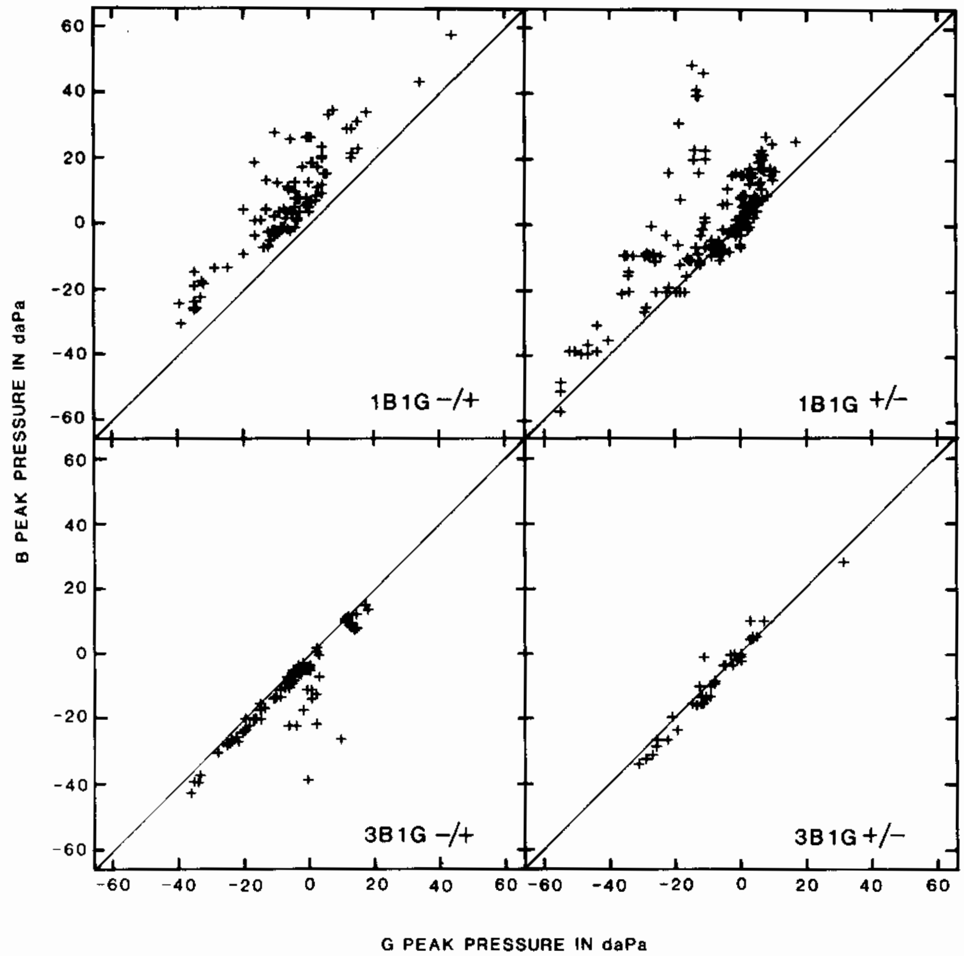


FIGURE 2.9. Bivariate plots of the conductance (G, abscissae) and susceptance (B, ordinates) peak pressures (in daPa) obtained with the 678–Hz probe. The left panels represent the −/+ pressure runs, whereas the right panels depict the +/− pressure runs. The top panels contain the 1B1G peak pressure data and the lower panels illustrate the 3B1G peak data. From Wilson et al., 1984. Copyright 1984 by the American Speech–Language–Hearing Association. Reprinted by permission.

Y_1, φ_{y_1} tympanograms, given below, apply only to admittance magnitude and phase–angle tympanograms recorded at the tip of the probe. For different measurement planes, tympanometric shapes can differ. Thus, no ear canal or other corrections are required to apply this classification.

Type 1Y1φ

For this simple set of Y_1, φ_{y_1} tympanograms both admittance components display only one extreme (Figure 2.10). The admittance tympanogram is single–peaked, with one maximum, and the phase–angle tympanogram is V–shaped, with one minimum. The 1Y1φ pattern occurs in most normal ears at 220 Hz and at 660 Hz.

Type 3Y1φ

In this case (Figure 2.10) the phase–angle tympanogram φ_{y_1} is still V–shaped, but the admittance curve has three extrema, including two maxima and one central minimum. The central minimum is located near the pressure value corresponding to the phase–angle minimum. In order for the 3Y1φ pattern to be classified as normal at 660 Hz, the pressure interval between the admittance maxima must not exceed 60 daPa (Van Camp et al., 1983). According to the Vanhuyse et al. (1975) model this pattern should occur only for mass–controlled ears (i.e., $X_o > 0$). It occurs in a small proportion of normal ears, but more commonly in cases of eardrum or ossicular abnormality.

Type 3Y3φ

The most complex type of normal admittance–phase tympanograms shows three extrema for both components (Figure 2.10). In the type 3Y3φ, the pressure interval between admittance peaks is larger than the pressure interval between peaks in the phase–angle tympanogram. As in the 3Y1φ pattern, the pressure width between the admittance maxima must not exceed 60 daPa (at 660 Hz) in order to be classified as normal (Van Camp et al., 1983).

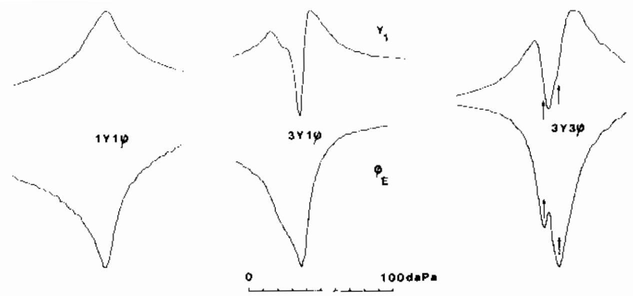


FIGURE 2.10. Simultaneous 660–Hz admittance Y_1 and electrical phase φ_e recordings on three normal ears, each representing one of the three possible types of normal admittance–phase pairs of tympanograms: 1Y1φ, 3Y1φ, and 3Y3φ. Arrows on the 3Y3φ recording accentuate the relative position of the extrema. From Van Camp et al., 1983. Copyright 1983 by The Almqvist & Wiksell Periodical Company. Reprinted by permission.

This pattern, which was not examined in the Vanhuyse et al. (1975) model, occurs if reactance is shifted substantially into positive values ($X_o >> 0$).

These three Y_1, φ_{y_1} types are the only patterns that occur in normal ears. Because there are fewer single–peaked B_1, G_1 patterns compared to single–peaked Y_1, φ_{y_1} tympanograms (Van Camp et al. 1983), the Y_1, φ_{y_1} approach may offer important advantages (see Section 7.5). The essential features of normal Y_1, φ_{y_1} tympanograms are summarized in Table 2.2.

In the theory of tympanometric shapes derived by Van Camp et al. (1978), Creten, Van Camp, Maes et al. (1981), and Creten, Van Camp, Vanpeperstraete et al. (1981), a more elaborate development of the possible combinations of B_1, G_1 and Y_1, φ_{y_1} tympanograms was described. As the reactance progresses from large negative values, toward positive values, the patterns become increasingly complex. Although the simpler Vanhuyse et al. (1975) model is a reasonable first approximation, the Van Camp model suggests that systematic exceptions to the general cases described in the earlier theory do occur. Figure 2.11 (from Correwyn & Laureyns, 1981) demonstrates the systematic deviations occurring to the Vanhuyse et al. theory in normal ears. Vanhuyse et al. predicted that as reactance approaches positive values the tympanometric patterns become more complex. The boundaries separating the tympanometric categories, however, are not exactly those that were originally predicted.

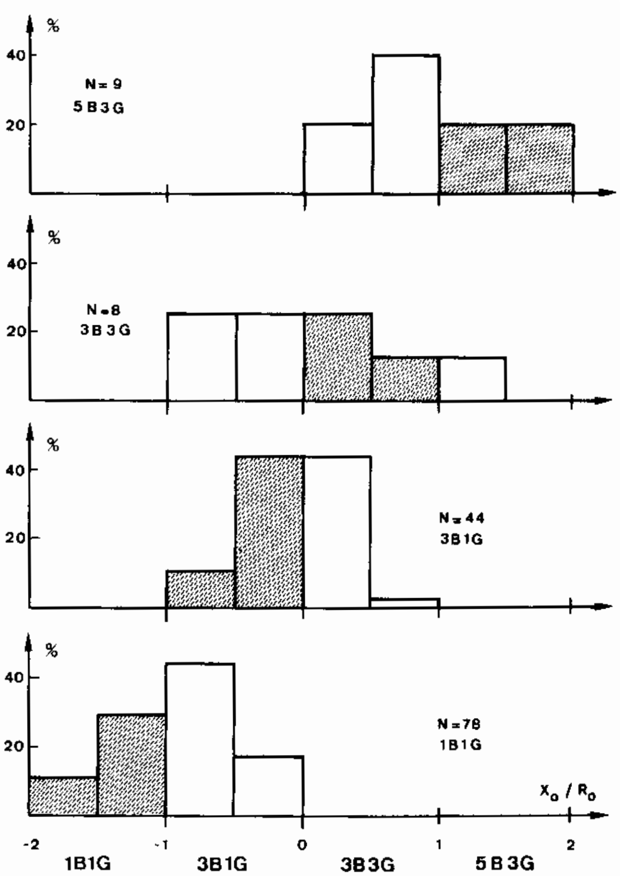


FIGURE 2.11. Experimental distributions of the X_oR_o ratio for the four types of normal B_1G_1 tympanograms. Data obtained from 139 normal ears. In the Vanhuyse et al. (1975) model the type of B_1G_1 set of tympanograms is determined by this ratio. The shaded areas are the cases that are predicted by the Vanhuyse et al. model.

2.3.4 Phasor Tympanometry

For the conductance, susceptance, and admittance tympanograms, only minor differences in shape exist between tympanograms measured at the probe tip and those that are corrected to the plane of the tympanic membrane. This is not true for the phase–angle φ_y tympanogram in which significant differences in tympanometric shapes occur for different measuring planes. In this section we will describe normal φ_y tympanograms and then describe a

TABLE 2.2. Sequence of extrema occurring during a tympanometric run for normal admittance–phase (Y_1, φ_{y_1}) recordings at the tip of the probe.

	Sequence of extrema						
Type	*Negative pressure*		*Central extrema*		*Positive pressure*		*Condition*
1Y1φ			Y(max)	(min)			$X_o < 0$
3Y1φ	Y(max)		Y(min)	(min)	Y(max)		$X_o > 0$
3Y3φ	Y(max)	(min)	Y(min)	(max)	(min)	Y(max)	$X_o > > 0$

method for deriving the phase angle at the eardrum using a technique called *phasor tympanometry*.

The behavior of the phase angle at the eardrum φ_y is rather unexpected. The φ_y tympanogram for normal ears is never multipeaked at any probe frequency that has been investigated (220–910 Hz). The ideal immittance component for differentiating between normal and abnormal ears would be the one that is consistently single peaked for normal ears and consistently multipeaked for abnormal ears. This appears to be the case for the phase angle at the eardrum. Unfortunately, the accurate recording of φ_y tympanograms requires computational support and precision (especially in correction for ear–canal volume) that is not currently feasible in most clinics. An alternative to recording φ_y, which maintains its advantages, is phasor tympanometry, introduced by Creten, Van Camp, Maes et al. (1981) and Creten, Van Camp, Vanpeperstraete et al. (1981).

Let us examine the behavior of normal φ_y tympanograms. From Chapter 1 (Table 1.1) we know that

$$\tan \varphi_y = \frac{B}{G}; \tag{2.1}$$

therefore

$$\varphi_y = \arctan \frac{B}{G}. \tag{2.2}$$

Similarly

$$\varphi_z = \arctan \frac{X}{R}. \tag{2.3}$$

Because $\varphi_y = -\varphi_z$ (Equation 1.10), impedance phase angle tympanograms and admittance phase angle tympanograms have identical shapes, one being inverted relative to the other. Because the resistance (R) tympanogram is rather flat, it has a negligible effect on the shape of the φ_y tympanogram. The inverted V–shape of the normal reactance (X) tympanogram (see Figure 2.1) essentially determines the V–shapes of normal phase angle tympanograms. At high positive and high negative ear–canal pressures, $|X| >> R$, therefore φ_y is large (near 90°) and reaches a minimum near ambient ear–canal pressure. As the probe frequency increases, the reactance tympanogram shifts upwards (towards positive reactance) and becomes broader. As a result, φ_y also becomes broader and the minimum approaches smaller phase angles. These X,R interactions result in the complicated shapes in conductance, susceptance, and admittance tympanograms discussed above, but the φ_y tympanogram remains single peaked for all normal ears. Examples of φ_y tympanograms corresponding to 3B1G, 3B3G, and 5B3G patterns are shown in Figure 2.12. Note that the phase–angle tympanogram is single peaked in each case.

Although the phase angle at the eardrum is difficult to obtain with clinical instrumentation, it can be inferred from the phasor tympanogram, which can be obtained with relatively simple equipment. The phasor tympanogram is useful for distinguishing between normal and abnormal multipeaked patterns, but is probably not clinically useful for low–frequency probe tones or for high–impedance ears. The phasor plot, which is very familiar in electrical engineering, is obtained by plotting the susceptance at the probe tip B_1 on the ordinate and the conductance at the probe tip G_1 on the abscissa.[9] An example of a phasor tympanogram is shown in Figure 2.13. From the phasor tympanogram the admittance components, Y, Y_1, φ_y, and φ_{y1}, can be derived. The admittance at the probe tip Y_1 is the length of the line projecting from the phasor to the origin, whereas the angle formed by that line and the horizontal axis is the phase angle at the probe tip φ_{y1}.

As we developed in the previous section, the phase angle at the eardrum φ_y has definite advantages compared to the phase angle at the probe tip φ_{y1}. The phase angle at the eardrum also can be deduced from the phasor tympanogram by the following method. The ear–canal volume is approximated as a pure acoustic compliance that is unaffected by ear–canal pressure changes. That is, the ear canal has a susceptance B_c that corresponds to the volume of air between the probe and the eardrum (Shanks & Lilly, 1981) and a conductance of zero. The phasor is evaluated relative to the point (B_c) (see Figure 2.14) that represents the correction for ear–canal volume. The length of the line from the phasor to Point B_c represents the admittance at the eardrum (Y) and the angle formed by that line and a horizontal line drawn through B_c is the phase angle at the eardrum φ_y that can be calculated for any point on the phasor. For Point Q on the phasor in Figure 2.14,

$$\tan \varphi_y = \frac{B_1 - B_c}{G} \tag{2.4}$$

and

$$\varphi_y = \arctan \frac{B_1 - B_c}{G}. \tag{2.5}$$

An adequate B_c estimate can be obtained from the lower of the two tail values of the susceptance tympanogram. For most subjects the negative pressure side of the susceptance tympanogram is the lower of the two tails, and provides the best estimate of ear–canal susceptance (Margolis & Smith, 1977; Shanks & Lilly, 1981). In order to estimate φ_y accurately it is important to obtain the true minimum tail value of B_c. This often requires recording to pressures approximating −400 daPa. If the gains of the B_1 and G_1 amplifiers of the recorder are identical, all Y_1, Y, φ_y, and φ_{y1} can be obtained graphically from the phasor plot without any computation.

We evaluated the estimates of φ_y obtained from phasor tympanometry with φ_y estimates obtained directly from phase angle tympanograms recorded with a measurement system that corrected for ear–canal volume and for the volume change that occurs as ear–canal pressure is varied. The estimates from the phasor tympanograms are quite accurate for low ear–canal pressures, with larger errors oc-

[9]This can be accomplished by feeding the B and G outputs of a two component admittance meter (e.g., Grason–Stadler, Model 1720) to the inputs of an X–Y recorder. Care must be taken to ensure that the gains of the two channels are identical.

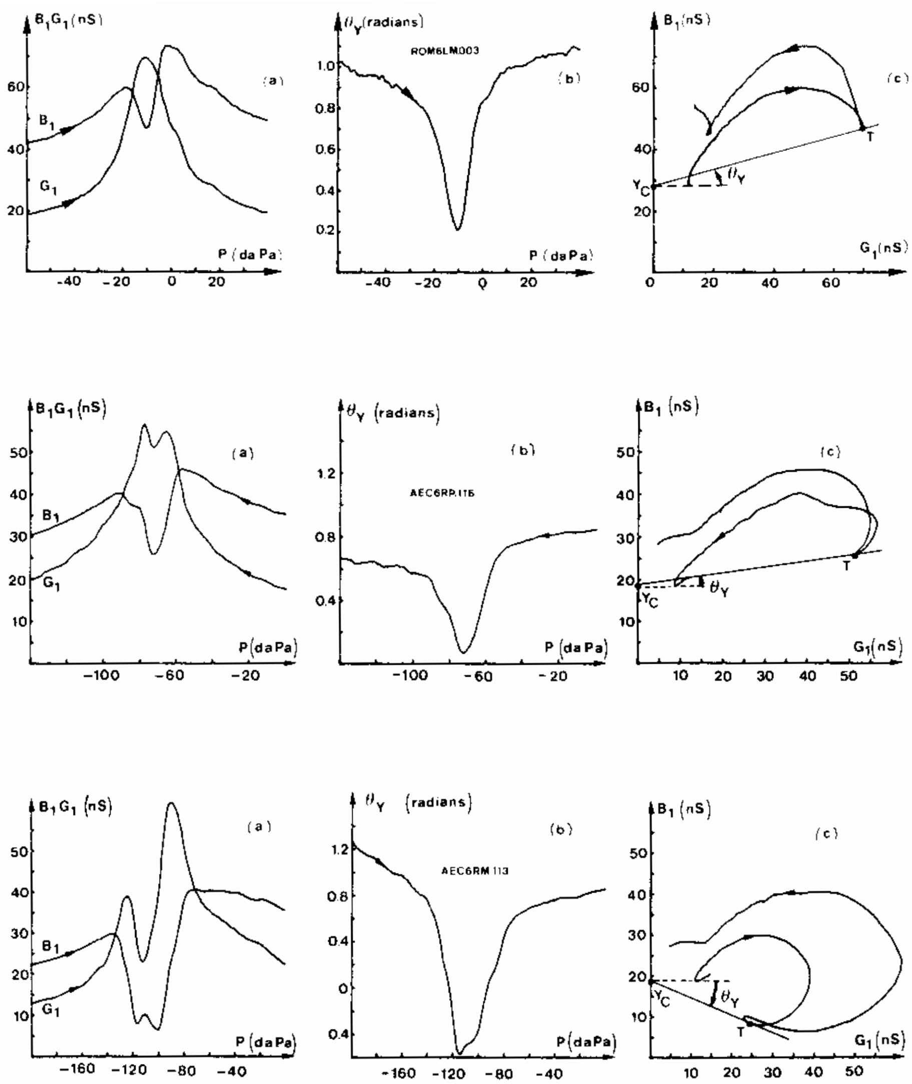


FIGURE 2.12. Simultaneous 660-Hz recordings of the susceptance (B_1) (660 Hz) and the conductance (G_1) (1 nS = 0.1 acoustic mmho) as functions of the ear-canal pressure for normal W-shaped patterns (a). Types 3B1G and 3B3G for decreasing ear-canal pressure and 5B3G on the same subject for increasing ear-canal pressure. Computed phase angle φ_y tympanograms at the drum (b) and corresponding phasor curves (c). Both subjects had normal hearing and normal looking tympanic membrane.

curring at the tails of the tympanograms. Because the direct estimate of φ_y requires sophisticated equipment, such as a flow meter (Vanpeperstraete et al., 1979) and a computer, phasor tympanometry represents a method of obtaining valuable phase information with relatively simple instrumentation.

Because the phase angle obtained from a phasor is not precise at high ear-canal pressures, φ_y will only be evaluated over a narrow range. The range corresponding to a pressure interval, somewhat larger than the one defined by the outer maxima of the susceptance tympanogram, is suitable in most cases. These points are denoted Q(+) and Q(−) on Figure 2.14. As the line projected from B_c passes through the phasor from Q(+) to Q(−), the angle φ_y passes through a minimum at the tip (T). If this angle is plotted in the form of a phase-angle tympanogram, then it will appear as a V-shaped function. As we indicated previously, this pattern occurs for all the normal tympanometric patterns discussed in the previous sections. The minimum in φ_y occurs when the line is tangent to the phasor. In Figure 2.14 the line is tangent to the phasor at Point T (see also examples in Figure 2.12c). Thus, the number of minima in the phase-angle tympanogram φ_y can be determined by counting the number of tangents that occur as the line projects from B_c to the phasor from Q(−) to Q(+). In multipeaked tympanometric patterns it is often necessary to evaluate the phasor over a wider pressure range, preferably slightly greater than the pressure range separating the outer susceptance maxima. In the case illustrated in Figure 2.15, five tangents occur.

This reflects an abnormal phase–angle tympanogram and the abnormality is observed in the phasor without the more sophisticated instrumental requirements of measuring the phase angle at the eardrum. As no pressure information is included in the phasor representation, in case of regular phasor curves one must check the pressure interval between the outer susceptance maxima in the conventional B_1 tympanogram, to make sure that the W–pattern is not too broad (and thus pathological).

Unfortunately, a commercial acoustic–immittance instrument currently is not available that is capable of simultaneous recording of B_1 and G_1 that is necessary for phasor tympanometry. The only commercial instrument that provides this capability is now out of production.[10]

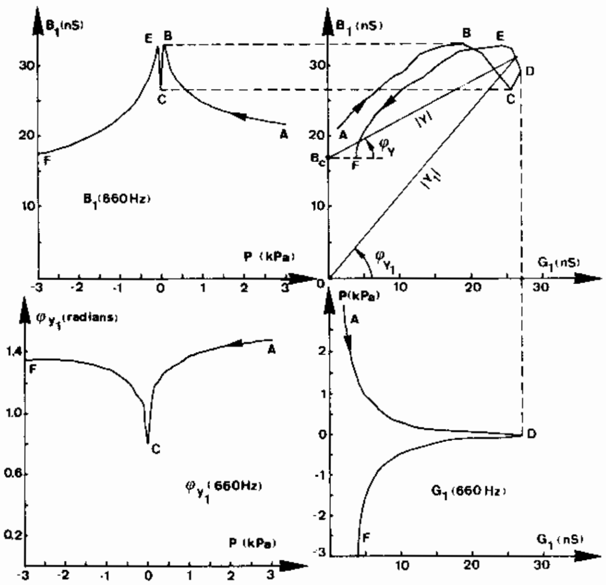


FIGURE 2.13. Phasor curve obtained from the susceptance (B_1) and the conductance (G_1) (1 nS = 0.1 acoustic mmho), recorded simultaneously (660 Hz) as functions of the ear–canal pressure (P). The corresponding susceptance and conductance tympanograms are drawn so that the relationship to the phasor curve is clearly shown. Graphical determination of φ_{Y_1} and approximate graphical determination of φ_Y in the recorded phasor curve are given. The V–shaped phase angle (φ_{Y_1}) tympanogram was computed from the B_1 and G_1 recordings. Subject with normal hearing and normal looking tympanic membrane.

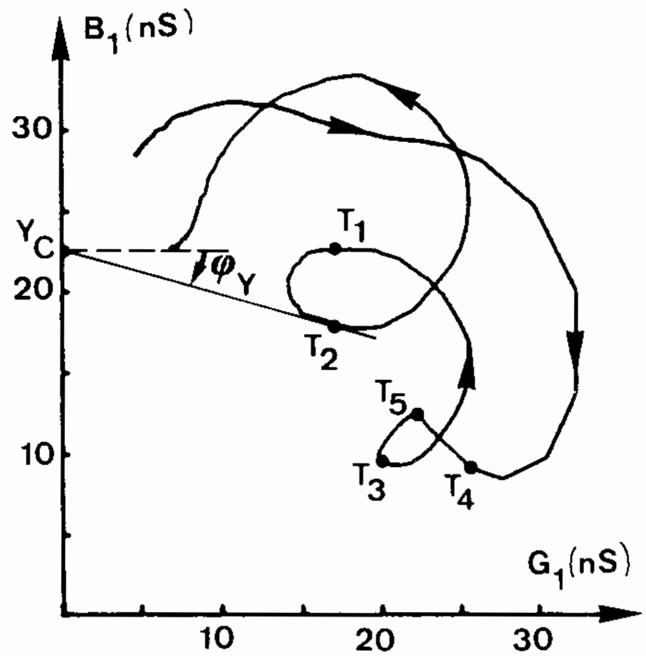


FIGURE 2.15. Example of a phasor trajectory corresponding to irregular 660–Hz tympanograms (1 nS = 0.1 acoustic mmho). The phasor curve displays five tangents $T_1 - T_5$ instead of one.

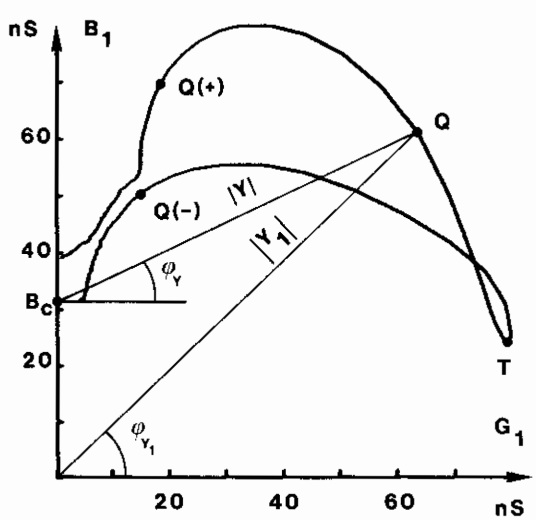


FIGURE 2.14. Example of a phasor trajectory corresponding to a type 3B1G set of 660–Hz susceptance–conductance tympanograms (1 nS = 0.1 acoustic mmho).

An interesting application of phasor tympanometry was suggested by Lutman and his colleagues (Lutman, 1984; Lutman, McKenzie, & Swan, 1984). They recorded phasor plots of the middle–ear admittance both during tympanometry and acoustic reflex activation. Assuming that ear canal air pressure primarily alters the admittance of the part of the eardrum that is not coupled to the ossicular chain, and that the acoustic reflex influences the admittance of the middle–ear transmission system, they proposed a method for distinguishing between eardrum and ossicular anomalies based on phasor tympanograms. The method may be useful in the evaluation of patients with mild disorders of the ossicular system in which the reflex is still sufficiently strong to effect a change in middle–ear admittance.

Parson, Kunov, Abel, and Alberti (1984) recorded impedance phasors as a function of probe frequency. They suggested that by recording phasor characteristics at a single ear–canal air pressure (tympanometric peak pressure) at a variety of frequencies, the resonance properties of the

[10]Grason–Stadler, Model 1720.

middle ear could be readily determined from the shape of the phasor plot. The method may be useful for evaluation of middle–ear function by assessing its resonant frequencies, as suggested by Colletti (1975, 1976, 1977).

2.3.5 The Electrical Phase-Angle

The foregoing discussion suggests that phase–angle tympanograms offer some advantages over the B,G approach. On the other hand, assessment of either φ_y or φ_{y_1} calls for equipment that is often not available in audiology and otology clinics. Because the electrical phase–angle φ_e between the electrical signals presented to the driver (probe signal) and the electrical output of the probe microphone is easily obtainable, the characteristics of this quantity were evaluated (Van Camp et al., 1983). The shape of φ_{y_1} (at the probe tip) and the φ_e tympanogram had remarkably similar shapes even in the small details (see also Section 7.7), but the relationship between φ_{y_1} and φ_e was nonlinear. Because φ_{y_1} and φ_e have similar shapes, the three normal types of (Y,φ_e) tympanograms—1Y1φ, 3Y1φ, and 3Y3φ—are obtained with either the phase angle at the probe or the electrical phase angle. The nonlinearity between φ_{y_1} and φ_e is due to the finite admittance of the probe assembly and is dependent on ear–canal volume. Because for many applications only the shape of the tympanogram is important, φ_e may be a useful tympanometric quantity. A one–component admittance meter and a simple phase–angle meter (see Chapter 4) can provide the capability for simultaneous two–component tympanometry, a tool that may prove very useful in the evaluation of middle–ear disease.

2.4 OTHER TYMPANOMETRIC PATTERNS OBTAINED FROM NORMAL EARS

While the Vanhuyse et al. (1975) model predicts the tympanometric patterns obtained from the vast majority of normal ears, other patterns are occasionally observed. These unusual patterns, which are accounted for by the more elaborate model proposed by Van Camp et al. (1978), result from interactions between acoustic resistance and acoustic reactance. When these two quantities assume

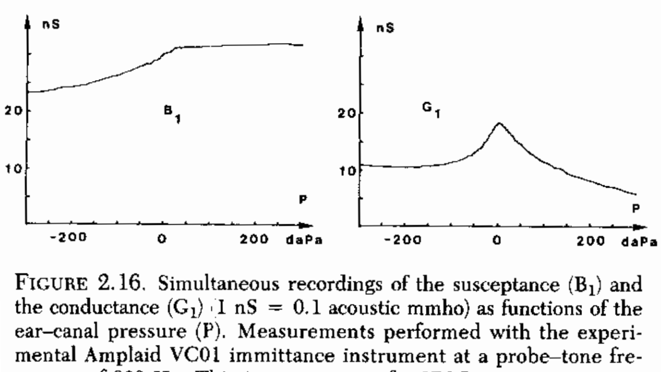


FIGURE 2.16. Simultaneous recordings of the susceptance (B_1) and the conductance (G_1) (1 nS = 0.1 acoustic mmho) as functions of the ear–canal pressure (P). Measurements performed with the experimental Amplaid VC01 immittance instrument at a probe–tone frequency of 860 Hz. This is a rare case of a 0B1G tympanogram recorded on a normal human ear.

similar absolute values, rather subtle aberrations can result in complex conductance, susceptance, and admittance patterns. Examples of these unusual patterns that are occasionally observed in normal ears are 0B1G, 1B2G, and 2Y1φ. When these patterns are observed in normal ears it is usually with probe frequencies above 660 Hz, but they occasionally occur at lower probe frequencies. In one sur-

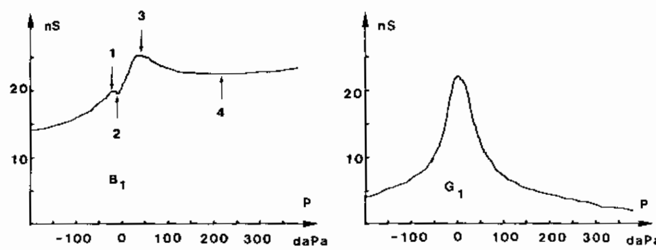


FIGURE 2.17. Simultaneous recordings of the susceptance (B_1) and the conductance (G_1) (1 nS = 0.1 acoustic mmho) as functions of the ear–canal pressure (P). Measurements performed with the experimental Amplaid VC01 immittance instrument at a probe–tone frequency of 710 Hz. This is a rare case of a 4B1G tympanogram recorded on a normal human ear. The extrema are marked.

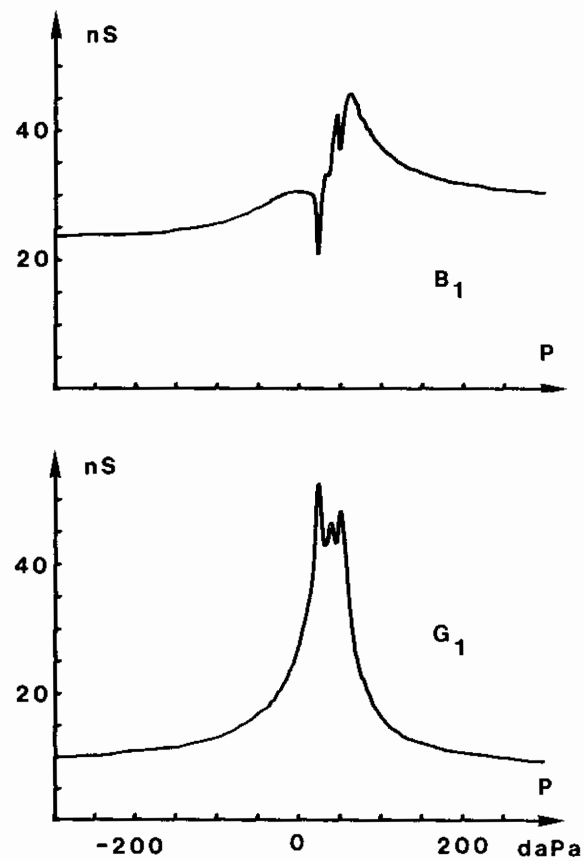


FIGURE 2.18. Example of an irregular set of 660–Hz tympanograms (1 nS = 0.1 acoustic mmho). Although the set does not fit in the Vanhuyse et al. (1975) model, it is not a sign of pathology as the pressure interval between the outer susceptance maxima is less than 75 daPa.

vey of 132 normal ears with a 660–Hz probe frequency (Van de Heyning et al., 1982) none of these patterns were observed. We have, however, occasionally recorded these patterns and they have been reported or predicted in the literature (Alberti & Jerger, 1974; Margolis & Popelka, 1977). In order to determine whether or not these tympanograms fall within the realm of normal patterns, it may be necessary to convert them into resistance and reactance and evaluate them within the guidelines discussed in Section 2.2.

Figure 2.16 presents an example of a 0B1G pattern obtained from a normal ear with an 860–Hz probe. Figure 2.17 is a 4B1G pattern from a normal ear obtained with a 710–Hz probe. These tympanograms were recorded with an experimental immittance device (Amplaid, Model VC01), together with a measurement system that allowed for an analysis of the change in ear–canal volume that resulted from pressurizing the ear canal. In both cases unusually large volume changes occurred that probably account for the unusual tympanometric patterns. The 4B1G pattern in Figure 2.17 probably would have been a normal 3B1G pattern if the ear–canal volume change were not unusually large.

Occasionally abnormal patterns are observed that are not associated with ear disease or hearing loss. The very sharp multipeaked patterns illustrated in Figure 2.18 were recorded from an ear that does not require otologic treatment or audiologic management. The abnormality may have resulted from the unusual exposure to barometric pressure changes that the subject encountered while piloting military aircraft. When the width of the outer extrema of the susceptance tympanogram does not exceed 75 daPa, the pattern is seldom a sign of ear disease that requires further attention.

Chapter 3

Procedural Variables that Influence Tympanometric Values and Shapes

3.1 INTRODUCTION

Tympanometric results are systematically related to a number of procedural variables that influence static immittance and tympanometric shapes. These variables complicate comparisons of results that were obtained with different measurement procedures. Due to the absence of standards, clinical instruments have employed a wide variety of measurement parameters that produce differences in tympanograms that have only recently been studied systematically.

In this chapter the following procedural variables and their effects on tympanometric shapes and static immittance will be discussed: (a) the rate of ear–canal air pressure change (pump speed); (b) the direction of ear–canal air pressure change (pressure direction), negative–to–positive (−/+), or positive–to–negative (+/−); and (c) the number of consecutive tympanometric runs. In addition, the relation between tympanometric peak pressure and middle–ear pressure will be discussed.

3.2 RATE OF EAR–CANAL PRESSURE CHANGE

The rate of ear–canal pressure change (pump speed) can influence the peak values of immittance components. In addition to the effect that pump speed has on the reactance and resistance values at the tympanic membrane, it also affects the shapes of tympanograms. For a given pressure direction, as pump speed is increased, the peak susceptance, conductance, and admittance values for single–peaked tympanograms increase (Creten & Van Camp, 1974; Koebsell & Margolis, 1985). Stated differently, as the pump speed increases, the tympanometrically measured impedance of the middle ear decreases. Although the effect of pump speed on tympanograms has been demonstrated consistently, the cause of this effect is not well understood. It appears, however, that as pump speed increases, the reactance tympanogram shifts toward positive values, thereby increasing the complexity of the tympanometric patterns (see Chapter 2). If at a slow pump speed (e.g., 20 daPa/s), we are in the condition for single–peaked susceptance and conductance tympanograms (1B1G) because $X_0 < -R_0$, then a faster pump–speed (e.g., 60 daPa/s) may shift the reactance tympanogram so that $X_0 > -R_0$, which is the condition that results in a 3B1G tympanogram (Vanhuyse et al., 1975). This effect is illustrated in Figure 3.1. Similarly, an increase in pump speed may transform a 3B1G pattern into a 3B3G, and a 3B3G into a 5B3G. There are important practical advantages to recording with a fast pump speed. In addition to the time saved, a fast pump speed allows the recording of tympanograms from uncooperative subjects who are unable to remain quiet long enough for the completion of a slower recording. Early commercial instruments employed a pump speed in the vicinity of 30 daPa/s. At that speed a tympanogram recorded over a pressure range of −400 to 200 daPa requires 20 s. At 600 daPa/s, the same recording requires 1 s. Even an uncooperative subject can usually be coerced into remaining still for 1 s. At this point there do not appear to be any contraindications to the use of pump speeds in the vicinity of 400 to 600 daPa/s and perhaps higher. The engineering problems associated with accu-

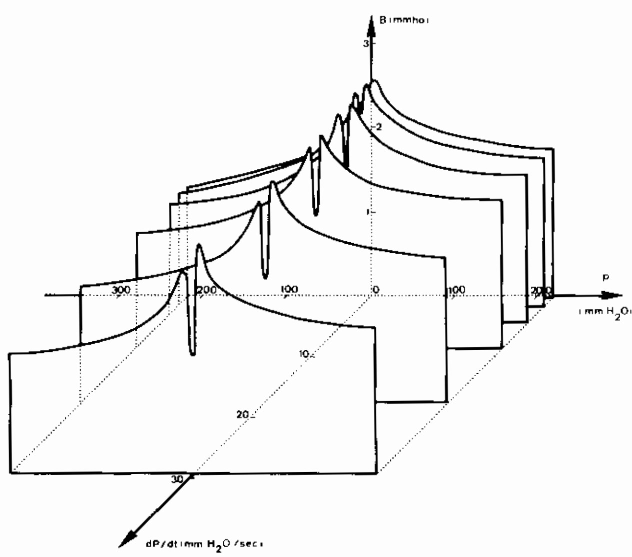


FIGURE 3.1. Three–dimensional representation of 660–Hz susceptance tympanograms recorded at different rates of pressure change on an ear showing a type 3B1G normal W–pattern. From Creten and Van Camp, 1974. Copyright 1974 by Almqvist & Wiksell Periodical Company. Reprinted by permission.

rate recording at these pump speeds appear to be manageable (Ivarsson, Tjernstrom, Bylander, & Bennrup, 1983). Although additional clinical experience and the accumulation of normative data are necessary to optimize the clinical utility of tympanometry at these high speeds, future commercial instruments will probably incorporate these faster pump speeds. The resulting time savings and capability to test uncooperative subjects will enhance the usefulness of tympanometry.

3.3 DIRECTION OF EAR–CANAL PRESSURE CHANGE

The pressure direction, negative–to–positive (−/+) or positive–to–negative (+/−), also affects the shapes and values of tympanograms. For single–peaked tympanograms, recording in the +/− direction usually results in lower admittance (higher impedance) values than the −/+ direction (Creten & Van Camp, 1974, Figure 3; Margolis & Smith, 1977, Table 2; Wilson et al., 1984). The pressure direction also affects the maximum reactance value at the tympanic membrane, and therefore, the shapes of all other immittance tympanograms. This effect, which has been discussed by Alberti and Jerger (1974), Creten and Van Camp (1974), and Van Camp, Creten, Vanpeperstraete, and Van de Heyning (1981), is illustrated in Figure 3.2.

In many cases, the type of tympanogram set becomes more complex when the pressure direction is −/+ in comparison to the +/− direction (Margolis, Osguthorpe, & Popelka, 1978, Figure 1; Margolis & Smith, 1977; Porter & Winston, 1973; Williams, 1976; Wilson et al., 1984), although there are conflicting results (Alberti & Jerger, 1974). The pressure direction used clinically might be dictated by the immittance instrument employed and/or one's desire to obtain the most accurate estimate of ear–canal volume. If an accurate estimate of ear–canal volume is desired, then −/+ is the direction of choice (see Chapter 5). On the other hand, because +/− produces fewer multipeaked tympanograms in normal ears, it may be the preferred direction particularly for high–frequency tympanometry.

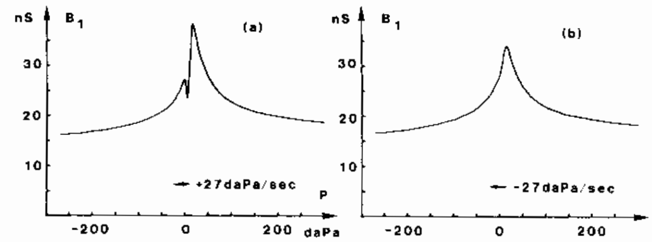


FIGURE 3.2. Susceptance tympanograms (1 nS = 0.1 acoustic mmho) at 660 Hz recorded from the same ear, both at 27 daPa/s, but with opposite directions of ear–canal pressure change: (a) recorded (−/+) and (b) recorded (+/−).

3.4 NUMBER OF TYMPANOMETRIC RUNS

Vanpeperstraete et al. (1979) and Osguthorpe and Lam (1981) noted that consecutive tympanometric runs appear to change the characteristics of tympanograms in two ways. First, the magnitudes of admittance peaks increase with an increase in the number of tympanometric runs. Second, the shapes of tympanograms become more complex with an increased number of runs. As Osguthorpe and Lam demonstrated, a set of tympanograms can evolve from a simple type in the first run to a more complex type in the following runs (e.g., from 1B1G to 3B1G).

This effect is illustrated in Figure 3.3. The acoustic impedance of the ear decreases with consecutive tympanometric runs (Wilson et al., 1984). An analysis of the components of impedance revealed that the effect is primarily due to a shift in acoustic reactance toward positive (mass)

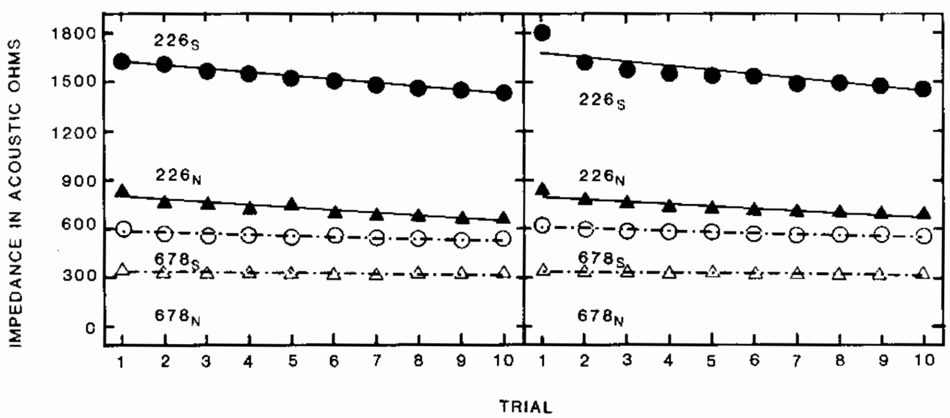


FIGURE 3.3. Acoustic impedance at the tympanic membrane (|Z|) from 8 subjects with single–peaked 660–Hz tympanograms (open symbols and subscript S) and from 8 subjects with notched 660–Hz tympanograms (filled symbols and subscript N) for ten consecutive tympanometric runs. The ten tympanometric recordings were made over a 15 min session during which the probe remained in the ear. The data in the left panel were obtained with the −/+ pressure direction; the data in the right panel were obtained with the +/− direction. All subjects had single–peaked 220–Hz tympanograms. (Based on data from Wilson et al., 1984.)

values. Recall from Chapter 2 that as the reactance tympanogram shifts toward positive values, B,G tympanograms progress from 1B1G to 3B1G to 3B3G to 5B3G. In some cases the shift in reactance resulting from consecutive runs is adequate to change the type of B,G tympanograms. No explanation of this effect has been proposed.

3.5 THE RELATION BETWEEN TYMPANOMETRIC–PEAK PRESSURE AND MIDDLE–EAR PRESSURE

The ear–canal air pressure at which the tympanometric peak occurs (tympanometric–peak pressure) is generally regarded as an indication of the pressure status of the middle ear. The tympanometric–peak pressure has often been misconstrued as a measure of middle–ear pressure. The fact that the tympanometric–peak pressure is not equal to the middle–ear pressure is clearly indicated by a number of observations. For example, tympanometric peaks for different, simultaneously recorded, immittance quantities often occur at different ear–canal pressures. Direction and rate of ear–canal pressure change are known to influence the tympanometric–peak pressure, while the middle–ear pressure remains constant. Although tympanometry can, within limits, provide an assessment of middle–ear pressure status, tympanometric–peak pressure is not a perfect measure of middle–ear pressure for at least four reasons.

3.5.1 Instrumental Lag

When the transducer, measuring the change of pressure in the ear canal, is not located in or at least very near the ear canal, an hysteresis effect may occur resulting in a lag between the actual ear–canal pressure and the measured ear–canal pressure. When the pressure transducer is coupled to the ear canal by a tube, the viscosity of air can cause a pressure difference at either end of the tube. The longer and narrower the tube, the greater the pressure difference. If the pressure transducer is situated between the pump and the ear probe, the difference between the measured and the actual ear–canal pressure is positive for the (−/+) pressure direction and vice versa. The shift is proportional to the rate of pressure change and to the volume of the ear canal. The proposed international standard for acoustic immittance instruments requires that for the more complete instruments this shift should not exceed 10 daPa or 10%, whichever is greater, for cavities up to 5 cm^3.

3.5.2 Ear "Hysteresis"

A shift in tympanometric–peak pressure that is related to the direction of pressure change in the ear canal has been observed in normal human subjects (Beattie & Leamy, 1975) and in chinchillas (Woodford, Henderson, Hamernik, & Feldman, 1975). This effect, which is of the order of 20 daPa, is similar in direction to the instrumental lag described in Section 3.5.1. The peak is shifted toward positive pressure when the ear–canal pressure is swept from negative–to–positive, and is shifted toward negative pressure when the ear–canal pressure is swept from positive–to–negative. Although this effect is not well understood, it appears to be related to the viscoelastic properties of the tympanic membrane and middle–ear structures (Decraemer, Creten, & Van Camp, 1984).

3.5.3 Asymmetrical Acoustic Resistance

Moller (1965) initially reported the asymmetrical behavior of the acoustic resistance tympanogram in cats (see Chapter 2). Similar observations have been made for human subjects (Lidén et al., 1977; Margolis & Popelka, 1977; Van Camp et al., 1978). This asymmetry differentially influences the tympanometric–peak pressures for other acoustic quantities. For example, the peak of the normal susceptance tympanogram usually is displaced toward positive pressures relative to the peak of the conductance tympanogram. It is primarily due to the asymmetry of acoustic resistance that peaks of simultaneously recorded immittance quantities occur at different ear–canal pressures (see also Section 2.3.2).

3.5.4 Middle–Ear Volume Change

Another source of disparity between tympanometric–peak pressure and middle–ear pressure results from the change in middle–ear pressure that results from eardrum displacements during tympanometry. This effect was described quite early in the development of clinical acoustic–immittance measurement (e.g., Flisberg, Ingelstedt, & Örtegren, 1963; Zollner, 1942), but has been largely overlooked in the literature relating tympanometric results to middle–ear function. It is interesting that the first investigators to study middle–ear function tympanometrically used the peak of the tympanogram to indicate pressure equality between the middle ear and the ear canal rather than as a measure of middle–ear pressure (Terkildsen & Thomsen, 1959; Thomsen, 1958, 1960).

The term middle–ear pressure properly refers to the pressure in the middle–ear space that exists when the ear–canal pressure is ambient. When a tympanometric probe is inserted into the ear canal and pressure changes are effected, the resulting eardrum displacement creates a pressure change in the middle ear. A negative ear–canal pressure will cause an outward displacement of the tympanic membrane resulting in a decreased (negative) middle–ear pressure relative to the ambient ear–canal condition. Assuming that the effects described in the previous sections are negligible, the peak of the tympanogram occurs when pressure equality exists between the ear canal and the middle ear (Terkildsen & Thomsen, 1959). The ear–canal pressure that produces pressure equality will be more negative than a pre–existing negative middle–ear pressure, and more positive than a pre–existing positive middle–ear pressure. That is, the absolute value of tympanometric–peak pressure always overestimates middle–ear pressure. This effect has been observed by several investigators (Eliachar & Northern, 1974; Ingelstedt & Jonson, 1967; Renvall & Holmquist, 1976; Renvall & Lidén, 1978).

The magnitude of this overestimation is related to the properties of the tympanic membrane and the middle ear. The greater the eardrum displacement, the greater the difference will be between the tympanometric–peak pressure and the middle–ear pressure. Similarly, smaller middle–ear spaces will produce larger peak pressure differences because the eardrum displacement constitutes a larger proportion of the middle–ear volume. Renvall and Holmquist (1976) measured differences between tympanometric–peak pressure and manometrically measured middle–ear pressures in human temporal bones. When the middle–ear pressure was −100 daPa, the tympanometric–peak pressures varied among their specimens between −110 and −170 daPa. Similar differences existed for positive middle–ear pressures. Eliachar and Northern (1974) measured differences between middle–ear pressures induced in a pressure chamber and tympanometric–peak pressures in normal human subjects that did not exceed 30 daPa. However, as Flisberg et al. (1963) noted, the difference between tympanometric–peak pressure and middle–ear pressure is likely to be the greatest in patients with eardrum and middle–ear abnormalities. Edema of the middle–ear tissues can result in a reduced middle–ear volume, increasing the effect of eardrum displacement on middle–ear pressure. Monomeric tympanic membranes may be displaced to a greater extent by ear–canal pressure changes again resulting in greater middle–ear pressure changes.

Tympanometric–peak pressure, then, should be interpreted with caution. The same peak pressure may reflect different middle–ear pressures for two individuals. Conversely, the same middle–ear pressures may produce different tympanometric–peak pressures. Although negative tympanometric–peak pressure indicates a negative middle–ear pressure, the two quantities are not equivalent, nor predictable, one from the other. For these reasons, the term *tympanometric–peak pressure* should be used to describe the position of the peak of the tympanogram.

Chapter 4

Design Principles of Acoustic–Immittance Instruments

4.1 INTRODUCTION

Commercial acoustic–immittance instruments include a wide variety of devices that measure some acoustic immittance quantity in the ear canal. As tympanometry began to be widely incorporated into the audiologic and otologic evaluations, instrument manufacturers developed a variety of instruments to meet various clinical and commercial objectives. The design of these instruments determined the measurement parameters with which clinical acoustic immittance data would be obtained, and thus, had an important influence on research and clinical experience with tympanometry.

Terkildsen and Scott–Nielsen (1960) described an instrument that was the electroacoustic equivalent of the Metz (1946) acoustic bridge.[11] Since then, a variety of laboratory and commercial instruments have been developed that measure different quantities, expressed in different units. Even the same quantities (e.g., ear–canal air pressure) have been expressed in different units by different instrument manufacturers. In this chapter, the design principles of the major classes of acoustic immittance instruments are discussed.

4.2 GENERAL SCHEME FOR TYMPANOMETRIC INSTRUMENTS

Instruments used for tympanometry measure the acoustic immittance of the ear by presenting a sinusoidal probe tone to the sealed ear canal[12] and by measuring the resulting sound pressure with a miniature microphone. The output of the probe microphone is processed electronically to produce a measurement of either acoustic impedance or acoustic admittance. The measurement is usually recorded on a hard–copy recording device and displayed on a meter located on the front panel of the instrument. Acoustic immittance is measured as a function of ear–canal air pressure, varied by an air pump that is coupled to the ear by a tube. A block diagram of the general scheme for tympanometric devices is shown in Figure 4.1. In this chapter we will discuss the basic design principles for clinical acoustic–immittance instruments.

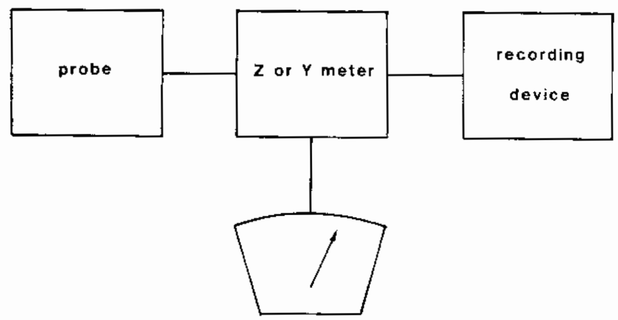


FIGURE 4.1. General scheme for an acoustic immittance meter.

4.3 THE PROBE

In Section 1.2 we developed the concept of acoustic impedance as the ratio of the pressure to the volume velocity. That is,

$$|Z| = p_o/U_o. \quad (4.1)$$

From Equation 4.1 it is evident that if we produce a constant peak volume velocity (U_o), the resulting peak sound pressure (p_o) will be proportional to the acoustic impedance at the probe tip. The probe, therefore, consists of devices that produce a volume velocity and that measure the resulting sound pressure. A miniature loudspeaker, referred to throughout this work as the driver, contains a diaphragm that sets the air into motion. That is, the driver creates a volume velocity. A microphone in the probe transduces the sound pressure into a proportional electrical voltage that is displayed on a panel meter and/or recording device. The driver and microphone, then, by creating a volume velocity and measuring the resulting sound pressure, provide the basis for acoustic–immittance measurements. These transducers, along with a tube that delivers air pressure from the pump, are coupled to the ear canal by soft "probe tips" of various sizes and shapes that hermetically seal the probe assembly to the ear.

[11]Because of the historical relation to acoustic bridges, electoacoustic impedance instruments have often been erroneously referred to as "bridges."

[12]The sound–pressure level of the probe is, ideally, high enough to produce an adequate signal–to–noise ratio, but below the threshold of the ipsilateral acoustic reflex.

Because the sound pressure is proportional to the acoustic impedance only if the volume velocity is constant (see Equation 4.1), then it is desirable for the probe to be a constant volume–velocity source. That is, the volume velocity at the probe tip should be independent of the "load," in this case, the acoustic impedance of the ear. A constant volume–velocity source is achieved by coupling the transducers and the air pump to the ear by narrow tubes.[13] The amplitude of the probe microphone voltage (V_m), then, is an electrical quantity that is proportional to the acoustic impedance at the probe tip. The relation between V_m and p_o should be linear over a range of impedance values that represents the distribution of normal ears. The linearity of the microphone is determined by measuring V_m for known acoustic loads, which are provided by small calibration cavities (these are discussed in Section 4.9).

Figure 4.2 illustrates an impedance probe that is designed to produce a constant volume velocity in the ear canal. The insert shows calibration data obtained by measuring the microphone voltage (V_m) as a function of the volume of various calibration cavities. The linearity of V_m as a function of volume indicates that the probe is a constant volume–velocity source over a range of volumes from 0.5 cm³ to 2.0 cm³. The equivalent volume at the plane of the probe tip in human ears is virtually always within this range, so that linearity of V_m over this range of calibration volumes is adequate for clinical acoustic–immittance measurements.

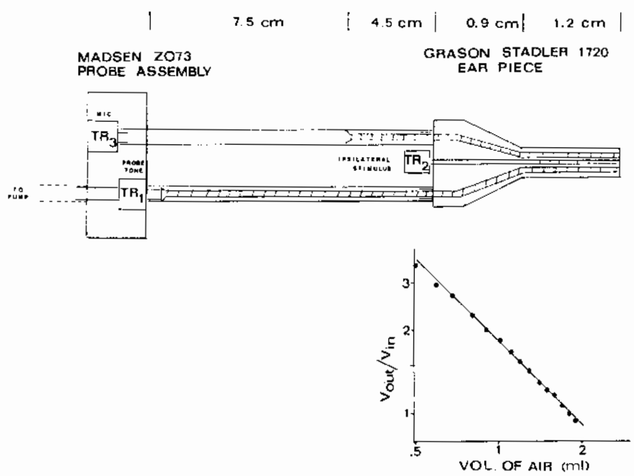


FIGURE 4.2. Example of an impedance probe designed to produce a constant volume velocity in the ear canal. The probe can be considered a constant volume velocity source if the relation between V_{out}/V_{in} and the volume of the calibration cavity is linear with a slope of 1.0.

[13]Stated differently, the output impedance of the probe tone delivery channel, and the input impedance to the microphone channel and the air pump must be much higher than the load impedance—the impedance at the distal end of the sealed ear canal. The high impedance of the driver channel ensures that the volume velocity delivered to the ear canal will be constant. The high impedances of the microphone and air pressure channels ensure that the coupling tubes will not contribute to the acoustic impedance measured at the probe tip.

4.4 THE IMPEDANCE METER

Because a constant volume–velocity source produces a peak voltage that is directly proportional to the impedance at the probe tip, the development of an impedance measuring device is rather straightforward. Typically, the microphone signal is rectified and filtered to convert it from an ac voltage to a proportional dc voltage V_m[14] and presented to a meter that displays the magnitude V_m. This simple design, which is depicted in Figure 4.3a, is complicated by the following. Because the probe is a constant volume–velocity source and the voltage from the probe microphone (V_m) is proportional to the impedance magnitude at the probe tip, the probe sound pressure depends on the impedance of the subject's ear. This means that the probe sound–pressure level at which tympanometric measures are made would differ for each subject, if compensation were not made for intersubject differences in impedance. It is usually thought desirable to make tympanometric measures with the same sound–pressure level for each ear (although it would be equally appropriate to keep the volume velocity the same for each ear). Instruments that employ the impedance meter approach, utilize an additional step to keep the probe sound pressure constant for each subject. This step is accomplished by a balance meter, that is shown in Figure 4.3b.

The balance meter compares the rectified microphone signal (V_m) with an internally–generated reference voltage (V_{ref}) (calibrated to represent the desired probe sound pressure) and produces a voltage (V_b) that is displayed on a

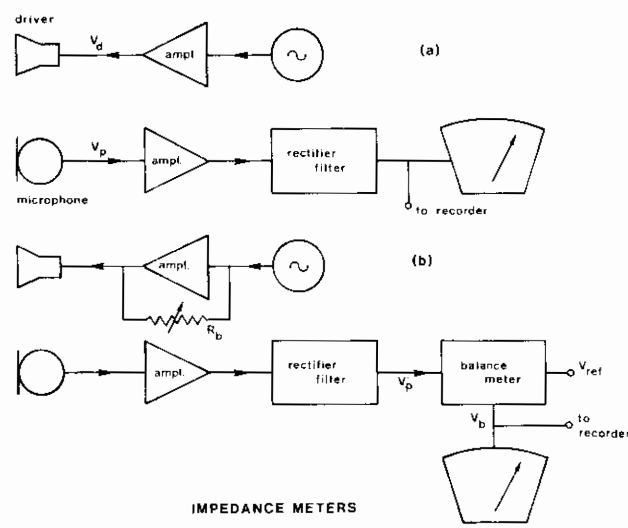


FIGURE 4.3. Block diagram of impedance meters. Design without (a) and with (b) a balance meter that compares the rectified microphone signal with the reference voltage.

[14]Alternating current (ac) is periodic or aperiodic and has positive and negative values. In contrast, direct current (dc) has either positive or negative values and is time invariant. Throughout Chapter 4, small v will denote the time–varying amplitude of an ac sinusoidal signal. Capital V will denote the peak amplitude of an ac signal or the amplitude of a dc signal.

meter and delivered to the recording device. When $V_m = V_{ref}$, the sound pressure is the desired value specified in the instrument manual and the balance meter produces a voltage (V_b) that corresponds to a meter reading of zero. When $V_m \neq V_{ref}$, the sound pressure differs from the intended value and the balance meter produces a voltage corresponding to a meter reading that is not zero, thereby indicating that the sound pressure is not the specified value. The output of the balance meter is nonlinearly related to the impedance at the probe.

The method for automatic tympanometric recording with these impedance instruments is as follows. With the ear–canal pressure set to a high positive or negative value, the meter is offset so that the needle is conveniently placed, usually at the extreme left. This is accomplished by changing the gain of the driver amplifier by adjusting a resistor (R_b) (see Figure 4.3b). Then V_b is measured as a function of ear–canal air pressure. As the ear–canal air pressure is changed, the impedance of the ear is altered and the instrument indicates a new value of V_b.[15] This change in V_b with ear–canal pressure, however, is nonlinearly related to the impedance change and thus a tympanogram is produced that cannot be expressed in physical units. For this reason, tympanograms produced with these instruments are presented in arbitrary units sometimes referred to as compliance units. Because for a probe tone of 220 Hz, the phase angle for a human middle–ear system is close to that of a pure compliant reactance (e.g., an enclosed volume of air) the quantity measured by these early instruments was erroneously referred to as *compliance,* a term that continues to be misused on a number of clinical acoustic–immittance instruments. This compliance, if not expressed in arbitrary units, is often expressed in cubic centimeters of air, which leads to an additional source of error. Immittance can be expressed as an equivalent volume of air only if appropriate corrections are applied for differences in atmospheric conditions that exist at various locations. These corrections were usually not employed and most instruction manuals did not describe the appropriate calibration procedures. The admittance, expressed in equivalent volume, of a normal ear measured in Antwerp, Belgium (5 m above sea level) and the admittance of the same ear measured in Santa Fe, New Mexico (2,138 m above sea level) differ by 18% (Lilly & Shanks, 1981) unless they are corrected for atmospheric conditions (see Section 4.9.1).

If the impedance measuring instruments employed the simpler approach depicted in Figure 4.3a, then impedance tympanograms could be produced that are plotted in linear physical units (e.g., acoustic ohms). This simple approach also would allow the measurement of the impedance phase angle. However, because no commercial instrument manufacturers have chosen to do so, and the principle of impedance phase–angle (φ_{z_1}) measurement is the same as the measurement of admittance phase angle (φ_{y_1}), we will delay the discussion of phase–angle measurements until the next section.

[15]An alternative procedure is a point–by–point tympanogram, in which the balance meter is rebalanced at each pressure point. This procedure is discussed in Section 4.5.

4.5 THE ADMITTANCE METER

In Section 1.3 we derived the definition of acoustic admittance:

$$|Y| = U_o/p_o. \tag{4.2}$$

From this equation it is evident that if the peak sound pressure (p_o) is constant, then the peak volume velocity (U_o) is directly proportional to the admittance at the probe tip. As U_o is directly proportional to the rectified driver signal (V_d), this quantity is displayed on a meter as a measure of the admittance at the tip of the probe (see Figure 4.4). Keeping p_o constant can be accomplished by the use of an automatic gain control (AGC) circuit[16] that controls the voltage applied to the driver. This approach is depicted in Figure 4.4.

The AGC circuit is a feedback loop between the probe microphone and the amplifier that provides the signal to the driver. When the sound pressure in the ear–canal changes, creating a change in the sinusoidal microphone voltage (v_m), the AGC adjusts the gain of the driver amplifier to compensate for the change in sound pressure. The driver voltage is adjusted continuously by the AGC so that the ear–canal sound pressure (and v_d) are maintained at a constant level. Because these adjustments require some time to be made, the response time of the AGC circuit

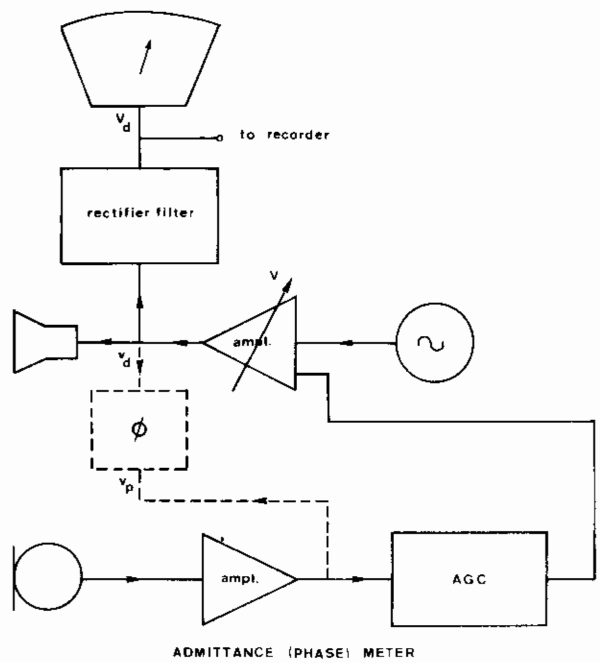


FIGURE 4.4. Block diagram of an admittance meter. The AGC circuit is used to keep the microphone voltage at a constant level. A possible phase–angle meter is included in dotted lines.

[16]Also referred to as automatic volume control (AVC).

must be sufficiently fast to "follow" changes in ear-canal sound pressure that result from air pressure changes during tympanometry and from middle-ear muscle contraction during acoustic-reflex testing. Inadequate temporal characteristics of the AGC result in distortions of tympanometric shapes and acoustic-reflex responses (Creten et al., 1978, Figure 4; Van Camp & Creten, 1975).

Adjustment of the balance meter in Figure 4.3b is very similar to the function of the AGC in Figure 4.4. In fact, a "point-by-point" admittance tympanogram can be recorded with the impedance meter in Figure 4.3b by rebalancing the instrument at each ear-canal air pressure. The AGC, then, simply represents an automatic adjustment of the balance meter in Figure 4.3b.

4.6 THE ADMITTANCE-PHASE METER

Although there is no commercially available admittance-phase meter in current production, the design is identical to the admittance meter depicted in Figure 4.4 with the addition of a phase meter (shown in dotted lines). The phase meter is a device that compares waveforms presented to its two inputs. If the inputs are sinusoidal with the same frequency, then a measure of the time delay between zero-axis crossings can be easily converted into a measure of the phase difference between the two sinusoidal input signals. Thus, the phase meter in Figure 4.4 measures the phase difference between v_d and v_m.

The principle of the admittance-phase meter is as follows. The phase angle between the volume velocity and the sound-pressure waveforms in a calibration cavity is always 90° (see Section 1.5.2). On the other hand, the electrical phase angle between v_d and v_m may not be 90° because of phase shifts imposed by the transducers and the coupling tubes. Because these effects are constant for an ideal driver-microphone combination, the phase difference between v_d and v_m could be used to infer the acoustic-admittance phase angle at the probe tip (φ_{y_1}) (see also Section 2.3.4).

For a realistic driver-microphone combination, however, a nonlinearity in the φ_{y_1}, φ_e relation is introduced, due to the phase shift that results from the finite probe admittance. As this nonlinearity depends on the residual ear-canal volume admittance, the phase differences between tails and tops of the tympanograms can not be determined with reasonable accuracy from φ_e recordings. Nevertheless, shapes of φ_{y_1} and φ_e tympanograms proved to be similar, even for minor irregularities, so that the diagnostic value for both kinds of phase-angle tympanograms are identical (see Figure 7.7 at 660 Hz).

4.7 THE CONDUCTANCE-SUSCEPTANCE METER

The admittance-phase meter produces a measure of admittance in polar form. In contrast, the conductance-susceptance meter provides equivalent information in rectangular form. A block diagram of this type of immittance device is provided in Figure 4.5.

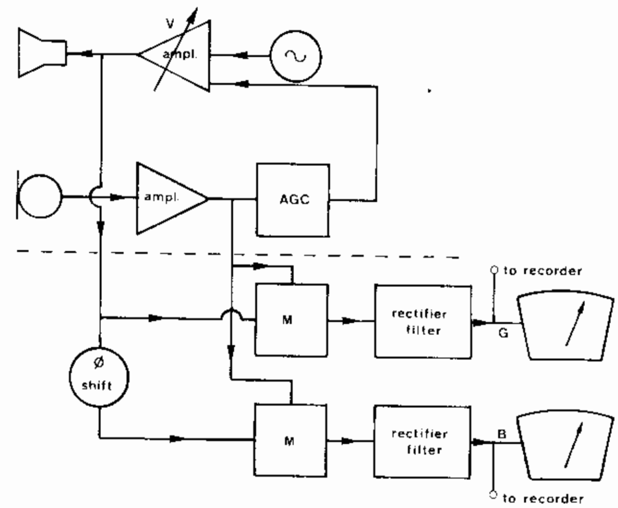


FIGURE 4.5. Block diagram of a susceptance-conductance meter.

The system employs an AGC circuit that keeps the sound pressure output of the probe constant, just as in the admittance meter. Instead of analyzing the magnitude and phase of v_m and v_d, however, the two signals are analyzed to produce an in-phase component and a 90° out-of-phase (quadrature) component (after compensation of acoustical phase shift due to the coupling tubes in the probe). Separation of the signal into the in-phase (or real) component and quadrature (or imaginary) component is accomplished by special electronic circuits called multipliers. In order to understand the principle of the device schematized in Figure 4.5, we must understand the analysis of a sinusoidal signal into its in-phase and quadrature components.

The driver signal (v_d) and the microphone signal (v_m) are sinusoidal voltages of the same frequency that differ in amplitude and phase. In order to describe the relation between these signals, the driver signal that is proportional to Y_1, the admittance at the probe tip can be analyzed into two sinusoidal components, one that is in-phase with the microphone signal and one that is 90° out-of-phase. This is illustrated in Figure 4.6, in which v_m and v_d are shown as two sinusoidal waveforms of the same frequency with a phase difference ($\varphi_{d,m}$) existing between the two sinusoids. In the figure v_d is analyzed into two components, $v_d(0°)$ and $v_d(90°)$, representing that part of v_d that is in-phase with v_m and that part that is 90° out-of-phase.

If the phase of v_d and v_m were identical, then v_d could be represented by an in-phase component with an amplitude of $V_d \propto G_1$ and an out-of-phase component with an amplitude of zero ($B_1 = 0$). Conversely, if v_d and v_m had a phase difference of 90°, then v_d could be analyzed into an in-phase component with an amplitude of zero ($G_1 = 0$) and an out-of-phase component with an amplitude of $V_d \propto B_1$. Phase differences between 0° and 90° produce amplitude values for the two components that are between zero and V_d.

If v_m and v_d are presented to the inputs of a multiplier, then the result is a signal with an amplitude that is propor-

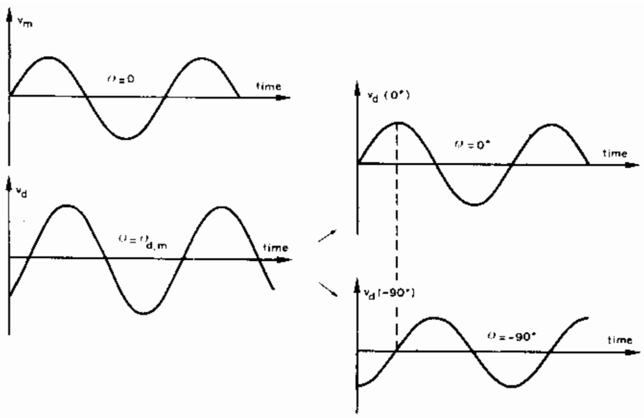


FIGURE 4.6. Driver and microphone signals in a susceptance–conductance meter. In–phase and out–of–phase components of the driver signal related to the acoustic susceptance and acoustic conductance.

tional to G_1 and to the component of v_d that is in–phase with v_m. If a 90° phase shift were inserted between v_d (or v_m) and the multiplier input, then the output is a signal with an amplitude that is proportional to B_1 and thus to the 90° out–of–phase component of v_d. Accordingly, the device schematized in Figure 4.5 produces two signals, one proportional to the in–phase component (G_1) and one proportional to the quadrature component B_1.[17]

The device depicted in Figure 4.5 provides susceptance and conductance outputs simultaneously, which is similar to the Grason–Stadler, Model 1720. With that instrument it is possible to present the B and G outputs to the inputs of an X–Y recorder and obtain a phasor tympanogram (see Section 2.3.4). Unfortunately, the currently–produced (B,G) meter (Grason–Stadler, Model 1723) does not allow for simultaneous recording of conductance and susceptance because only one multiplier is used with a phase shifter that is switched in or out. Thus, phasor tympanometry is not possible with currently–produced instruments.

4.8 INSTRUMENTS WITH NON–SINUSOIDAL PROBE SIGNALS

Recently, efforts have been undertaken to obtain impedance information for a broad spectrum of probe tone frequencies in a short measuring time and a minimal burden for the patient.

Stirneman (1980, 1981) constructed an impedance meter with a noise probe signal. Through the use of filters and computational support, he was able to assess tympanograms with probe tone frequencies between 200 and 6000 Hz in a single run. Arslan, Canavesio, and Cerutti (1979) used a click as probe signal. Mathematically, one can treat a click as an infinite sum of continuous sinusoidal signals with an infinitely broad spectrum of frequencies through the use of Fourier transforms. This mathematical technique can be programmed in a computer to analyze the responses picked up by the microphone in the probe. This again results in multifrequency information (100 to 1000 Hz) in a single run.

4.9 CALIBRATION PROCEDURES

The calibration of nearly all immittance components can be performed by means of hard–walled calibration cavities. Calibration cavities are small air–filled enclosures that can be hermetically coupled to the probe. Because the impedance of a small enclosed volume of air (< ≈5 cm^3) can be calculated, a calibration cavity provides an accurate and inexpensive physical reference. Calibration cavities are usually supplied by manufacturers of acoustic–immittance devices. Alternatively, they can be fabricated from plexiglas or similar materials. Variable syringes modified to accept the impedance probe also can be adapted for use as a variable calibration cavity. Examples of these cavities are shown in Figure 4.7.

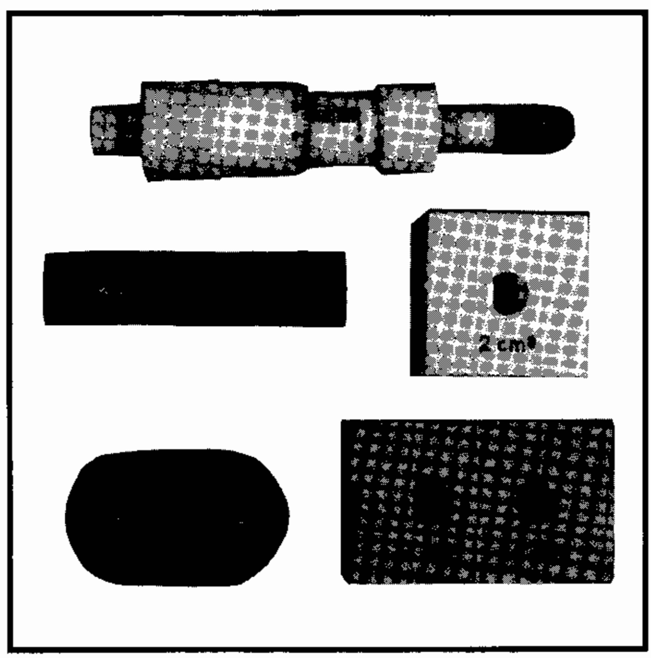


FIGURE 4.7. Examples of calibration cavities for immittance audiometers.

4.9.1 Calibration at Low Probe–Tone Frequencies

At low probe frequencies (e.g., 220 Hz), the acoustic immittance of a small enclosed volume of air (< ≈5 cm^3) can be determined precisely by knowing only the volume of the cavity and the atmospheric conditions at the meas-

[17]Before the two components can be accurately converted into the conductance and susceptance of the ear, the electrical phase angle φ_e between v_m and v_d must be converted to the acoustical phase angle at the probe tip. This is usually accomplished by a two–step electrical calibration, with one adjustment (a phase shift) introduced before rectification and a second adjustment (a dc shift) made after rectification of v_d. Because the final step is after rectification, a simple phase meter cannot accurately estimate φ_{y1}.

urement site. The acoustic impedance of an enclosed volume of air is given by Equation 1.26

$$|Z| = \rho c^2/2\pi f V \qquad \varphi_z = -90°$$

or Equation 1.27

$$B = 2\pi f V/\rho c^2 \qquad G = 0$$

where ρ is the density of air (grams/cm³), c is the velocity of sound (cm/s), f is the frequency (Hz), and V is the volume of the enclosure (in cm³). The susceptance B is then obtained in cgs mhos. When reference atmospheric conditions[18] are entered in Equation 1.26, one obtains

$$c^2/2\pi = 226{,}059 \text{ g/cm s}^2; \tag{4.3}$$

then Equation 2.11 can be simplified as follows:

$$|Z| = 226{,}059/fV \qquad \varphi_z = -90° \tag{4.4}$$

or

$$B = fV/226{,}059 \qquad G = 0. \tag{4.5}$$

At standard atmospheric conditions, then, a volume of 1 cm³ of air has an acoustic–impedance magnitude of 1,000 cgs acoustic ohms or an acoustic–admittance magnitude of 1 cgs acoustic mmho at 226 Hz. Due to this simple relationship between the 226–Hz frequency and the immittance of enclosed volumes, 226 Hz is preferred over 220 Hz for low–frequency tympanometry. If laboratory or clinic conditions differ from reference conditions, then a correction must be applied to determine the acoustic impedance of a calibration cavity.

4.9.2 Corrections for True Atmospheric Conditions

The sound velocity (c) and the density of air (ρ) (see Equation 2.11) are dependent on the true atmospheric conditions of the location. Sound velocity (c) varies with temperature and with the water vapor content in the air. Ignoring the relative humidity effect, the velocity of sound in air is (Beranek, 1954)

$$c = 33{,}145\,(T/273.15)^{1/2} \quad \text{cm/s} \tag{4.6}$$

where T is the temperature in degrees Kelvin. The density of air is

$$\rho = \rho_o\,(T/T_o)\,(P/P_o) \tag{4.7}$$

where ρ_o = the standard density of air (0.0012929 g/cm³),
T_o = 273.15° K(elvin),
P_o = standard atmospheric pressure (any units), and
P = true atmospheric pressure (same units as P_o).

[18]Values of reference atmospheric conditions suggested by Lilly and Shanks (1981) are ρ = 0.001204693 gm/cm³, which corresponds to a temperature of 20°C and an atmospheric air pressure of 760 mmHg (1.013 × 10⁴ daPa).

The true atmospheric pressure at the location should be measured with a barometer not corrected to sea level. For example if the atmospheric pressure corrected to sea level is 760 mmHg (or 1,013.25 mbar), the true atmospheric pressure at a location 2,200 m above sea level would be 577.12 mmHg. If only a corrected barometer is available, the standard true atmospheric pressure can be computed from:

$$P = 10^{[(53012.2 - h)/18401.8]} \text{ mmHg} \tag{4.8}$$

or

$$P = 1.333 \times 10^{[(53012.2 - h)/18401.8]} \text{ mbar} \tag{4.9}$$

where h is expressed in meters above sea level (1 mbar = 100 Pa). A table for conversion from atmospheric pressure at sea level to true atmospheric pressure at various altitudes is given by Lilly and Shanks (1981).

4.9.3 Calibration at Higher Probe–Tone Frequencies

At higher probe–tone frequencies the impedance of a calibration cavity is dependent on the dimensions of the cavity as well as on its volume. The following equation, actually a more general form of Equation 1.26, expresses the admittance (in polar form) of a cylindrical air–filled cavity (Beranek, 1954):

$$Y = j\,\frac{\pi R^2}{\rho c}\,\tan(2\pi f l/c) \tag{4.10}$$

or equivalently, in rectangular form

$$B = \frac{\pi R^2}{\rho c}\,\tan(2\pi f l/c) \qquad G = 0 \tag{4.11}$$

where R is the radius (in cm) of the circular cross section, l (in cm) is the length of the cylindrical cavity and B is the susceptance of the cavity in cgs mho.

If the dimensions of the cavity fall within certain limits, the length and the radius of the cylinder need not be considered in determining the acoustic impedance of the cavity. For small values of $2\pi f l/c$, one finds that $\tan(2\pi f l/c) \approx 2\pi f l/c$, so that $\pi R^2 l = V$. This means that Equation 4.11 is then equivalent to Equation 1.26. It is possible to compute an upper limit of the length (l) for which the simple Equation 2.11 is still acceptable. If one allows an underestimation of 3% for a probe–tone frequency of 660 Hz, this upper limit for the length of a cylindrical cavity proves to be 2.5 cm. At high probe–tone frequencies, one must also take into account that some distance is needed before the sound out of the probe becomes a plane acoustical wave. Otherwise stated, it takes some distance before the sound has spread out and fills the cavity. This effect, described by Mawardi (1949), puts an upper limit to the radius (R) of the cavities used. In order to use Equation 4.10 for a probe–tone frequency of 660 Hz, the ratio l/R must at least be $l/R > 2$.

Chapter 5

Determination of the Immittance at the Tympanic Membrane

5.1 INTRODUCTION

The clinical utility of the quantitative measurement of the acoustic immittance at the tympanic membrane (static immittance) has not been widely accepted. This may be due to inadequate normative data and a lack of standard measurement procedures. The estimation of static immittance requires an accurate procedure for correcting the measured immittance for the volume of air between the measurement plane (the probe tip) and the tympanic membrane. In this chapter, the principles of static-immittance measurement are discussed and a procedure is recommended.

5.2 THE EAR CANAL AS AN ACOUSTICAL PARALLEL ELEMENT

The immittance measured by a probe inserted into the ear canal is determined by the complex combination of all the acoustical elements that comprise the ear. One of these elements is the volume of air that occupies the ear canal between the probe tip and the tympanic membrane. This air volume is determined by a number of factors that are not related to the status of the middle ear. These include the depth of insertion of the probe tip, the dimensions of the canal, and the amount of air displaced by cerumen and other material. Ideally, an acoustic–immittance measure would relate to the status of the middle ear, and be unaffected by these clinically irrelevant variables. The immittance of the middle ear can be estimated by converting the immittance at the probe to the immittance at the tympanic membrane. This conversion can be made by employing the simplifying assumption that the ear canal represents an acoustical parallel element.

Recall from Section 1.6.1 that elements upon which the same sound pressure acts are said to be configured in parallel. If the same sound pressure exists at the probe tip and at the tympanic membrane, then the ear canal can be approximated as an element that is in parallel with the middle ear. Intuitively, we would expect the sound pressure for low frequency tones to be identical at the probe and at the tympanic membrane because of the dimensions involved. The distance from the probe tip to the eardrum is typically about 1.5 cm. The wavelength of a 226–Hz tone in air is 1.52 m and 0.51 m at 678 Hz. Because the length of the ear canal is small compared to the wavelength of the probe tone, the pressure cannot vary substantially along the length of the canal. The higher the frequency, the greater the pressure changes with distance from the source.

Empirical support for our intuitive expectation is evident in Figure 5.1 from Shaw (1974). The difference in sound pressure level at the eardrum and at the entrance to the ear canal is less than 1.0 dB for frequencies below 1000 Hz.

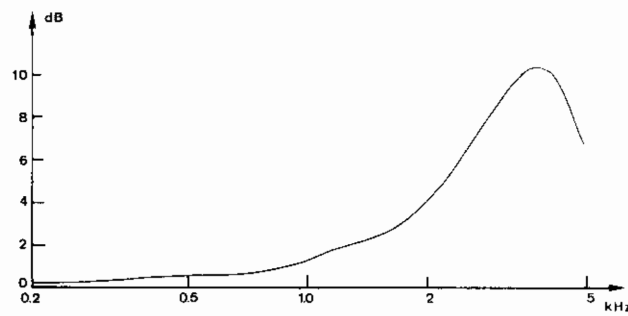


FIGURE 5.1. Ratio of sound pressures at the eardrum and at the entrance to the ear canal in dB. From Shaw, 1974. Copyright 1974 by the Acoustical Society of America. Adapted by permission.

If the ear canal is in parallel with the middle ear, the sound pressure at the two locations must be identical not only in magnitude but also in phase. The dimensions involved similarly lead us to expect very little phase difference along the length of the ear canal for low frequencies. The phase difference at two locations in a medium is determined by the ratio of the distance between measuring points and the wavelength. That is

$$\varphi = 360°\frac{d}{\lambda} \tag{5.1}$$

where φ is the phase difference in degrees, d is the distance between measuring points, and λ is the wavelength of the sound. In our case d is the distance between the probe tip of probe and the drum. Since wavelength (λ) is the ratio of velocity to frequency, v/f, and taking an average value for d of 1.5 cm, Equation 5.1 can be rewritten

$$\varphi \text{ (in degrees)} = 0.0158 f. \tag{5.2}$$

From Equation 5.1 it is evident that if the distance is a small proportion of the wavelength, the phase difference will be small. The phase difference between the probe and the eardrum is typically about 16° for a 1000–Hz probe tone, and diminishes as frequency decreases (Equation 5.2).

Another observation that supports the assumption that the ear canal and middle ear are parallel elements at low probe–tone frequencies is related to the magnitude of the impedance at the probe tip. If the ear canal and middle ear were series elements, then the impedance at the probe tip would be greater than that of either individual element.[19] The impedance measured at the probe tip in normal ears, however, is less than the impedance of either the ear canal or the middle ear measured separately, a relationship that exists for elements configured in parallel.

In conclusion one can say that the ear canal and middle ear can be approximated as acoustical parallel elements for frequencies below 1000 Hz.

5.3 THE IMMITTANCE OF THE EAR CANAL

The anatomy of the external ear suggests that the ear canal, sealed by the measuring probe, can be treated acoustically as an enclosed volume of air. In Chapter 1 we noted that if the length of the enclosed space is not too long relative to its cross–sectional area, then the impedance of an enclosed volume of air can be determined by Equation 1.26

$$|Z| = \rho c^2/2\pi f V \qquad \text{and} \qquad \varphi_z = -90°,$$

or equivalently by Equation 1.29

$$B = 2\pi f V/\rho c^2 \qquad \text{and} \qquad G = 0$$

where ρ is the density of air, c is the velocity of sound, f is the probe tone frequency, and V is the volume of the enclosure. Above 1000 Hz the ear canal is no longer an acoustical parallel element to the middle ear and Equations 1.26 and 1.29 are certainly no longer valid. For further exploration of the problem, the reader is referred to textbooks on fundamental acoustics such as Kinsler and Frey (1962) and Beranek (1954) or to Rabinowitz (1981). There is a small amount of friction resulting in a minor sound absorption by the hairs and the cerumen in the ear canal, leading to a conductance $G_c \neq 0$, but the approximation of the ear canal as a frictionless, compliant element is not unreasonable. Excessive cerumen, however, has a definite influence, leading to high conductance tail values (Feldman, 1976, p. 145). For further discussion of the immittance of enclosed spaces and the application to the ear canal the reader is referred to Beranek (1954), Lilly and Shanks (1981), Margolis and Smith (1977), Moller (1960, 1972), and Shanks and Lilly (1981).

Early procedures for measuring middle–ear immittance employed a direct measurement of ear–canal volume by filling the canal with alcohol from a calibrated syringe. The volume of alcohol required to fill the canal was assumed to be equivalent to the air volume between the probe and eardrum. It should be noted, however, that this measurement provides only one value for the volume near ambient pressure, whereas the volume is certainly not constant during a tympanometric run. This direct volume measurement procedure was used in conjunction with Equation 1.26 or 1.29 to determine the immittance of the ear canal (Burke, Nilges, & Henry, 1970; Feldman, 1967; Shanks & Lilly, 1981; Tillman, Dallos, & Kuruvilla, 1964; Zwislocki, 1957b; Zwislocki & Feldman, 1963). While this procedure gives accurate ear–canal volume estimates, it is not feasible for routine clinical measurement. Consequently, an indirect method is used in which the ear–canal volume is estimated from immittance measurements.

If our assumption is correct that the ear canal and middle ear are parallel elements, then the ear–canal immittance can be measured directly only if the middle–ear impedance is infinitely high. Stated differently, if the tympanic membrane were a rigid wall, then the immittance at the probe would result exclusively from the air enclosed in the ear canal. This principle would allow the estimation of ear–canal immittance from the tympanogram.

The effect of pressurizing the ear canal with either positive or negative pressure is to stiffen the eardrum so that it approaches the condition of a rigid wall. It is clear that the middle–ear impedance is not infinitely high when the ear canal is pressurized during tympanometry because the probe tone is clearly audible even with the highest ear–canal pressures used. Rabinowitz (1981) estimated that on the average the sound transmission was reduced only by 16.4 dB at an ear–canal pressure of ± 400 daPa. A high ear–canal pressure, therefore, cannot block the middle–ear system completely and a residual drum admittance [Y(+)] at extreme positive and a residual drum admittance [Y(−)] at extreme negative pressure must be taken into account. Without knowledge of either Y(+) or Y(−), the tail value of an admittance tympanogram cannot be used as a precise estimate of the residual ear–canal admittance: the tail value of a tympanogram will always overestimate the real ear–canal admittance. From the attenuation of the sound level heard by the patient between zero and an extreme negative pressure difference across the eardrum, Rabinowitz (1981) computed that below 630 Hz

$$B(-) = 0.28\,B(0) \qquad \text{and} \qquad G(-) = 0, \quad (5.3)$$

where B(−) and G(−) are the residual eardrum susceptance and conductance at −400 daPa and B(0) is the susceptance at a zero pressure difference across the drum.

This estimate is high in comparison with the direct estimates of Shanks and Lilly (1981). By comparing the immittance measurements at extreme negative ear–canal pressure (−400 daPa) with direct volume measurements using alcohol also pressurized to −400 daPa they found the following average relations between B(−) and the tail values at negative pressure B_c:

[19]This is true only if the impedance phase angle of the two elements are similar.

$$B(-) \approx 0.09\ B_c \qquad \text{at 220 Hz} \qquad (5.4)$$

and

$$B(-) \approx 0.03\ B_c \qquad \text{at 660 Hz.} \qquad (5.5)$$

The middle–ear impedance corrected tympanometrically thus always overestimates the impedance corrected by direct volume measurement. From the same experiments, Shanks and Lilly found that the estimations of B(+) always exceeded the B(−) values, so that ear–canal immittances measured at the positive pressure side produced a greater overestimate of the real value.

Vanpeperstraete et al. (1979) provided an indirect estimate of B(−) at 220 and 660 Hz. By measuring simultaneously the susceptance at the probe tip B_1 and the volume change of the residual ear canal during a tympanometric run, they found that the asymmetry of susceptance tympanograms cannot be fully explained by ear–canal volume changes alone and, on the average, a B(−) of 3 to 4 nS (see Section 1.7.3) must be introduced at 660 Hz in order to obtain a meaningful (positive) residual drum susceptance at +400 daPa. At 220 Hz a value of 1.5 nS was necessary. Three potential sources of the volume change are eardrum movement, distension of the ear–canal walls, and probe movement. This effect is large in infants (Margolis & Popelka, 1975) and smaller in adults (Margolis & Smith, 1977; Vanpeperstraete et al., 1979).

In conclusion one can say that the value of the residual eardrum immittance is still controversial and is probably strongly different from subject to subject. The residual eardrum conductance G(−) was always estimated to be zero. This estimation, however, is more a postulate incorporated in calibration techniques of immittance instruments than the result of a direct measurement. For clinical purposes a practical solution to the problem is given in the following section.

5.4 CALCULATION OF THE IMMITTANCE AT THE TYMPANIC MEMBRANE

In the previous sections we developed the two principles that will allow the tympanometric determination of the acoustic immittance at the eardrum. They are: (a) that the ear canal and middle ear represent acoustical parallel elements, and (b) that the immittance measured by the probe when the ear canal is pressurized is a reasonable estimate of the immittance of the air between the probe tip and the eardrum. However, before these principles can be used to calculate the immittance at the eardrum we must make two decisions. They are: (a) Which value of ear–canal pressure should be used to determine the ear–canal immittance? and (b) Which value of ear–canal pressure should be used to determine the immittance at the tympanic membrane?

The optimal ear–canal pressure for estimating the ear–canal immittance would be that pressure that results in the highest middle–ear impedance. Because the acoustic resistance of the middle ear is normally higher for negative than for positive pressure, the highest middle–ear impedance almost always occurs when the ear–canal pressure is negative (at −400 daPa or more) (Margolis & Smith, 1977; Moller, 1965; Shanks & Lilly, 1981; Vanpeperstraete et al., 1979). This is confirmed by the fact that B(−) is smaller than B(+) as stated in Section 5.3. Exceptionally, however, positive pressure may result in the highest middle–ear impedance. The minimum value of the susceptance tympanogram (usually at −400 daPa) and the minimum value of the conductance tympanogram are the best estimates of the ear–canal contribution.

Due to the dynamic nature of the gas exchange between the middle ear and the external environment, the pressure behind the eardrum is always changing. (See Elner, Ingelstedt, & Ivarsson, 1971a,b, and other papers from that laboratory for detailed analyses of the dynamics of the middle ear.) Terkildsen and Thomsen (1959) pointed out that for probe–tone frequencies of 220 Hz, the peak of the tympanogram occurs when the pressure on either side of the tympanic membrane is the same, that is, the pressure difference is zero. For higher probe tones in which multi-peaked tympanograms occurs, the Vanhuyse et al. (1975) model suggests that the central extremum of all immittance components (except resistance) is situated near zero pressure difference across the drum. While minor deviations do occur (Decraemer et al., 1984), it is a reasonable approximation. Just as the characteristics of a physical system should be determined under specifiable conditions (e.g., with a specified input and with the proper load), the measurement of the input immittance of the ear best reflects the nature of the system under test if the measurements are made under standard conditions. The condition of zero pressure difference across the tympanic membrane is one that is easily specifiable and represents a realistic condition for assessing the transmission characteristics of the ear.

Others have suggested that determination of the immittance at ambient ear–canal pressure is preferred because it represents the "use" condition of the ear (see, for example, Wiley & Block, 1979). On a purely practical level, it has been shown that immittance values computed in this manner are so variable that their clinical usefulness is compromised. The determination of the immittance at the tympanic membrane should be done with zero pressure difference across the drum, thus, at the pressure for which the central extrema of the tympanograms occur.

Because the ear canal and middle ear can be approximated as a parallel combination, the rules governing the combination of parallel elements (developed in Chapter 1) can be used to estimate the middle–ear immittance. Recall that the conductances of parallel elements combine by simple addition (Equation 1.41). Similarly, the susceptances of parallel elements combine by simple addition (Equation 1.44). Thus, we can express the conductance at the probe G_1 as

$$G_1 = G + G_c \qquad \text{or} \qquad G = G_1 - G_c \qquad (5.6)$$

where G_c is the conductance of the ear canal and G is the conductance of the middle ear. The susceptance at the probe (B_1) is

$$B_1 = B + B_c \quad \text{or} \quad B = B_1 - B_c \qquad (5.7)$$

where B_c is the susceptance of the ear canal and B is the middle-ear susceptance. The conductance and susceptance of the middle ear, therefore, are defined by Equations 5.6 and 5.7 where G_1 and B_1 are central extrema on the tympanograms (at 220 Hz the maximum value) and G_c and B_c are the minimum tail values. This method is referred to as the MAX/MIN method, first suggested by Margolis and Popelka (1975). For research purposes a more elaborate method, taking into account ear-canal volume changes, was developed by Vanpeperstraete et al. (1979).

Equations 5.6 and 5.7 can be employed only if conductance and susceptance tympanograms are recorded separately, but simultaneously. Most instruments record the magnitude of admittance. The MAX/MIN procedure applied to the admittance tympanogram yields

$$Y = Y_1 - Y_c \qquad (5.8)$$

where Y is the admittance of the middle ear, Y_1 is the maximum admittance at the probe, and Y_c is the minimum tail value. However, Equation 5.8 will provide an accurate estimate of middle-ear admittance only if the phase angle of the middle-ear admittance and the phase angle of the ear-canal admittance are identical. As these phase angles become more disparate, Equation 5.8 produces more erroneous estimates. For normal ears these phase angles are sufficiently similar at 226 Hz that the MAX/MIN method provides a reasonable estimate of middle-ear admittance. At 678 Hz, however, the MAX/MIN method results in errors of about 20% for normal ears, an unacceptably large error, which becomes even greater for ears with low impedance abnormalities. Thus, a one-component, high-frequency immittance instrument does not allow accurate determination of middle-ear immittance.

For impedance tympanograms, the calculation of middle-ear immittance is more complicated. Because there are no commercially available, two-component impedance meters, the calculation of resistance and reactance at the eardrum will not be discussed here. However, we can express the impedance equivalent to Equation 5.8:

$$Z = \frac{Z_c Z_1}{Z_c - Z_1} \qquad (5.9)$$

where Z is the impedance at the eardrum, Z_c is the maximum tail value, and Z_1 is the minimum (peak) value. Just as Equation 5.8 is inaccurate when the phase angles of the ear-canal and middle-ear impedances are unequal, Equations 5.9 is subject to the same constraint. It provides a reasonable estimate of middle-ear impedance at 226 Hz but not at 678 Hz. Equation 5.9 was used to estimate middle-ear impedance with several early immittance devices (see Jerger, 1970; Jerger & Northern, 1979; Terkildsen & Scott-Nielsen, 1960).

Chapter 6

Normative Static Acoustic Immittance

6.1 INTRODUCTION

The term static acoustic immittance is used to denote the measurement of some immittance quantity at a specified probe frequency and ear–canal air pressure, corrected for ear–canal volume. Usually the measurement is made with the ear–canal air pressure that produces maximum admittance (tympanometric peak pressure). Except for some early measurements made with the Zwislocki acoustic bridge, these measurements are not really static in that they are usually taken from tympanograms that are recorded under dynamic pressure conditions. Recent evidence that the details of the pressure change (e.g., rate and direction) influence the results, underscores the importance of distinguishing truly static measurements, those made during fixed conditions of air pressure and probe frequency, from dynamic measurements, made under continuously changing measurement conditions. Since both the American National Standard for Aural Acoustic–Immittance Instruments (ANSI S3–60, Draft A, 1984) and the International Electrotechnical Commission standard on Instruments for the Measurement of Aural Acoustic Impedance/Admittance (1985) define static immittance as ear–canal–compensated tympanometric measurements, the term is likely to remain in use. However, it is important to recognize that they are not truly static measures and that the effects of the details of the dynamic measurement conditions are substantial. The effect of rate of pressure change, for example, is sufficiently large that separate norms for various pump speeds are necessary. In this chapter we will discuss the diagnostic potential of static–immittance values, review the procedural variables that affect the computation of static immittance, propose guidelines for obtaining static values, and present normative data.

6.2 DIAGNOSTIC USE OF STATIC ACOUSTIC IMMITTANCE

Due to the lack of norms, the diagnostic value of static measurements has not been thoroughly investigated. The evaluation of tympanometric shapes is widely used in preference to static measurements for determining the presence or absence of middle–ear pathology. It seems likely that, given appropriate norms, quantitative static measurements might increase the sensitivity of tympanometry for detecting some pathological conditions. This is especially likely with a 226–Hz probe frequency, where there is less variation in tympanometric shapes among various middle–ear conditions.

Otosclerosis is a case in point. Evaluation of tympanometric shapes led Jerger, Anthony, Jerger, and Mauldin (1974) to conclude that tympanograms are normal in otosclerotic patients. Zwislocki (1957a), on the other hand, found distinctly different acoustic reactance values in otosclerotic subjects compared to normal subjects. Margolis et al. (1978) reported that while tympanograms from cats with experimentally produced stapedial fixation were qualitatively normal, quantitative measurements produced nonoverlapping distributions of acoustic–immittance values.

The most widely used probe frequency, 226 Hz, is particularly well suited to the estimation of static immittance for the following reasons. First, at that frequency there is relatively little variation in tympanometric shapes. Virtually all normal ears (except neonate ears) and the vast majority of abnormal ears produce single–peaked tympanograms. This homogeneous distribution of tympanometric shapes allows for a simple method of ear–canal correction that can be applied to all tympanograms. Second, since most currently used instruments are admittance meters, the correction for ear–canal volume is more accurate at 226 Hz than at higher frequencies where a phase shift occurs as a result of ear–canal pressure changes. This phase shift introduces an error in ear–canal volume estimation by the subtraction of vector quantities. Third, tympanometric asymmetry is minimal at low frequencies making the static measurement relatively independent of the ear–canal pressure at which the ear–canal volume is estimated. This is important because some instruments perform the ear–canal compensation automatically, employing a method that deviates from the one recommended in this chapter. We recommend the use of static immittance measurements when a 226–Hz probe tone is used, and pattern recognition when higher probe tones are used.

6.3 VARIABLES THAT AFFECT STATIC ACOUSTIC IMMITTANCE

Although the quantification of static acoustic immittance facilitates a direct comparison of immittance measurements obtained in different clinics and is useful in the differential diagnosis of some middle–ear disorders, this quantification also necessitates greater measurement precision with frequent calibration, attention for correction for altitude, and careful correction for the effect of ear–canal volume.

Static acoustic–impedance measurements made with the Zwislocki acoustic bridge are made at ambient ear–canal air pressure and are corrected to the plane of the tympanic membrane by means of a direct measurement of ear–canal volume. With the exception of the Zwislocki instrument and systems that employ point–by–point tympanometric measurements (e.g., Madsen ZO–70) true static measurements are rarely performed. Instead static immittance is usually calculated from dynamically recorded tympanograms. The changing air pressure during automatic tympanometry introduces several procedural variables that are known to affect the height and/or shape of the tympanogram, and therefore, also affect static immittance (see Chapter 3). The following procedural variables must be specified if static data are to be compared among individuals and clinics.

First, the method used to correct for ear–canal volume must be specified. The MAX/MIN procedure (see Section 5.4) produces lower acoustic impedance estimates and more accurate ear–canal corrections than other methods that have been used for correcting for ear–canal volume. Vanpeperstraete et al. (1979) proposed a more precise method but the method is complex, requires computational support, and is therefore clinically impractical.

Second, the ear–canal pressure at which the static measurement is made must be specified. Tympanometric peak pressure and ambient pressure have been used for calculating static immittance. Wilson et al. (1984) reported that mean static admittance |Y| at 226 Hz was 23% lower at ambient pressure compared to tympanometric peak pressure in normal subjects. At 660 Hz the difference was 19%. Similar findings were reported by Porter and Winston (1973), Margolis and Popelka (1975), and Shanks and Lilly (1981). The large difference occurs despite very small differences in the ear–canal pressures at which the two types of measurements were made. The steep slope of the normal tympanogram in the vicinity of the peak results in large differences between ambient and peak measurements.

Third, the tympanometric quantities from which the static measurements were calculated must be specified. The peaks in admittance, susceptance, and conductance do not occur at the same ear–canal pressures even when the tympanograms are recorded simultaneously. As discussed in Section 2.3.2, peak susceptance generally occurs at a more positive pressure than peak conductance in single–peaked (1B1G) tympanograms, particularly when recorded from negative to positive pressures. For 3B1G tympanograms, the reverse is generally found. Static admittance (Y) can be calculated either using peak conductance and susceptance values (different ear–canal pressures), or at the ear–canal pressure corresponding to peak conductance or susceptance, or at the ear–canal pressure corresponding to peak admittance. Wilson et al. (1984) reported that admittance (Y) is 2% higher at 226 Hz and 5% higher at 678 Hz when calculated from peak conductance and peak susceptance compared to peak admittance.

Fourth, the direction of ear–canal pressure changes also has a significant effect on the magnitude of static admittance. Wilson et al. (1984) reported that the magnitude of admittance was 8% higher at 226 Hz and 10% higher at 678 Hz in the increasing (− to +) direction compared to the decreasing (+ to −) direction. This trend, however, was not invariant among individual subjects or among various tympanometric quantities. Margolis and Smith (1977) found higher 220–Hz and 660–Hz conductance values but lower 660–Hz susceptance values for increasing pressures and no significant direction effect at 226 Hz. Creten and Van Camp (1974) reported higher admittance values for increasing versus decreasing pressure changes (see also Section 3.3).

Fifth, the rate of ear–canal pressure change also has a significant effect on static admittance. Creten and Van Camp (1974) reported as much as a 50% decrease in tympanometric peak amplitude when the pressure rate was decreased from 30 daPa/s to 1 daPa/s. Notching of high frequency tympanograms also decreases when the pressure rate is reduced (Alberti & Jerger, 1974; Creten & Van Camp, 1974; Feldman, 1976; Van Camp, Raman, & Creten, 1976). In a study of normal 3– to 5–year–old children, Koebsell and Margolis (1985) found that the median static admittance at 226 Hz was 19% higher at 200 daPa/s compared to 50 daPa/s. This effect is probably related to nonlinear visco–elastic properties of the tympanic membrane that result in lower impedance values with increasing velocity. (See also Section 3.2.)

Sixth, recent experiments (see Section 3.4) have demonstrated that static admittance changes with successive tympanometric recordings (Osguthorpe & Lam, 1981; Wilson et al. 1984). Wilson et al. calculated static admittance for successive tympanometric runs. Admittance increased by 18% from Trial 1 to Trial 10 at 226 Hz and 10% at 678 Hz. The increase in admittance was slightly greater for decreasing pressure changes than for increasing pressures.

Seventh, normative static acoustic immittance values vary among subject groups. Some data indicate that acoustic immittance varies with sex and age. For example, Zwislocki and Feldman (1970) and Jerger, Jerger, and Mauldin (1972) reported higher compliance values for men than for women. Sex differences in static immittance are probably not large enough to warrant different norms for men and women. Age differences, however, are probably not negligible. Jerger et al. (1972) reported that compliance was highest in the 30– to 40–year age group compared to younger and older subjects. Several other investigators reported lower conductance and susceptance values (higher impedance) in children than adults (e.g., Margolis & Popelka, 1975; Porter, 1972). The suggested norms for children in Table 6.1 reflect substantially higher static impedance in 3– to 5–year old children compared to adults.

Eighth, static values differ considerably depending on whether or not subjects with notched tympanograms are

TABLE 6.1. Recommended admittance and impedance norms. Normative values are presented for a 226–Hz probe frequency for admittance magnitude |Y| in the impedance magnitude |Z|. [The units are cgs acoustic mmhos (|Y| and cgs acoustic ohms |Z|) given in Table 1.4.] Under standard barometric conditions the admittance magnitude units are equivalent to volume units (cm^3) and the impedance units are equivalent to cgs acoustic ohms. The norms for children were obtained from 3– to 6–year–old audiometrically and otoscopically normal children (Koebsell & Margolis, 1985). The adult norms for the slow pump speed (≤ 50 daPa/s) were obtained from adult subjects (mean age = 25.6 years) with a pump speed of 25 daPa/s (Wilson et al., 1984). The fast pump speed values for adults were calculated from the slow speed data assuming that the effect of pump speed is proportionately the same for children and adults.

		Pump speed			
		≤ 50 daPa/s		*200 daPa/s*	
		|Y|	|Z|	|Y|	|Z|
Children (3–5 yrs)	Lower limit	0.35	1100	0.40	970
	Median	0.53	1900	0.63	1600
	Upper limit	0.90	2900	1.03	2500
Adults	Lower limit	0.50	570	0.57	500
	Median	0.91	1100	1.08	925
	Upper limit	1.75	2000	2.00	1750

included in the sample. It is now clear that a significant proportion of normal subjects have notched tympanograms at 678 Hz (Van de Heyning, 1981). Experiments that eliminated these subjects from the normal sample (e.g., Chalmers & Knight, 1981; Margolis & Smith, 1977) obtained artifactually high–impedance values by eliminating the low end of the distribution of normal impedances. Because of the difficulty in calculating static immittance from notched tympanograms and the error associated with estimating ear–canal volume from admittance tympanograms obtained at high probe frequencies, we recommend the clinical use of static immittance norms only in conjunction with a low probe frequency (226 Hz).

6.4 GUIDELINES FOR CALCULATING STATIC ACOUSTIC IMMITTANCE

Based on available data and clinical efficiency, the following guidelines are suggested for calculating static acoustic immittance from tympanograms.

First, ear–canal volume should be estimated with the ear canal pressurized to a value that results in the minimum tail value. In some cases pressures as high as −400 daPa are necessary. In other cases the minimum occurs at much lower pressures. In most cases the minimum occurs on the negative pressure side of the tympanogram but when the minimum occurs on the positive pressure side that value should be used for the ear–canal correction (MAX/MIN method).

Second, static values should be calculated at the peak (MAX) of the tympanogram rather than at ambient pressure in order to reduce inter– and intra-subject variability and to provide a stable base against which to compare later measurements.

Third, either direction of pressure change can be used for a low probe frequency (226 Hz) but at higher frequencies (e.g., 678 Hz) the descending (+/−) direction should be used to minimize the occurrence of multipeaked tympanograms in normal ears.

Fourth, for two component instruments the components should be recorded simultaneously. If this is not possible, the components should be recorded with the same pressure direction and pump speed.

6.5 NORMAL STATIC ACOUSTIC IMMITTANCE VALUES

Although there have been many studies that have reported normal acoustic–immittance values, the widely disparate measurement procedures do not allow the compilation of those data into a set of norms. Consequently, the recommended normative values in Table 6.1 are based on limited data from studies that used a 226–Hz probe frequency and obtained values in accordance with the guidelines outlined previously. Normative data on large groups of subjects are badly needed. These studies should obtain normative data with the procedures outlined in this chapter for various age groups and pump speeds.

The recommended norms for children were obtained from admittance tympanograms recorded at two pump speeds (50 and 200 daPa/s) from 3– to 6–year–old children who passed audiometric and otoscopic screening (Koebsell & Margolis, 1985). The upper and lower limits represent the 90% range. The adult values at the slow pump speed (denoted ≤ 50 daPa/s) were obtained from tympanograms recorded at 25 daPa/s with a two–component admittance meter (Wilson et al., 1984). The 200 daPa/s values for adults were estimated by adjusting the slow pump speed values by proportions calculated from the data obtained from children.

Chapter 7

Low-Impedance Pathological Ears

7.1 INTRODUCTION

Two classes of pathological conditions result in abnormally low aural acoustic impedance: interruption of the ossicular chain, and eardrum abnormalities. Both types can be caused by disease, trauma, and surgical procedures. In general, these middle–ear conditions produce a wider variety of tympanometric shapes than those associated with normal middle ears and with high–impedance abnormalities. These tympanometric shapes are systematically related to the pathology of the ear, to probe frequency, and to the immittance component that is measured. Schemes for classifying tympanometric shapes are very useful for distinguishing between normal and low–impedance middle ears.

7.2 OSSICULAR CHAIN PATHOLOGY

The long process of the incus and incudo–stapedial joint represent the weakest link in the ossicular chain. Lesions related to mechanical, nutritional, and embryologic etiologies all tend to affect this region of the middle–ear transmission system (Andersen, Jepsen, & Ratjen, 1962). Elbrønd (1970) and Schuknecht (1974) described several factors that lead to necrosis of the long process of the incus. These are summarized in Table 7.1. Most frequently incus necrosis is associated with middle–ear infection and results from decalcification due to acid hydrolytic enzyme activity (Thomsen, Bretlau, Jorgensen, & Kristensen, 1974; Thomsen, Bretlau, & Kristensen, 1975). This process of bony rarefaction results in the following successive stages of deterioration:

1. partial bone resorption without affecting ossicular continuity;
2. partial ossicular discontinuity characterized by a fibrous band connecting the incus superstructure to the stapes (Terkildsen, 1976); and
3. complete ossicular interruption.

These stages of incus degeneration can be experimentally induced by the application of a few drops of 1 N HCl to the incudo–stapedial joint of a temporal bone specimen (Van de Heyning et al., 1982). Tympanograms recorded at successive intervals following acid application demonstrate the effects of ossicular degeneration on the input immittance of the ear. Similarly, experimentally produced traumatic middle–ear lesions produce systematically abnormal tympanometric patterns (Jerger, Mauldin, & Igarashi, 1978; Margolis et al., 1978; Van de Heyning et al., 1982). Otosurgical procedures such as stapedectomy (for otosclerosis) and incudectomy (for translabyrinthine VIII nerve surgery) also result in abnormally low–impedance tympanograms. Lidén et al. (1977) pointed out the utility of tympanometry for assessing the status of surgical reconstructions of the middle ear.

TABLE 7.1. Etiologies of the necrosis of the long process of the incus.

inflammation and infection
cholesteatoma
congenital deformities
trauma
aseptic bone necrosis
radionecrosis
iatrogenic defect

7.3 EARDRUM PATHOLOGY

Chronic middle–ear pathology can lead to a variety of eardrum abnormalities. Areas of normal tissue can coexist with areas of scar tissue and/or tympanosclerosis. These lesions result in high eardrum impedance. Healed perforations, on the other hand, may leave areas that are unsupported by the fibrous connective tissue layer that normally separates the external epidermis from the medial mucosa. These monomeres or atrophic scars are abnormally compliant and result in low acoustic impedance at the eardrum (Chesnutt, Stream, Love, & McLarey, 1975; Feldman, 1974; Feldman, 1976, p. 137). The variety of eardrum lesions that can occur produces a wide variety of tympanometric patterns that can reflect normal, low–impedance, or high–impedance middle–ear systems. In this chapter we will consider those tympanometric patterns that reflect abnormally low–impedance middle ears.

Another eardrum pathology that results from middle–ear disease is myringostapediopexia, fixation of the eardrum to the incudo–stapedial joint (Schuknecht, 1974).

The tympanometric characteristics produced by this lesion seem to be determined by the mechanical properties of the incudo–stapedial joint itself (Van de Heyning et al., 1982).

Although the effects of surgical alterations of the tympanic membrane have not received much experimental attention, clinical observations and some experimental data (Margolis et al., 1978) suggest that healed perforations resulting from a variety of surgical procedures (e.g., myringotomy, implanted tympanic membranes, and tympano–ossicular homograph) are characterized by normal tympanograms.

7.4 TYMPANOGRAMS ASSOCIATED WITH LOW IMPEDANCE: LOW PROBE FREQUENCIES

The tympanometric manifestations of abnormalities that result in low impedance at the eardrum differ at different probe frequencies. At the conventional low probe frequency (220 or 226 Hz) the typical effect of monomeres and ossicular interruptions is an increase in the height of the tympanometric peak. Susceptance and conductance tympanograms remain in the 1B1G category with increased amplitudes. Admittance tympanograms similarly remain single peaked with elevated peak amplitudes. These tympanometric patterns are classified as Type A_D in the Jerger (1970) classification system. As recorded on several commercial instruments, these tympanograms are scaled in such a way that the tympanometric peaks are off the scale of the tympanogram form (see, e.g., Jerger & Northern, 1979). Figure 7.1 is an example of a Type A_D tympanogram recorded from a patient with ossicular discontinuity.

Differentiation of normal and abnormal tympanograms that are characterized by the same tympanometric shape is difficult without quantitative analysis. Qualitative judgment of the normality or abnormality of the height of a tympanometric peak is, an unnecessarily imprecise clinical method. At low probe frequencies at which tympanometric determination of the immittance at the tympanic membrane is reasonably accurate, quantitative measurement can be quite helpful in detecting abnormalities.

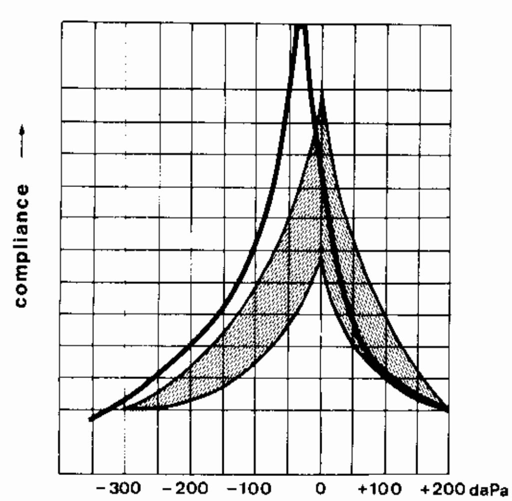


FIGURE 7.1. Typical 220–Hz probe–tone admittance tympanogram for an ossicular chain disruption. Recorder and meter go "off scale" near ambient pressure.

The value of quantitative measurement for detection of low impedance with a low probe frequency was demonstrated experimentally in a study of tympanometric effects of middle-ear lesions in cats (Margolis et al., 1978). Following stapedectomy or incudostapedectomy, results from several animal subjects would have been difficult to distinguish from normal (Jerger, Type A) patterns based on visual inspection alone. However, upon calculation of acoustic immittance at the eardrum, the values from normal and abnormal ears fell into essentially nonoverlapping distributions.

Occasionally, more complex patterns can be recorded at 226 Hz. In adult subjects with very low acoustic impedance such as that caused by complete ossicular discontinuity, the conditions required to produce multipeaked tympanograms can occur at 226 Hz. In normal neonates, multipeaked tympanograms commonly occur with low–frequency probes (Himelfarb, Popelka, & Shanon, 1979; Keith, 1973, 1975). These patterns are probably related to the immature neonatal anatomy of the tympanic ring (Anson & Donaldson, 1981) and a resulting high acoustic resistance (Himelfarb et al., 1979). In a study of normal, 2– to 4–month infants (Margolis & Popelka, 1975), no multipeaked tympanograms were observed at 220 or 660 Hz. Tympanograms recorded from these infants were characterized by asymmetries that were attributed to ear–canal volume changes during tympanometric recording. These results with neonates and infants suggest that the anatomical changes that occur in the external ear during the first several months of life have important acoustical effects that result in a developmental sequence of tympanometric patterns. These progress from multipeaked to single peaked with essentially adult characteristics in the first year of life, perhaps reaching maturity as early as 6 months.

7.5 TYMPANOGRAMS ASSOCIATED WITH LOW IMPEDANCE: HIGH PROBE FREQUENCIES

While low–impedance abnormalities usually result in simple tympanometric shapes at low probe frequencies, that is, high single peaks, at high frequencies a wide variety of tympanometric patterns are observed. Some can be accounted for by the simple model of Vanhuyse et al. (1975), whereas others are more complicated. This variety of patterns can be very helpful in distinguishing normal from pathological ears. However, because a significant proportion of normal middle ears produces multipeaked tympanograms, it is necessary to establish guidelines for distinguishing normal low–impedance ears from those with significant pathology. The characteristics of normal tympanograms were detailed in Chapter 2 and are reviewed here.

7.5.1 Normal Low–Impedance Patterns

Normal low–impedance middle ears[20] produce B,G tympanograms that fall into the following categories: 3B1G, 3B3G, and 5B3G. The pressure intervals between outer susceptance maxima are narrow, not exceeding 75 daPa for 3B1G and 3B3G, and 100 daPa for 5B3G. The Y,φ tympanograms are $3Y1\varphi$ or $3Y3\varphi$ with interpeak intervals for the admittance not exceeding 60 daPa. Occasionally, narrow patterns are recorded from normal ears that do not fall into any of these categories. These irregular patterns are characterized by very sharp peaks and the same narrow interpeak intervals given above (see Figure 2.18). The common features of all normal low–impedance patterns are sharp peaks and narrow interpeak intervals.

7.5.2 Abnormal Low–Impedance Patterns

Abnormal low–impedance patterns are characterized by broad peaks and wide interpeak intervals. Two categories of abnormal low impedance tympanograms have been described:

1. Broad regular W–patterns: These tympanograms fall into the following categories: 3B3G, 5B3G, $3Y1\varphi$, and $3Y3\varphi$. The peaks are broad and the interpeak intervals exceed the limits given in Section 7.5.1. An example of a broad 3B3G is given in Figure 7.2. Broad regular patterns have also been recorded in normal neonate ears (Himelfarb et al., 1979) and certain stages of otitis media (see Chapter 8). These patterns are produced by the simple transformations of the resistance and reactance tympanograms outlined by Vanhuyse et al. (1975) and illustrated in Figures 1.17 through 1.20. Reactance tympanograms are generally smooth, single–peaked, symmetrical patterns that are shifted up (toward mass reactance) and sometimes broadened by the pathology.

2. Broad irregular multipeaked patterns: Broad multipeaked patterns that do not fit into the above mentioned categories usually reflect low–impedance abnormalities. These patterns often can be analyzed as regular multipeaked patterns upon which supplemental peaks are superimposed. As a rule, these supplemental peaks appear on all tympanograms recorded from that ear at that frequency. The example in Figure 7.3 shows a basic 3B1G pattern on which a supplementary peak appears on the positive pressure side; the phase angle at the drum (which for a normal ear may never notch—see Section 2.3.4) clearly reveals the supplementary peak. Note that superimposed peaks (arrows in Figure 7.3) appear in all tympanograms, whereas the regular basic pattern takes different forms for different immittance quantities according to the Vanhuyse et al. (1975) model. In some cases multipeaked tympanograms can be regarded as two separate superimposed W–patterns (W–in–W). Figure 7.4 is an example of a set of tympanograms that appear as a normal sharp W–pattern

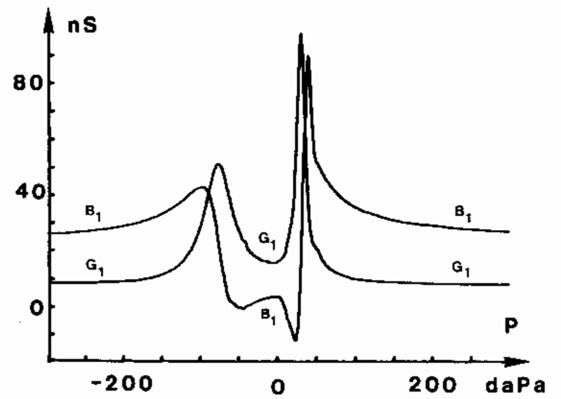


FIGURE 7.2. Simultaneous 660–Hz recordings of the susceptance (B_1) and the conductance (G_1) (1 nS = 0.1 acoustic mmho) as functions of the ear–canal pressure from a traumatized temporal bone. This pattern can be labeled as an abnormally broad 5B3G.

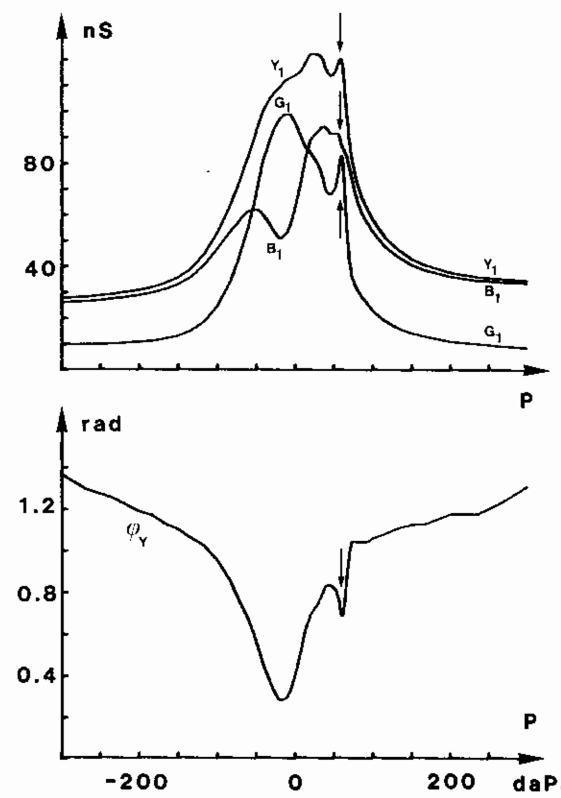


FIGURE 7.3. Simultaneous 660–Hz recordings of the susceptance (B_1) and the conductance (G_1) (1 nS = 0.1 acoustic mmho) as functions of the ear–canal pressure. Computed admittance (Y_1) and phase angle at the drum (φ_Y) tympanograms. The basic pattern being a broad 3B1G, the supplementary peak (marked with arrows) is most easily detected in the phase angle (φ_Y) tympanogram. Ear showing a necrosis of the processus lenticularis.

[20]Normal low–impedance middle ears are those with multipeaked tympanograms at 660 Hz and no history of middle–ear pathology and those with minor eardrum abnormalities that are not associated with active disease or hearing loss.

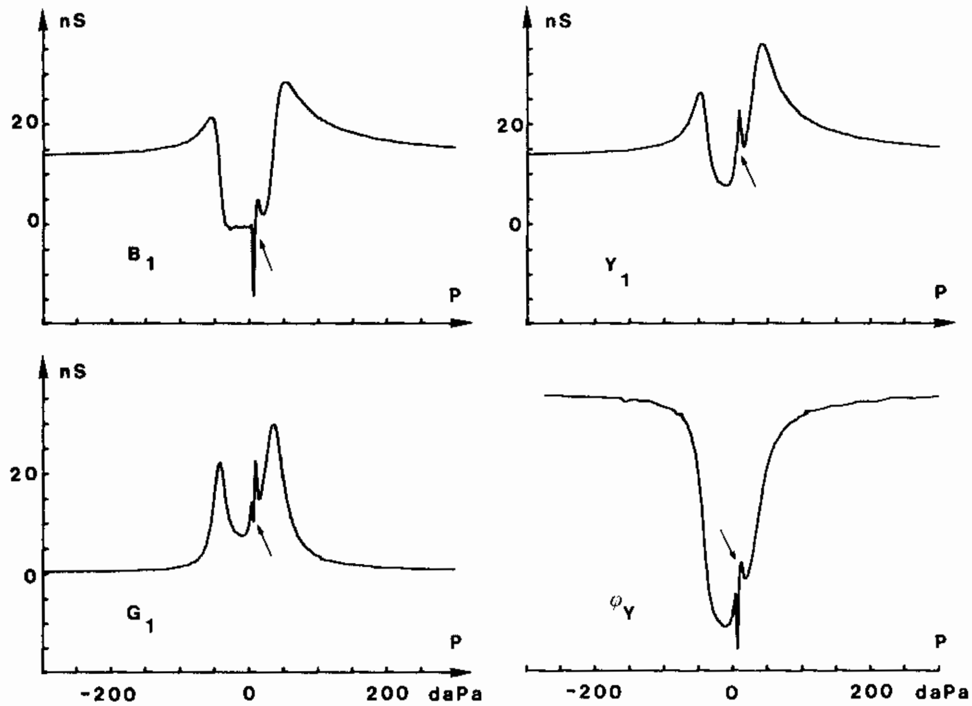


FIGURE 7.4. Simultaneous 660–Hz recordings of the susceptance (B_1) and the conductance (G_1) (1 nS = 0.1 acoustic mmho) as functions of the ear–canal pressure. Computed admittance (Y_1) and phase angle at the drum (φ_y) tympanograms. The basic (broader) pattern is a 3B3G — 3Y1φ in which a second very sharp W–pattern (see arrows) occurs. Traumatized temporal bone.

superimposed on a broad regular W–pattern. These patterns result from more complicated changes than those outlined in the Vanhuyse et al. (1975) model. As in the broad, regular patterns, the reactance tympanograms are shifted up toward mass reactance. In addition, one or more irregularities may occur on the resistance and/or reactance tympanograms. These small, supplemental peaks result in the more complicated, irregular, multipeaked B–G and Y–φ patterns exemplified in Figures 7.3 and 7.4. Additional examples of these complex patterns are presented in Chapter 9.

7.5.3 Ears With Dual Disorders

Examination of an analog model of the middle ear provides a basis for predicting the effects of various abnormalities on aural acoustic immittance. Figure 7.5 presents a block diagram of Zwislocki's middle–ear model (Zwislocki, 1982). Note that the tympanic membrane appears in two places in the model, as a shunt component, representing that part of the eardrum vibration that is not coupled to the ossicular chain, and as a series component, representing that part of the eardrum vibration that is transmitted to the malleus. Due to the shunting effect of the eardrum, a low–impedance eardrum abnormality will obscure the effects of other more medially located middle–ear anomalies on the immittance at the eardrum. Consequently, an eardrum abnormality produces a low impedance tympanogram (high peaks and/or multiple peaks) in spite of a more medial high–impedance abnormality (e.g., ossicular fixation). Examples of this effect have been noted by Moller (1965) in animals, and by Chesnutt et al. (1975) and Feldman (1976) in patients with scarred eardrums. Diseases that result in high middle–ear impedance (e.g., otosclerosis, lateral ossicular fixation) may be masked by a low–impedance, monomeric tympanic membrane. Accurate diagnosis of these conditions requires careful audiometry and otoscopy in order to identify the high–impedance abnormality that might otherwise be obscured by the eardrum abnormality.

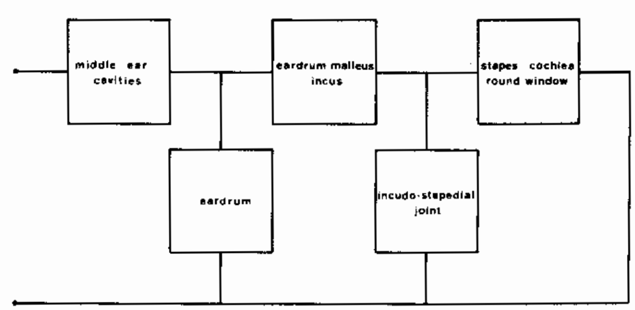


FIGURE 7.5. Block diagram of the human ear. From Zwislocki, 1982. Copyright 1982 by S. Karger Medical and Scientific Publishers. Reprinted by permission.

7.6 SENSITIVITY AND SPECIFICITY

Van de Heyning et al. (1982) studied 14 ears with surgically confirmed pathologies and 8 temporal bones with experimentally produced lesions to examine the sensitivity and specificity[21] of tympanometry for identifying low–impedance abnormalities. The three types of abnormal patterns described in Section 7.5.2 were observed in these cases, but unfortunately there was no apparent relationship between the type of pathology and the type of tympanometric abnormality. All abnormal cases, however, produced abnormal patterns (for at least one direction of pressure change) suggesting excellent sensitivity to low–impedance abnormalities. A subsequent study of abnormal low–impedance ears (Van Camp et al., 1983) in which B_1,G_1 and Y_1,φ_e recordings were obtained for probe frequencies ranging from 510 to 910 Hz produced similarly high sensitivity. Although a few misses have been reported (e.g., Chesnutt et al., 1975, who presented a normal 3B3G pattern from a patient with ossicular discontinuity) the sensitivity of high frequency tympanometry to low–impedance abnormalities appears to be quite good.

The specificity of tympanometry is not as good as its sensitivity. That is, cases with abnormal low–impedance tympanograms in the absence of middle–ear disease are not uncommon. The absence of middle–ear pathology that requires medical intervention is almost always easily determined by the otologic examination as well as other auditory tests. Patients with eardrum abnormalities that produce abnormally low impedance typically have normal audiometric thresholds and acoustic reflexes. Thus, while abnormal low–impedance tympanograms are not uncommon in patients with no auditory dysfunction, these cases are usually correctly diagnosed with the aid of other tests and observations.

7.7 SELECTION OF OPTIMAL IMMITTANCE COMPONENTS AND PROBE FREQUENCY

Several investigators (e.g., Colletti, 1976, 1977; Moller, 1965; Vanhuyse et al., 1975; Zwislocki, 1957a, 1962) investigated immittance characteristics of normal and abnormal ears over a wide range of probe frequencies. This body of work along with four recent sets of experimental data were analyzed to determine the optimal combination of immittance components and probe frequency for detection of low–impedance abnormalities. The four recent experiments include:

1. normative data from 80 subjects obtained with a 660–Hz probe (Van de Heyning, 1981);
2. normative data from 10 subjects obtained with probe frequencies ranging from 220 to 910 Hz (Margolis, Van Camp, Wilson, & Creten, 1985);
3. tympanometric recordings from 14 subjects with low–impedance abnormalities and 8 temporal bones with experimentally produced lesions (Van de Heyning et al., 1982); and
4. tympanometric recordings from 10 subjects with low–impedance abnormalities obtained with probe frequencies ranging from 220 to 910 Hz (Van Camp et al., 1983).

7.7.1 The Optimal Immittance Components

Low–impedance tympanograms in which only one component is recorded (usually admittance magnitude, e.g., Colletti, 1975, 1976; Lidén et al., 1974) are often difficult to interpret because normal multipeaked patterns cannot be distinguished from abnormal low–impedance tympanograms. Two–component recordings (B,G or Y,φ) are seldom characterized by this ambiguity. As R, X, and φ_y tympanograms require extensive computational support, these immittance components are not recommended for clinical use.

Recall from Section 2.3.3 that while the phase angle at the tip of the probe φ_{y_1} is useful for defining the characteristics of normal multipeaked tympanograms, the determination of this component also requires computational support that is not currently feasible for routine clinical use. Recording the electrical phase angle, however, requires no mathematical transformations and produces the same tympanometric shapes as the phase angle tympanogram at the tip.

The selection of B_1,G_1 (susceptance and conductance at the probe tip) or Y_1,φ_e (admittance magnitude at the probe tip and electrical phase angle) will be made based on the following considerations:

1. relative occurrence of multipeaked patterns in each of the two sets of tympanograms (B_1,G_1 or Y_1,φ_e) obtained from normal ears;
2. ability to discriminate tympanometric shapes obtained from normal and abnormal ears;
3. instrument design considerations; and
4. ease of conversion to other tympanometric quantities.

7.7.1.1 Occurrence of Multipeaked Patterns from Normal Ears

In a study of 192 audiologically and otoscopically normal ears (Van Camp et al., 1983) tympanograms were recorded at 660 Hz with a pump speed of 27 daPa/s. The occurrence of normal multipeaked patterns is summarized in Table 7.2. These data suggest that at 660 Hz, B_1,G_1 tympanograms obtained from normal subjects include more multipeaked or W–patterns than Y_1,φ_e tympanograms. Single–peaked B_1,G_1 tympanograms occurred in 57% of the cases whereas 83% of the Y_1,φ_e tympanograms were single peaked. For the susceptance–conductance 9% were 5B3G patterns, whereas no Y_1,φ_e tympanograms had five peaks. We conclude that Y_1,φ_e tympanograms from normal subjects are characterized by fewer multipeaked pat-

[21]Sensitivity refers to the proportion of abnormal ears correctly classified as abnormal (also referred to as "hit rate"). Specificity refers to the proportion of normal ears correctly categorized as normal (also referred to as "correct rejection rate").

TABLE 7.2. The occurrence of different types of susceptance–conductance and admittance–phase tympanograms for 132 normal ears at a probe–tone frequency of 660 Hz. Average rate of pressure change of 27 daPa per second.

	1B1G	3B1G	3B3G	5B3G	Total
1Y1φ	56.8%	25.8%			82.6%
3Y1φ		2.3%	4.5%		6.8%
3Y3φ			1.5%	9.1%	10.6%
Total	56.8%	28.1%	6.0%	9.1%	

terns than B_1,G_1 tympanograms, suggesting that the identification of normal ears is simpler with Y_1,φ_e recording.[22]

7.7.1.2 *Discrimination Between Normal and Abnormal Patterns*

Inspection of a large sample of abnormal low–impedance B_1,G_1 and $Y_1\varphi_e$ patterns over a period of several years led to the following conclusions. Occasionally, an abnormality may be more easily recognized with B_1,G_1 tympanograms, and occasionally Y_1,φ_e recordings produce more easily detectable abnormalities. As a general rule, low–impedance abnormalities are easily detected with either approach. For the purpose of detecting low–impedance abnormalities, B_1,G_1 and Y_1,φ_e recordings are equally useful. This is evident in the sample tympanograms presented in Chapter 9.

7.7.1.3 *Instrument Design Considerations*

In Chapter 4 we described the principle of operation of several types of immittance instruments. A B,G meter requires a complex system that analyzes the probe microphone signal into an in–phase component and a 90° out–of–phase (quadrature) component. The magnitudes of the in–phase and quadrature components represent the magnitudes of the acoustic conductance and susceptance at the probe tip, provided that the instrument compensates for the phase shifts in the tubing and the electrical components in the probe. This compensation represents a time–consuming calibration procedure that may be frequently required for accurate measurement. The phase shift compensation is strongly dependent on the probe–tone frequency.

A Y,φ meter on the other hand, is relatively simple in design. The instrument must measure the magnitude of the microphone signal and compare the phase of the input (driver) signal with the phase of the output (microphone) signal. These measurements can be made with much simpler electronic circuitry than is required for a B,G meter. Because no phase shift compensation is necessary, this approach facilitates multifrequency tympanometry. From the standpoint of production cost and ease of calibration, the Y,φ approach has definite advantages.

7.7.1.4 *Ease of Conversion to Other Quantities*

In the laboratory situation it often is desirable to convert the measured tympanometric quantities to other immittance quantities in order to explore interactions among various immittance components. For this purpose the B,G meter provides some advantages. Susceptance can be plotted against conductance to produce a phasor tympanogram without transformation of the measured signals (see Section 2.3.4). The measured susceptance and conductance tympanograms can be easily corrected to the plane of the tympanic membrane (see Section 5.3). While these transformations can be made with a Y,φ meter, computations and calibrations are tedious.

In summary, a two–component approach is required to maximize the rate of detection of low–impedance abnormalities. The Y,φ approach produces a higher proportion of simple patterns from normal ears and can be accomplished with simpler instrument design. The B,G approach provides some advantages for conversion to other tympanometric quantities. For a clinical instrument, the Y,φ meter is optimal for detection of low–impedance abnormalities. For a research instrument, the B,G meter offers some versatility that may be advantageous for laboratory purposes.

7.7.2 Selection of Probe Frequency

In their pioneering work, Terkildsen and Scott–Nielson chose a 220–Hz probe frequency "partly at random" and partly for the following reasons:

1. transducers that were available at that time were nonlinear at higher frequencies;
2. low frequencies allow a one–component admittance approach, because the phase angle is nearly constant over the entire tympanogram;
3. the probe signal level can be relatively high at 220 Hz without activating the acoustic stapedial reflex; and
4. 220 Hz is not a harmonic of the 50–Hz line frequency used in Europe.

Three additional, and more compelling, reasons can be added to the list:

5. a substantial amount of clinical experience and data have been acquired with the low frequency probe;
6. calculation of the immittance at the tympanic membrane is more precise at low frequencies (Chapter 5); and
7. the proposed I.E.C. and American standards pertain to instruments that use a 226–Hz probe.

As we pointed out in Section 7.2, low frequency tympanometry does not allow effective differentiation between

[22]Because the proportions of various patterns differs at different probe frequencies, pump speeds, and directions of pressure change, the analysis summarized in Table 7.2 applies only to the conditions used in that experiment. Caution must be exercised in comparing data that were collected under different conditions. Special care must be taken to categorize tympanograms based on recordings made with the same pressure direction.

normal and abnormal tympanometric shapes. A high probe–tone frequency allows a more distinct separation between normal ears and those with middle–ear or eardrum pathologies (e.g., Colletti, 1977; Feldman, 1976; Lidén et al., 1974; Van de Heyning et al., 1982). These experiments utilizing higher probe frequencies are inconclusive with regard to the optimal frequency for detecting low–impedance abnormalities. In a recent study using probe frequencies ranging from 510 to 910 Hz from the experimental two–component Amplaid VC01 immittance instrument, the low–impedance abnormalities in 10 patients were equally detectable at all frequencies in this range (Van Camp et al., 1983) as illustrated in Figures 7.6 and 7.7.

The following considerations lead us to a recommendation of 660 Hz (or 678 Hz) as the frequency of choice.[23]

1. With probe frequencies higher than 660 Hz, the proportion of normal subjects with multipeaked patterns increases, with a concomitant increase in the potential number of false positives.
2. A substantial amount of data exists from normal and impaired ears that were obtained with a 660–Hz probe.
3. At frequencies above 660 Hz, the ear canal approaches a condition of a transmission line rather than an acoustical parallel element, resulting in a more complicated relationship between the immittance at the probe tip and the middle–ear immittance (Gardner & Hawley, 1973).

Although the continued use of the low probe frequency may be advantageous for many applications (Jerger & Northern, 1979), there are a number of arguments in favor of adding high frequency tympanometry to the routine test battery. These include:

1. High frequency tympanometry provides a more effective basis for categorizing middle–ear conditions based on tympanometric shapes. Low–impedance abnormalities result in unique tympanometric shapes at high frequencies but not at low frequencies. Certain high–impedance conditions (see Chapter 8) are similarly more distinguishable using a high probe frequency. Because calculation of the immittance at the tympanic membrane (static immittance) has not been widely accepted as a clinical test, the optimal probe frequency would be the one that maximizes the ability to classify tympanograms based on shape.
2. Because acoustic reflex measurement is often performed along with tympanometry, the selection of probe frequency should also be suitable for reflex recording. While 220 Hz is adequate for contralateral

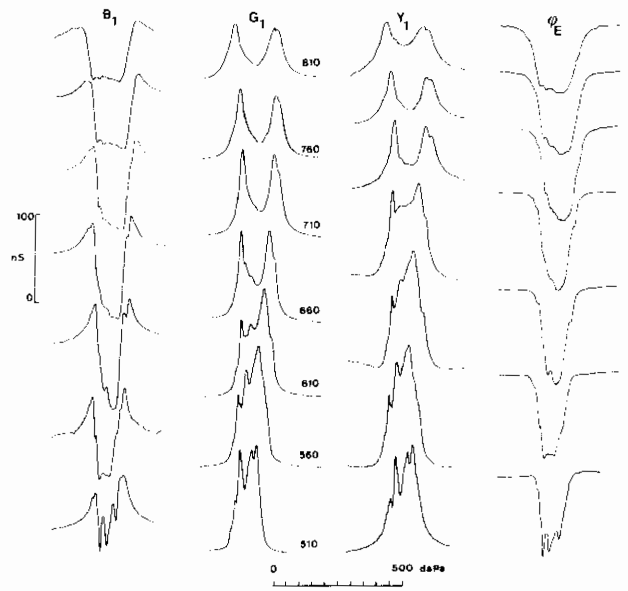


FIGURE 7.6. Simultaneous recordings of the susceptance (B_1), the conductance (G_1), the admittance (Y_1), and the electrical phase angle (φ_e), on an ear showing a luxated ossicular chain. Both component pairs (B_1,G_1) and (Y_1,φ_e) evolve from irregular patterns at 510 Hz to an abnormally broad regular W–shaped patterns at frequencies of 760 Hz and higher. Pressure, B_1, G_1, and Y scaling is indicated; φ_e scaling is arbitrary. From Van Camp et al., 1983. Copyright 1983 by The Almqvist & Wiksell Periodical Company. Reprinted by permission.

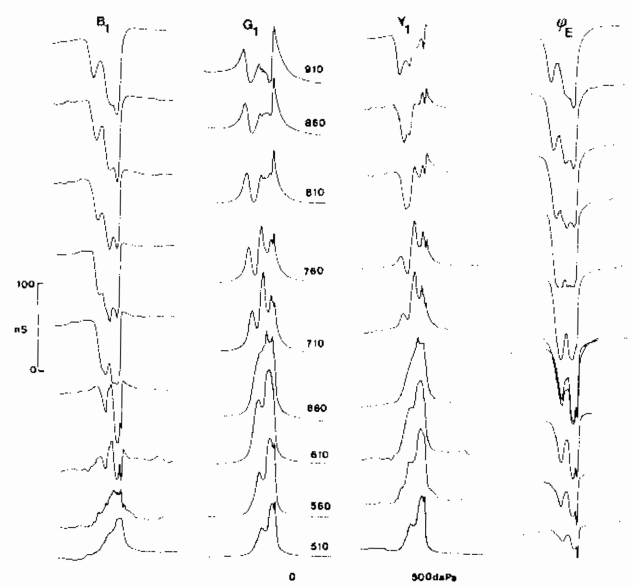


FIGURE 7.7. Simultaneous recordings of the susceptance (B_1), the conductance (G_1), the admittance (Y_1), and the electrical phase angle (φ_e), on an ear showing a myringo–stapediopexia with necrosis of the lenticular process of the incus. Probe–tone frequencies of 510 to 910 Hz. Both component pairs (B_1,G_1) and (Y_1,φ_e) display irregular patterns for all frequencies. Also included is a comparison of φ_{y_1} and φ_e tympanograms at 660 Hz. Pressure, B_1, G_1 and Y_1 scaling is indicated; φ_e scaling is arbitrary. From Van Camp et al., 1983. Copyright 1983 by The Almqvist & Wiksell Periodical Company. Reprinted by permission.

[23]Although the proposed international and American standards apply to instruments that use a 226–Hz probe, a 678–Hz frequency may be preferred for high frequency tympanometry because 678 is an integral multiple of 226. This relationship facilitates certain comparisons and transformations.

reflex recording in adults, it is not suitable for measuring reflexes in neonates (Bennett & Weatherby, 1982; Weatherby & Bennett, 1980). While 660 Hz is also too low for optimal reflex testing in neonates, it is high enough to obtain reflex responses from a high proportion of newborns.

3. Because ipsilateral reflex measurement has important advantages over contralateral recording (Green & Margolis, 1983a,b), the probe frequency should be suitable for this measurement. Using a 220–Hz probe, the ipsilateral reflex is often contaminated by an "eardrum artifact" (Kunov, 1977; Green & Margolis, 1983a) that does not occur for higher frequency probe tones.

7.7.3 Sweep Frequency Tympanometry

Another option that has been recently explored is sweep frequency tympanometry (Funasaka, Funai, & Kumakawa, 1984; also see Lilly, 1984 for a review). Berg (see Lilly, 1984) constructed a three–dimensional tympanogram by recording admittance with a sweep–frequency (200–2000 Hz) probe tone at 25 ear–canal pressures (−300 to 300 daPa). Funasaka et al. (1984) recorded ear–canal sound pressure level and phase angle at two ear–canal air pressures (−200 and 0 daPa) and plotted those quantities as a function of probe frequency (220–2000 Hz). They also presented their measurements in the form of a phasor plot similar to the technique described in Section 2.3.4 except that Funasaka et al. varied the probe frequency rather than ear–canal air pressure. These representations appear to be valuable, especially for detecting ossicular abnormalities.

The value of multifrequency tympanometry has been demonstrated. With current technology, a device that produces a three–dimensional video or hard–copy display of admittance, probe frequency, and ear–canal air pressure, compensated for ear–canal volume, in less time than many current instruments require to produce one tympanogram can be produced at a reasonable cost. A tympanometric recording made at 10 probe frequencies with a pump speed of 400 daPa/s over a pressure interval from −400 to 200 daPa would require 15 s. Even higher pump speeds may be feasible (Ivarsson et al., 1983). This technique holds great promise for detection of middle–ear pathology by pattern recognition techniques.

7.8 CONCLUSION

Low–impedance abnormalities produce a variety of tympanometric shapes. The higher the probe frequency, the greater the variety of tympanometric patterns that is observed for normal ears as well as for abnormal ears. While this variety of shapes may seem to complicate the clinical problem of middle–ear evaluation, it also provides a great deal of information that can be utilized in audiologic/otologic assessment.

The primary reason that most acoustic immittance measurements have been made with a low probe frequency is that instrument manufacturers have offered instruments with a 220–Hz probe almost exclusively. While this decision is probably based on sound marketing principles, examination of existing data does not support the exclusive use of low frequency tympanometry in the clinical evaluation of patients. We conclude that for low–impedance abnormalities, the most effective clinical decisions can be made with a two–component (Y, φ) admittance meter and a 660–Hz probe tone frequency. In the future a multiple–frequency technique may prove to be the optimal method for detecting many abnormal conditions of the middle ear.

Chapter 8

High Impedance Pathological Ears

8.1 INTRODUCTION

This chapter presents audiometric and tympanometric data from patients with middle–ear pathologies that result in flat tympanograms or tympanograms with abnormally low peak admittance. Audiometric results from these patients range from normal to a maximum conductive loss of approximately 60 dB. Although tympanic membrane perforations are not, strictly speaking, high impedance pathologies, they present qualitatively similar results and are discussed in Section 8.2. High impedance pathologies not accompanied by tympanic membrane perforations are discussed in Section 8.3. A discussion of the utility of ear canal volume estimates (Section 8.4) and a discussion of the criteria recommended for medical referral (Section 8.5) follow the presentation of audiometric and tympanometric results from selected cases with high impedance abnormalities.

Tympanograms recorded from patients with high impedance pathologies often are flat regardless of the probe frequency or the immittance quantity measured. When a flat tympanogram is obtained, an estimation of the volume of air in front of the probe may help to identify a tympanic membrane perforation or a patent pressure–equalization (PE) tube.

The volume of an enclosed cavity of air, terminated at one end by a probe device, can be estimated from immittance measurements made with a low frequency probe tone (< 1000 Hz), if the dimensions of the cavity meet certain constraints (Beranek, 1954; Lilly & Shanks, 1981; Van Camp & Creten, 1976). If a right circular cylinder has length and radius that do not exceed the limits given in Table 8.1, then the resistance and mass reactance will be negligible and the volume of air can be approximated as a pure compliance reactance according to the following equations that were introduced in Chapter 1:

$$X_c = -j\rho c^2/2\pi f V \qquad \text{(acoustic ohms)} \qquad (8.1)$$

$$B_c = j2\pi f V/\rho c^2 \times 1000 \qquad \text{(acoustic mmhos)}. \qquad (8.2)$$

Stated differently, these equations will be accurate if the mass reactance is ≤ 3% of the compliance reactance. Equations 8.1 and 8.2 can be simplified if measurements are made with a 226–Hz probe tone under standard atmospheric conditions: ambient temperature = 20°C and ambient air pressure = 1013 mbar (760 mm Hg).[24] Substituting values for ρ, c, and f and solving Equations 8.1 and 8.2 for V, we obtain

$$V = 1000/X_c \qquad (\text{cm}^3) \qquad (8.3)$$

$$V = B_c \qquad (\text{cm}^3). \qquad (8.4)$$

Under standard conditions, a 1 cm^3 cavity will have a susceptance of 1 acoustic mmho and a reactance of 1000 acoustic ohms.

Although only the imaginary component of immittance (X_c or B_c) is proportional to the volume of an enclosed cavity of air, most commercially available instruments measure only the magnitude of the immittance vector ($|Z_a|$ or $|Y_a|$) and express the result with reference to the immittance of an enclosed volume of air in cm^3. To make volume estimates at 226 Hz with these instruments, Z_a is substituted for X_c and Y_a is substituted for B_c in Equations 8.3 and 8.4. When volume is estimated from the impedance or admittance vector, it is called equivalent volume (V_{eq}). The equivalent volume and the actual volume will be equal only if conductance and mass susceptance (or resistance and mass reactance) are very small with respect to compliance susceptance (or compliance reactance), that is, when the cavity is a right circular cylinder with dimensions that are within the constraints given in Table 8.1. Because the mass reactance increases and the compliance reactance decreases with frequency, the constraints placed on the dimensions of an enclosed cavity are more critical for a 678–Hz probe tone than for a 226–Hz probe tone. For the high impedance ears with intact tympanic mem-

TABLE 8.1. Dimension constraints to approximate an enclosed volume of air as a pure compliance.

Probe frequency (Hz):	*226*	*678*
Minimum radius (cm)	0.33	0.19
Maximum radius (cm)	4.42	1.47
Maximum length (cm)	7.60	2.53

[24]See Lilly and Shanks (1981) for a complete discussion of the immittance of an enclosed volume of air and a procedure for correcting for elevation.

branes discussed in this chapter, little difference should exist between the actual volume calculated from susceptance or reactance and the equivalent volume calculated from the 226–Hz admittance or impedance vector. For cases with eardrum perforations, however, the complex geometry of the middle ear and mastoid spaces can result in substantial errors in estimation of the volume in front of the probe.

One additional assumption must be understood in using immittance measurements to estimate the volume of air trapped in front of a probe device. In Chapter 5 we pointed out that although immittance measurements made at the plane of the probe tip represent the combined effect of the immittance characteristics both of the ear canal and the middle ear, the influence of the middle ear can be eliminated by introducing a high ear–canal pressure. This high pressure (e.g. −400 daPa) drives the impedance of the middle ear toward infinity (admittance toward zero) and allows an estimate of the immittance characteristics of the ear canal.

The volume of air trapped in front of the probe can be estimated from tympanograms by substituting the immittance measurements made at a high ear–canal pressure into Equation 8.3 or 8.4. Shanks and Lilly (1981) reported that estimates of the volume of air trapped between a probe and an intact tympanic membrane vary with the ear–canal pressure used to make the measurements. A comparison of tympanometric and direct measurements of ear–canal volumes showed that −400 daPa produced the most accurate volume estimates at 226 Hz (+13% error), whereas the commonly used pressure of 200 daPa produced the least accurate estimates (+45% error). Because ear–canal volume varies with the sex and age of a patient, each clinic should obtain a range of normal tympanometric volume estimates appropriate for its patient population. For the adult male ears shown in subsequent examples, mean tympanometric estimates of ear–canal volume from 226–Hz susceptance and admittance tympanograms at −400 daPa, were 1.25 cm^3 and 1.30 cm^3, respectively, with a range of 0.6 to 2.0 cm^3.

When the tympanic membrane is perforated, the volume estimated from immittance measurements represents the combined volume of the ear canal, middle–ear space, and the mastoid air cell system. Direct estimates and tympanometric estimates of this volume in temporal bones demonstrate considerable intersubject variability. Volume estimates range from 2 to 22 cm^3 with mean volumes ranging from 6.5 to 8.6 cm^3 (Molvaer, Vallersnes, & Kringlebotn, 1978; Zwislocki, 1962). Terkildsen and Thomsen (1959) estimated volume from admittance tympanograms at 220 Hz on two fresh temporal bones prior to and immediately following perforation of the tympanic membrane. Volumes for the two preparations were 0.75 and 0.80 cm^3 for the intact tympanic membrane condition and 4.0 and 2.6 cm^3 for the perforated condition. Similarly, Northern (1980) reported that a perforation will produce a volume estimate that is 3 to 4 times greater than the normal ear–canal volume, and often greater than 5 cm^3. A flat tympanogram with a volume estimate exceeding 2.0 to 2.5 cm^3 in adults and 1.5 to 2.0 cm^3 in children is consistent with a tympanic membrane perforation or patent PE tube (Feldman, 1976; Wilber & Feldman, 1976). Wilber and Feldman also suggested that a difference in volume between the two ears greater than 0.5 cm^3 for children and 0.5 to 1.0 cm^3 for adults is indicative of a perforation.

Volume estimates calculated from flat tympanograms can be placed in three categories: (a) a normal ear–canal volume suggests middle ear fluid or lateral ossicular fixation; (b) an abnormally large volume suggests a perforated tympanic membrane or a patent PE tube; and (c) an abnormally small volume suggests impacted cerumen or placement of the probe against the ear–canal wall.

8.2 TYMPANIC MEMBRANE PERFORATIONS

8.2.1 Normal Middle–Ear Mucosa

Six cases of tympanic–membrane perforations with and without middle–ear disease are presented in this section. The first three cases illustrate audiometric and tympanometric findings from 3 patients with perforations and normal middle–ear mucosa.

Case 1 is a 37–year–old male with a 13–year history of central perforation involving approximately 80% of the tympanic membrane. Surgery revealed normal middle–ear mucosa and an intact ossicular chain. The audiogram in the left panel of Figure 8.1 shows a moderate, essentially flat conductive hearing loss with air–bone gaps ranging from 10 to 50 dB. No consistent degree or slope of hearing loss has been associated with the size or location of a tympanic membrane perforation.

The 226–Hz and 678–Hz tympanograms for Case 1, shown in the right panel of Figure 8.1, are flat. Conductance at 226 Hz is close to zero (0.36 acoustic mmhos at −400 daPa) and susceptance is directly proportional to the volume of the enclosed cavity. The volume estimated from the susceptance tympanogram at −400 daPa is 3.41 cm^3. Because conductance is approximately equal to zero, the susceptance and admittance tympanograms in Figure 8.1 are nearly identical (3.41 and 3.43 acoustic mmhos at −400 daPa, respectively). Stated differently, the admittance phase angle of 84° is close to the value of 90° expected from a hard–walled cavity. As long as the phase angle is close to 90° (conductance is small compared to susceptance) estimates of volume from the susceptance and admittance tympanograms are approximately equal. Similarly, because the tympanograms are essentially flat, the ear–canal volume estimates are approximately equal for all ear–canal pressures.

At 678 Hz (Figure 8.1, right panel), the ear does not function like an ideal, hard–walled cavity. Conductance is equal to 3 acoustic mmhos at −400 daPa rather than the zero value expected in a hard–walled cavity. In addition, the ratio of the susceptance at 678 Hz to that at 226 Hz is greater than 3.0, expected from a hard–walled cavity (see Equation 8.2). The susceptance value at 678 Hz corresponds to a volume estimate of 4.62 cm^3 in comparison to an estimate of 3.41 cm³ at 226 Hz. This difference probably occurs because the ear with a tympanic membrane perforation cannot be approximated as a pure acoustic compliance, especially at high probe frequencies.

Figure 8.2 gives the audiometric and tympanometric data for Case 2, a 35–year–old male with a posterior–superior, marginal perforation over 35% of the eardrum and a 16–year history of otorrhea. The audiogram revealed a rising, mild–to–moderate, conductive hearing loss with decreasing air–bone gaps of 60 to 20 dB with increasing frequency. Surgical observation revealed erosion of the long process of the incus. This case is included to point out that any abnormality of the ossicular chain (e.g. ossicular discontinuity or fixation) will not be evident from the tympanogram in an ear with a tympanic membrane perforation. The tympanograms for Case 2 are very similar to those presented for Case 1. At 226 Hz, conductance is close to zero (0.26 acoustic mmhos at −400 daPa) and the susceptance and admittance tympanograms, which are nearly coincident, are equal to 2.54 and 2.55 acoustic mmhos at −400 daPa, respectively. Again, conductance at 678 Hz (2.07 acoustic mmhos at −400 daPa) is higher than conductance at 226 Hz and susceptance at 678 Hz is slightly more than three times greater than susceptance at

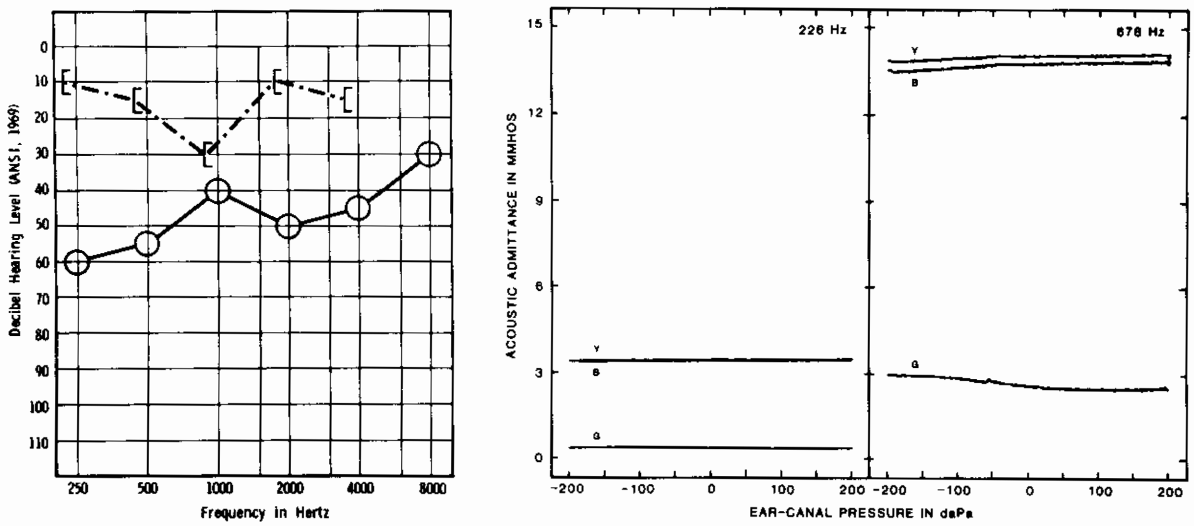


FIGURE 8.1. Case 1. Audiogram and tympanograms from a 37–year–old male with a central perforation, normal middle–ear mucosa, and intact ossicular chain. The tympanograms are ordered from top to bottom as follows: admittance, susceptance, conductance. At 226 Hz, the admittance and susceptance tympanograms are essentially coincident.

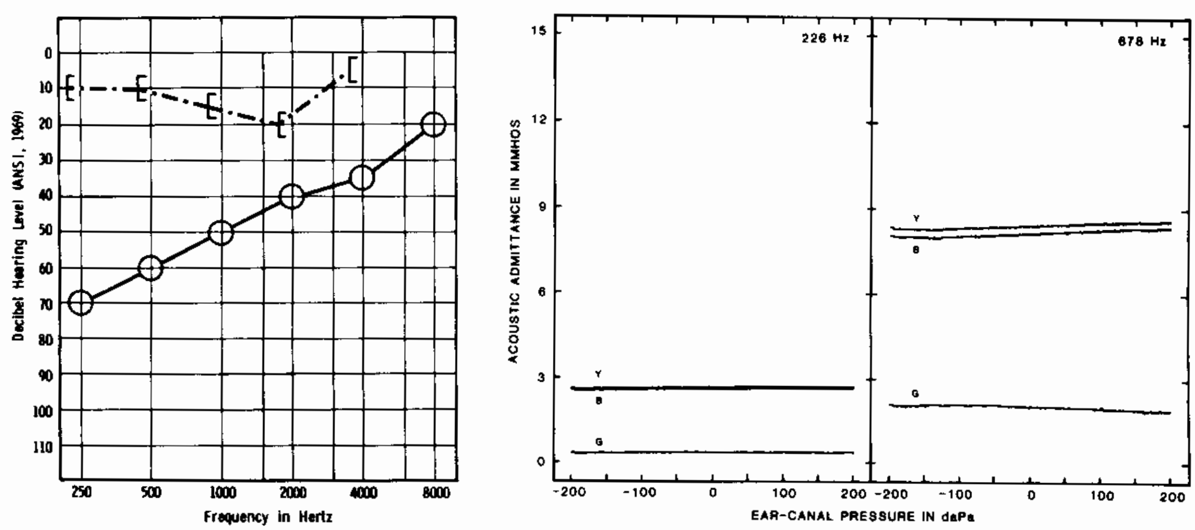


FIGURE 8.2. Case 2. Audiogram and tympanograms from a 35–year–old male with a posterior, marginal perforation and erosion of the long process of the incus. The tympanograms are ordered from top to bottom as follows: admittance, susceptance, conductance. At 226 Hz, the admittance and susceptance tympanograms are essentially coincident.

226 Hz. Susceptance at −400 daPa is equal to 8.38 acoustic mmhos, corresponding to a volume estimate of 2.79 cm³, compared to the 226–Hz volume estimate of 2.54 cm³. Case 2 is a closer approximation to a hard–walled cavity than Case 1, perhaps the result of a different ear–canal and middle–ear geometry.

Figure 8.3 depicts the audiogram and tympanograms obtained from Case 3, a 59–year–old male with a 39–year history of an anterior, central perforation involving 20% of the tympanic membrane. The audiogram shows a consistent conductive component of 20 to 30 dB at all frequencies. Surgery revealed an intact ossicular chain and normal middle–ear mucosa. The 226–Hz susceptance value of 4.40 acoustic mmhos indicated the presence of a tympanic membrane perforation. The conductance value (1.01 acoustic mmhos at −400 daPa) was greater for this case than for Cases 1 and 2. At 678 Hz, the tympanometric results were unusual. Susceptance was approximately 2.5 times smaller than at 226 Hz, rather than the expected ratio of 3.0. Conductance had a very high value rather than the expected value of zero. The phase angle was 20 degrees rather than the 90 degree angle expected from a hard–walled cavity.

This tympanometric pattern has been recorded only in ears with no evidence of diseased middle–ear mucosa or mastoid disease. This case demonstrates that when the eardrum is perforated, the acoustic system comprised of the ear canal, middle–ear space, aditus, and mastoid air cell system becomes a complex acoustic network. The mass and resistance of the enlarged volume of air must be taken into consideration. The volume cannot be approximated by a pure acoustic compliance. Volume estimates from tympanometry, therefore, do not accurately estimate actual middle ear volume, and the error increases with probe frequency.

An extreme example of this tympanometric pattern was encountered in a patient with a nasopharyngeal tumor and a patent PE tube in the tympanic membrane. At 226 Hz, the admittance and susceptance values were very large, indicating a volume greater than 5.0 cm³. A flat conductance tympanogram was obtained at approximately 0.8 acoustic mmhos. At 678 Hz, the admittance and conductance tympanograms were both off scale (> 15 acoustic mmhos) and the susceptance tympanogram was off scale in the negative direction (< −0.6 acoustic mmhos). Added mass and resistance may have been contributed by the mastoid air cells and the narrow lumen through the PE tube.

The first three cases illustrate audiometric and tympanometric findings for 3 patients with tympanic–membrane perforations and normal middle–ear mucosa. The magnitude and shape of the conductive component varied among the cases. The 226–Hz and the 678–Hz tympanograms for all immittance components were essentially flat. Volume estimated from the 226–Hz susceptance tympanogram at −400 daPa indicated combined ear–canal and middle–ear volumes of 2.54 to 4.40 cm³. The commonly used value of 2.5 cm³ appears to be a good criterion for distinguishing patients with intact tympanic membranes from patients with perforations and normal middle–ear mucosa. Because the 226–Hz susceptance and admittance tympanograms are very similar (i.e., conductance is very close to zero acoustic mmhos and the admittance phase angle is close to 90°), the criterion value can be applied to volume estimates derived from either susceptance or admittance tympanograms. Volume estimates derived from 678–Hz tympanograms are subject to considerable error. A significant mass component for the higher frequency probe tone is introduced when the middle ear and mastoid air cell system are contiguous with the ear canal. Because the cavity cannot be represented as a pure compliance at the higher frequency, volume estimates made with the

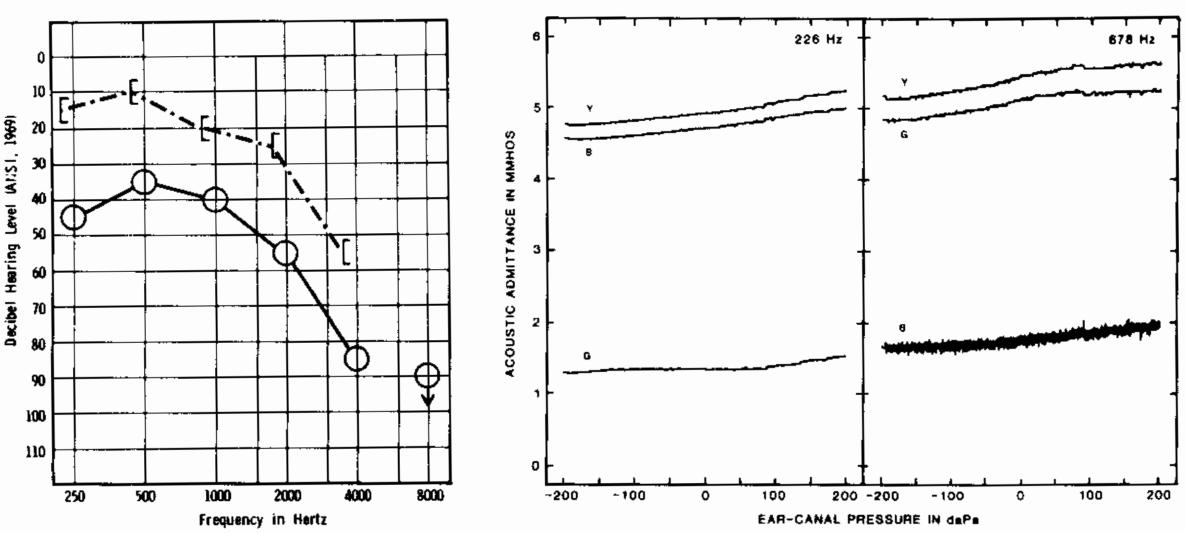


FIGURE 8.3. Case 3. Audiogram and tympanograms from a 59–year–old male with an anterior, central perforation, normal middle–ear mucosa, and intact ossicular chain. At 226 Hz the tympanograms are ordered from top to bottom as follows: admittance, susceptance, conductance. At 678 Hz, the susceptance and conductance tympanograms are reversed.

678–Hz probe tone are not as useful for detecting tympanic membrane perforations as those obtained with a 226–Hz probe.

8.2.2 Diseased Middle–Ear Mucosa

The next three cases illustrate tympanic–membrane perforations with active, middle–ear disease. Figure 8.4 gives the audiogram and tympanograms from a 65–year–old male with a 20–year history of a central perforation involving 30% of the tympanic membrane and intermittent otorrhea. Surgery revealed diseased middle–ear mucosa that was thick and edematous. The mastoid was extremely small and sclerotic, but the ossicular chain was intact. The small middle ear volume is reflected in the tympanograms. The 226–Hz conductance tympanogram is close to zero, but the susceptance and admittance tympanograms at −400 daPa indicate a combined ear canal–middle ear volume of 1.81 and 1.83 cm^3, respectively, well below the recommended 2.5 cm^3 criterion. The small volume is consistent with the surgical findings of diseased middle ear mucosa and small mastoid.

Case 5 (Figure 8.5) is a 32–year–old male with a 13–year history of a traumatic central perforation with superior and inferior retraction pockets and persistent otorrhea. An unsuccessful tympanoplasty was performed 4 years prior to

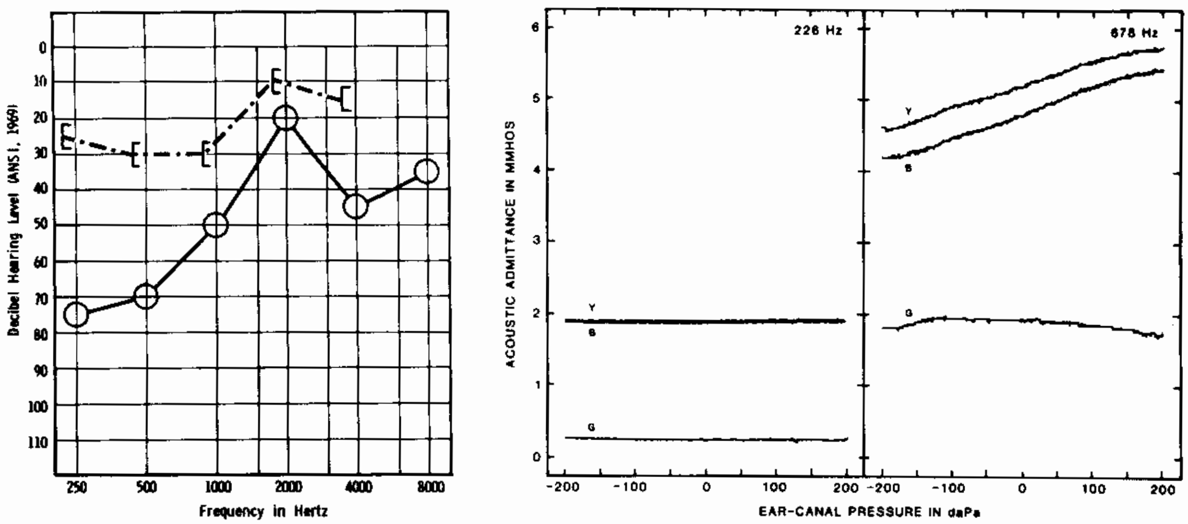


FIGURE 8.4. Case 4. Audiogram and tympanograms from a 65–year–old male with a central perforation and thick, edematous middle–ear mucosa, and a small sclerotic mastoid. The tympanograms are ordered from top to bottom as follows: admittance, susceptance, conductance. At 226 Hz, the admittance and susceptance tympanograms are essentially coincident.

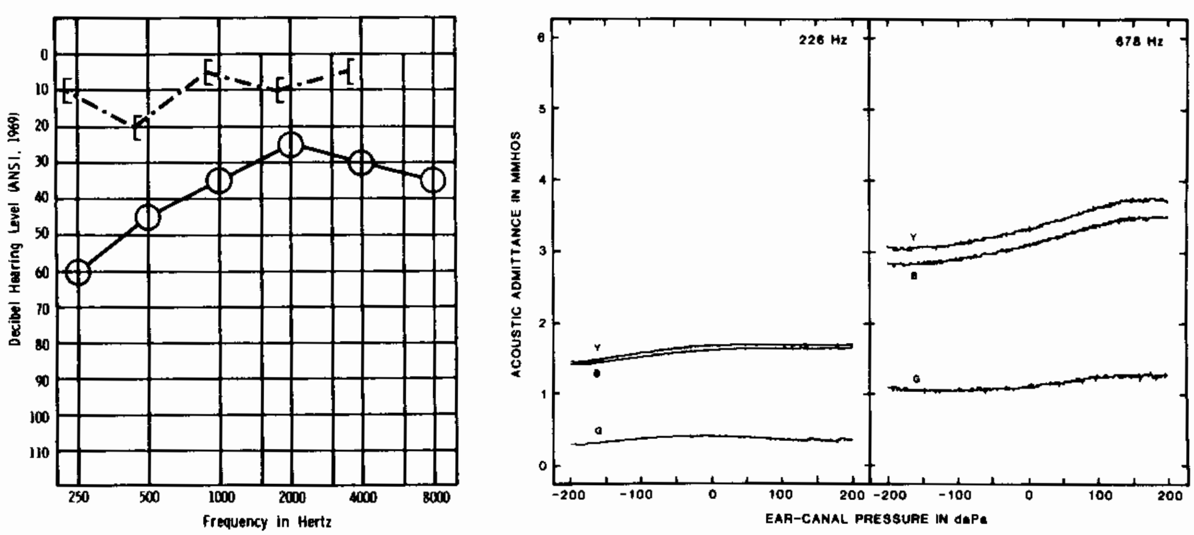


FIGURE 8.5. Case 5. Audiogram and tympanograms from a 32–year–old male with a central perforation, superior and inferior retraction pockets, keratoma filling the mastoid, and scar tissue filling the middle–ear space. The tympanograms are ordered from top to bottom as follows: admittance, susceptance, conductance.

these recordings. Surgery revealed a keratoma filling the mastoid and scar tissue completely filling the middle–ear space. The incudo–stapedial joint was disarticulated and the malleus and incus were fixed by the scar tissue. The absence of a middle–ear space and the small mastoid were reflected in the susceptance tympanogram. Middle–ear volume, calculated from the 226–Hz susceptance and admittance tympanograms at −400 daPa were 1.23 and 1.24 cm^3, respectively.

Case 6, presented in Figure 8.6, is a 63–year–old with a history of ear infections since childhood and purulent discharge for 15 years. At surgery, keratoma was found in the attic, middle–ear space, and over the horizontal semicircular canal. The stapes superstructure was absent. Volume estimated from the 226–Hz susceptance and admittance tympanograms were 2.49 and 2.50 cm^3, respectively. Although the middle–ear volume was reduced by the large keratoma, the tympanograms and volume estimates are indistinguishable from the results obtained from patients with perforation and normal middle–ear mucosa. This finding is not surprising in view of the large intersubject variability associated with middle ear and mastoid volumes.

These six cases indicate that although the 2.5 cm^3 criterion is useful for identifying tympanic membrane perforations when the middle–ear mucosa and the mastoid are normal, this value may not be adequate when middle–ear disease is present. Table 8.2 gives 226–Hz susceptance and admittance values at −400 daPa for 10 patients with tympanic membrane perforations. Five subjects had normal middle–ear mucosa and 5 had keratoma or fluid in the middle ear–space and/or mastoid air cells. For the 5 subjects with normal middle ears, volumes estimated from the 226–Hz susceptance tympanograms at −400 daPa ranged from 2.48 to 5.94 cm^3 with a mean volume of 3.98 cm^3.

TABLE 8.2. Comparison of volume estimates (in cm^3) from 226–Hz susceptance and admittance tympanograms for 10 patients with tympanic membrane perforations: 5 with normal middle–ear mucosa and 5 with abnormal middle ears.

Normal			*Abnormal*		
Subject	*B*	*Y*	*Subject*	*B*	*Y*
1	2.48	2.61	6	1.25	1.26
2	3.41	3.43	7	1.23	1.24
3	3.69	3.75	8	1.09	1.10
4	4.40	4.51	9	1.81	1.83
5	5.94	5.94	10	2.49	2.50

Volumes estimated from the more commonly measured 226–Hz admittance tympanograms ranged from 2.61 to 5.94 with a mean of 4.05 cm^3. The larger values obtained from the admittance tympanogram result from a small conductance component at −400 daPa.

For the subjects with active middle–ear disease, the mean volume estimated from the 226–Hz susceptance tympanogram was 1.57 cm^3 with a range of 1.09 to 2.49 cm^3. Volumes estimated from the admittance and susceptance tympanograms were essentially equal. None of these estimates exceed the 2.5 cm^3 criterion typically associated with a tympanic membrane perforation.

In summary, tympanic membrane perforations may not be obvious from tympanometry, particularly for patients with middle–ear and mastoid disease. Tympanometry, in conjunction with a thorough otologic examination, however, may be extremely valuable. In patients with tympanic membrane perforations, tympanometry may be useful in evaluating the status of the middle ear and mastoid. Although the middle–ear volume varies greatly among individuals, patients with large tympanometric volumes (e.g.

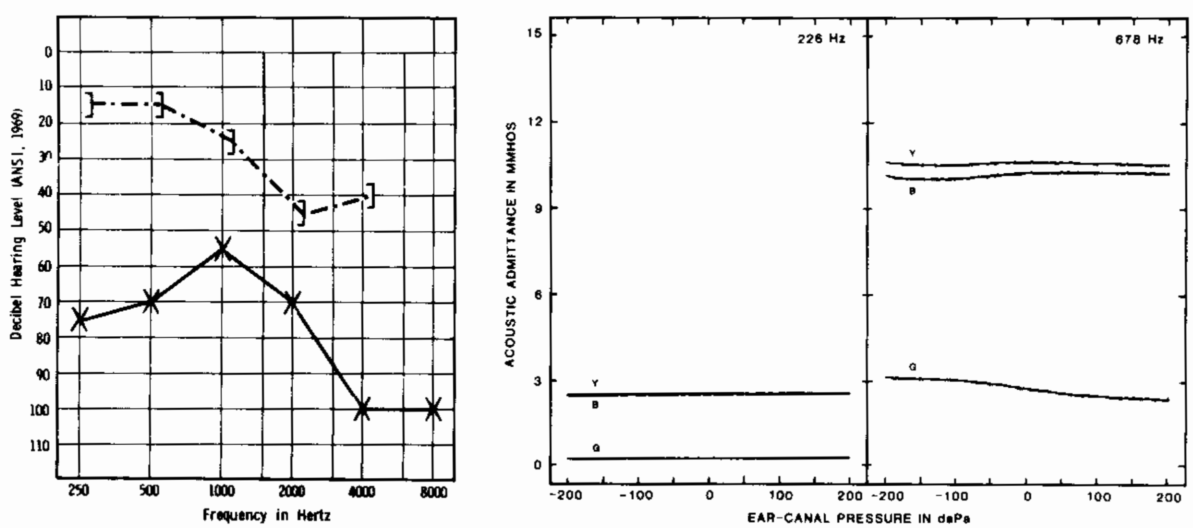


FIGURE 8.6. Case 6. Audiogram and tympanograms from a 63–year–old male with a perforation, and keratoma in the attic, middle ear space, and the mastoid overlying the horizontal semicircular canal. The stapes superstructure was absent. The tympanograms are ordered from top to bottom as follows: admittance, susceptance, conductance. At 226 Hz, the admittance and susceptance tympanograms are essentially coincident.

Case 3, Figure 8.3) usually have normal middle–ear mucosa. In contrast, patients with volume estimates less than 2.5 cm^3 (e.g. Case 5, Figure 8.5) usually have active middle–ear disease.

8.3 INTACT TYMPANIC MEMBRANES

8.3.1 Retracted Tympanic Membranes

The following two cases are patients with retracted tympanic membranes without perforations. Case 7 (Figure 8.7) presents the audiogram and tympanograms from a 63–year–old male with a history of intermittent drainage and hearing loss for 15 years and tinnitus and disequilibrium for 3 months. Surgery revealed a large posterior retraction pocket with no tympanic membrane perforation and a keratoma extending into the mastoid, attic, and antrum, and covering the stapes superstructure. The incus was absent and the malleus was eroded. The 226–Hz tympanograms, particularly the conductance tympanogram, were broadly rounded. The admittance tympanogram more closely resembled the conductance than the susceptance tympanogram. Although the tympanograms were recorded simultaneously, the broad conductance and susceptance peaks occur at different ear canal pressures. At 678 Hz, the admittance and susceptance tympanograms were similar in shape and increased monotonically as a function of ear–canal pressure. The conductance tympanogram, however, was not a monotonic function, but displayed a broad peak near 0 daPa. Volumes estimated at 226 Hz and −400 daPa were 1.44 and 1.56 cm^3 for susceptance and admittance, respectively. Although the large posterior retraction pocket increased the volume of air enclosed between the probe tip and the tympanic membrane, the volumes were below the 2.5 cm^3 criterion. The broadly rounded tympanometric shape also is not consistent with tympanic membrane perforation. This tympanometric type has been observed in several patients with severely retracted (atelectatic) tympanic membranes. These patients typically have a minimum conductive hearing loss and do not undergo surgery.

Case 8 (Figure 8.8) is a 65–year–old male with a history of middle–ear disease since childhood. Otoscopic inspection revealed an atrophic, retracted tympanic membrane with tympanosclerosis. The tympanic membrane was overlying the handle of the malleus with a large posterior retraction pocket that did not move with Valsalva or Politzerization. The ear canal volumes estimated from the 226–Hz susceptance and admittance tympanograms at −400 daPa are 1.95 and 1.97 cm^3, respectively, below the 2.5 cm^3 criterion for detecting tympanic membrane perforations.

8.3.2 Middle-Ear Adhesions

Case 9 (Figure 8.9) is a 64–year–old male who had a tympanoplasty 12 years ago. Four years ago the patient underwent an exploratory tympanotomy to correct a conductive hearing loss. Fibrous adhesions were noted with no other pathology present. His hearing improved for approximately 3 months following the surgery and then decreased to the levels given on the audiogram. A second exploratory tympanotomy again revealed fibrous adhesions among all parts of the middle ear.

The tympanograms for Case 9 are similar to those for Case 8. The 226–Hz tympanograms have shallow peaks near 0 daPa. A tympanometric peak at 678 Hz, however, is evident only in conductance. The 226–Hz susceptance and admittance values at −400 daPa provided volume estimates of 1.15 and 1.17 cm^3, respectively, within the normal range.

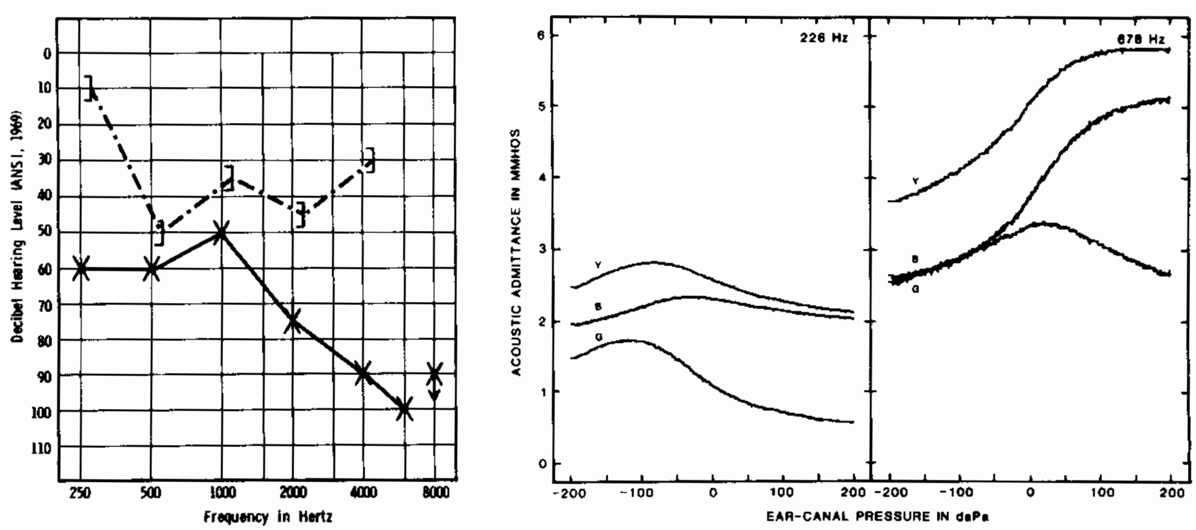


FIGURE 8.7. Case 7. Audiogram and tympanograms from a 63–year–old male with an intact tympanic membrane, a large posterior retraction pocket, and keratoma extending into the mastoid, attic, antrum, and over the stapes superstructure. The incus was absent and the malleus was eroded. The tympanograms are ordered from top to bottom as follows: admittance, susceptance, conductance.

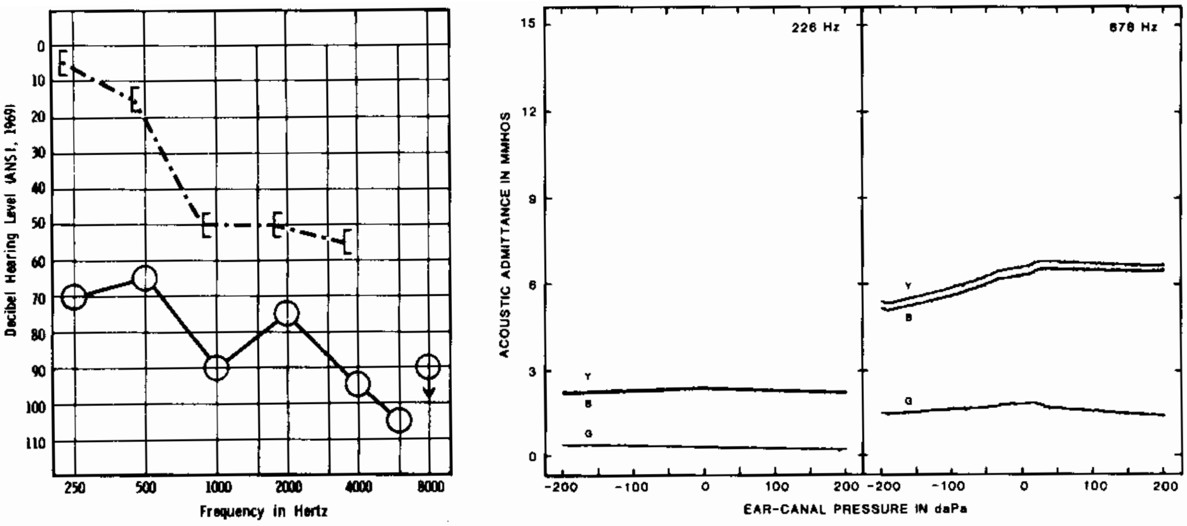


FIGURE 8.8. Case 8. Audiogram and tympanograms from a 65–year–old male with an atrophic tympanic membrane, a large posterior retraction pocket, and tympanosclerosis involving the tympanic membrane and handle of the malleus. The tympanograms are ordered from top to bottom as follows: admittance, susceptance, conductance. At 226 Hz, the admittance and susceptance tympanograms are essentially coincident.

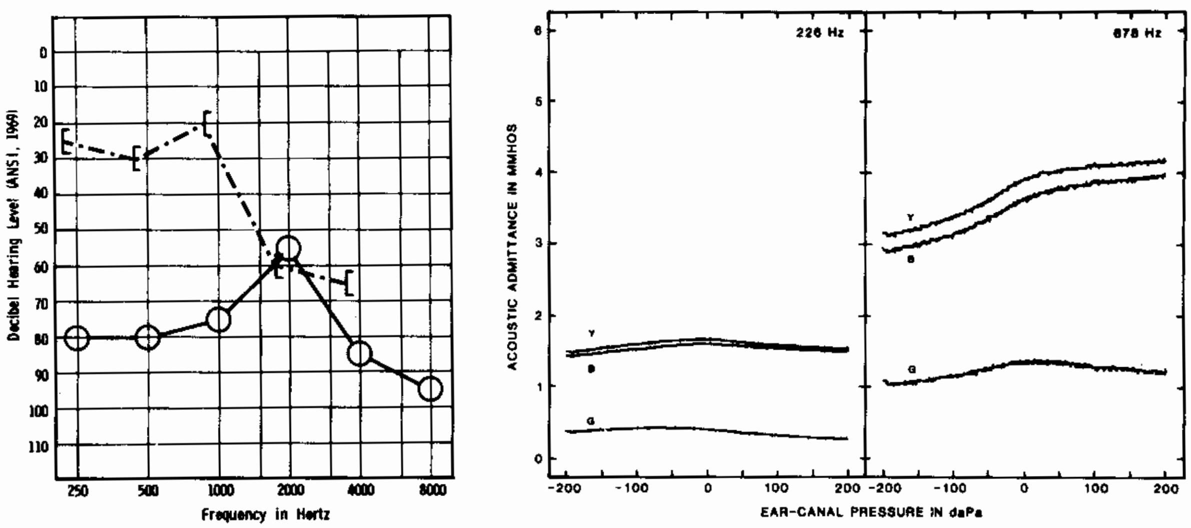


FIGURE 8.9. Case 9. Audiogram and tympanograms from a 64–year–old male who had undergone middle ear surgery. There were fibrous adhesions involving all parts of the middle ear. The tympanograms are ordered from top to bottom as follows: admittance, susceptance, conductance.

8.3.3 Secretory Otitis Media

Case 10 (Figure 8.10) is a 56–year–old male with surgically confirmed, bilateral, secretory otitis media secondary to a nasopharyngeal tumor occluding the eustachian tube orifice. The presence of thin, watery fluid was observed at myringotomy. The 226–Hz tympanograms were flat with susceptance and admittance volume estimates of 1.32 and 1.35 cm^3, respectively. The 678–Hz admittance and susceptance tympanograms were monotonically increasing functions of ear canal pressure. This monotonically increasing shape may be due to ear–canal volume changes that occur during tympanometry.

8.3.4 Otosclerosis

The following 3 patients with surgically confirmed otosclerosis presented with bilateral conductive hearing losses, normal tympanometric peak pressure, and absent ipsilateral and contralateral acoustic reflexes. Case 11 (Figure 8.11) is a 48–year–old male with a 10–year history of hearing loss who underwent stapedectomy. The malleus and incus were mobile and the stapes was thick and immobile. The 226–Hz tympanograms are single–peaked with normal tympanometric peak pressure and static impedance (1459 acoustic ohms) within the normal range (see Table 6.1). At 678 Hz, however, susceptance is larger than

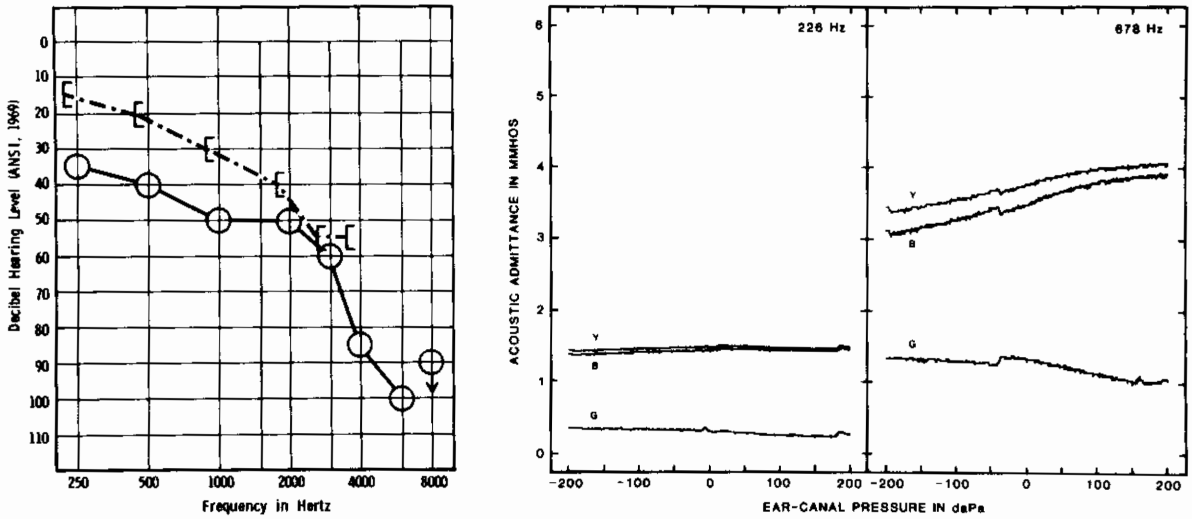


FIGURE 8.10. Case 10. Audiogram and tympanograms from a 56–year–old male with secretory otitis media secondary to a nasopharyngeal tumor occluding the eustachian tube orifice. The irregularities in the 678–Hz tympanograms are probably movement artifacts. The tympanograms are ordered from top to bottom as follows: admittance, susceptance, conductance.

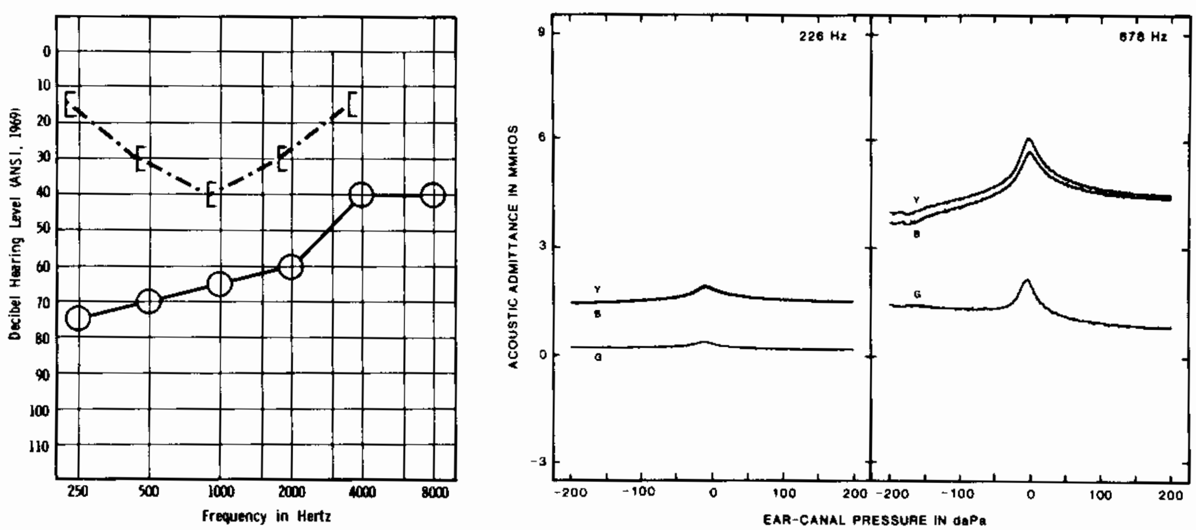


FIGURE 8.11. Case 11. Audiogram and tympanograms from a 48–year–old male with otosclerosis. The tympanograms are ordered from top to bottom as follows: admittance, susceptance, conductance. At 226 Hz, the admittance and susceptance tympanograms are essentially coincident.

conductance resulting in a phase angle greater than 45° Normally at this frequency, conductance is larger than susceptance resulting in a phase angle less than 45°. The abnormal phase angle in the otosclerotic patient results from the increase in stiffness reactance associated with stapes fixation. The 678–Hz probe frequency is more sensitive to the increased reactance than the 226–Hz probe because the higher frequency is closer to the resonance of the middle ear.

Case 12 (Figure 8.12) is a 58–year–old male with a 6–year history of progressive bilateral hearing loss and a family history of otosclerosis. The tympanograms for the right, surgically confirmed ear have normal shapes with peak admittance near 0 daPa. At 226 Hz static impedance (923 acoustic ohms) is within the normal range. As in Case 11, the relationship between susceptance and conductance (or phase angle) at 678 Hz yielded the greatest difference from the normal.

Tympanograms also are shown for the left, unoperated ear. The 678–Hz tympanograms, particularly the conductance tympanogram, have unusually narrow peaks. This pattern, also noted by Ivey (1975), has been frequently observed in otosclerotic patients. This characteristic of tympanograms from otosclerotic patients deserves further study.

Case 13 (Figure 8.13) is a 63–year–old male with surgically confirmed otosclerosis. Surgery revealed a mobile malleus and incus and fixed stapes. Four months prior to

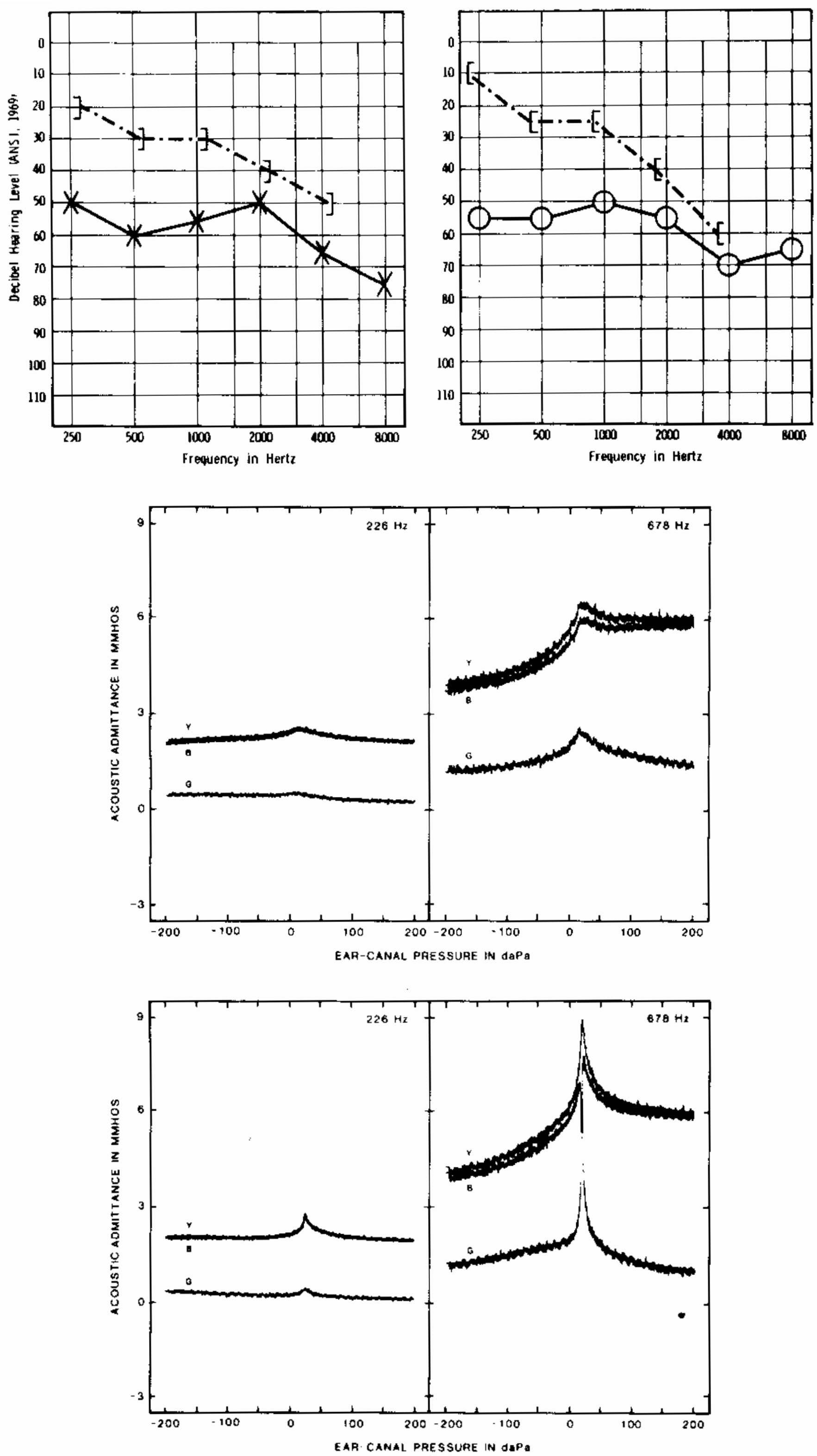


FIGURE 8.12. Case 12. Audiograms and tympanograms from a 38–year–old male with bilateral otosclerosis. (a) audiograms; (b) right ear tympanograms (upper panel) and left ear tympanograms (lower panel). The tympanograms are ordered from top to bottom as follows: admittance, susceptance, conductance. At 226 Hz, the admittance and susceptance tympanograms are essentially coincident. The noise on the tympanograms resulted from recording on FM tape.

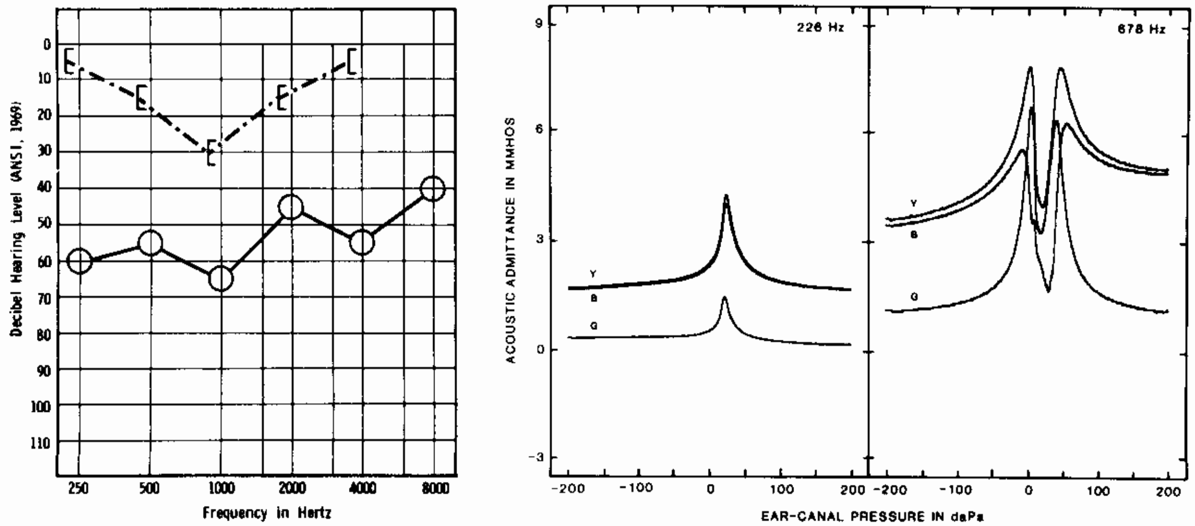


FIGURE 8.13. Case 13. Audiogram and tympanograms from a 63–year–old male with otosclerosis and a recently healed tympanic–membrane perforation. The tympanograms are ordered from top to bottom as follows: admittance, susceptance, conductance. At 226 Hz, the admittance and susceptance tympanograms are essentially coincident.

surgery the patient had a perforation of the tympanic membrane with otalgia and otorrhea associated with a respiratory infection. The admittance, susceptance, and conductance tympanograms at 678 Hz showed broad notching. Stapes fixation had very little influence on tympanometric shape due to the low–impedance tympanic membrane. The case illustrates that a low–impedance eardrum obscures the more medial high–impedance abnormality.

Of the high impedance abnormalities discussed in this chapter, the 3 patients with otosclerosis were the only ones that demonstrated clear admittance peaks near 0 daPa. The tympanograms, however, were of a variety of shapes. The impedance phase angle and tympanometric peak width (gradient) may be useful in detecting this high impedance abnormality.

8.4 CLINICAL UTILITY OF EAR–CANAL VOLUME ESTIMATES

Several patients with surgically confirmed middle–ear disease that results in high impedance or flat tympanograms were discussed in this chapter. When a tympanogram is flat, an estimate of the volume of air in front of the probe is sometimes useful for differentiating between intact and perforated tympanic membranes. When the tympanic membrane is severely retracted or when it is perforated in the presence of keratoma, fluid, or scar tissue in the middle ear, the perforation usually cannot be detected by tympanometry. This is demonstrated by the four histograms in Figure 8.14, which includes volume estimates from a group of normal ears and from the cases discussed in this chapter. Ear–canal volumes, estimated from 226–Hz susceptance tympanograms at −400 daPa, of 15 normal adult males are shown as the shaded bars in the histograms. Estimated volumes ranged from 0.6 to 2.0 cm^3 with a mean of 1.25 cm^3. While a criterion of 2.5 cm^3 seems to be effective for distinguishing between intact tympanic membranes and perforations with normal middle ear mucosa, this value may depend on factors like age, sex, and depth of probe insertion. Each clinic should establish its own criterion based on a sample of normal ears.

The first histogram shows ear–canal volume estimates from 3 patients with secretory otitis media and 1 with middle–ear adhesions (filled bars). These 4 patients had ear–canal volumes ranging from 0.72 to 1.32 cm^3, within the normal range. The second histogram presents the volume estimates from the 2 patients with severely retracted tympanic membranes (filled bars) whose volume estimates were within the normal range. The third histogram shows volume estimates from the 5 patients with tympanic membrane perforations and normal middle–ear mucosa (filled bars). These patients were clearly differentiated from normal ears and those with intact tympanic membranes by the 2.5 cm^3 criterion. The fourth histogram includes volume estimates from 5 patients with tympanic membrane perforations and abnormal middle–ear mucosa (filled bars). The 2.5 cm^3 criterion correctly indicated the presence of a perforation in only 1 of the 5 patients.

8.5 CRITERIA FOR MEDICAL REFERRAL

8.5.1 Middle Ear Conditions That Should Be Referred

In general, any defect of structure or function of the ear deserves medical attention. Since this chapter deals with tympanometry, a measure of middle ear function, the following discussion will focus on middle ear conditions that require medical consultation. These conditions can be broadly grouped into four nonexclusive categories: developmental abnormalities, mechanical disturbances, middle ear infections, and secretory otitis media.

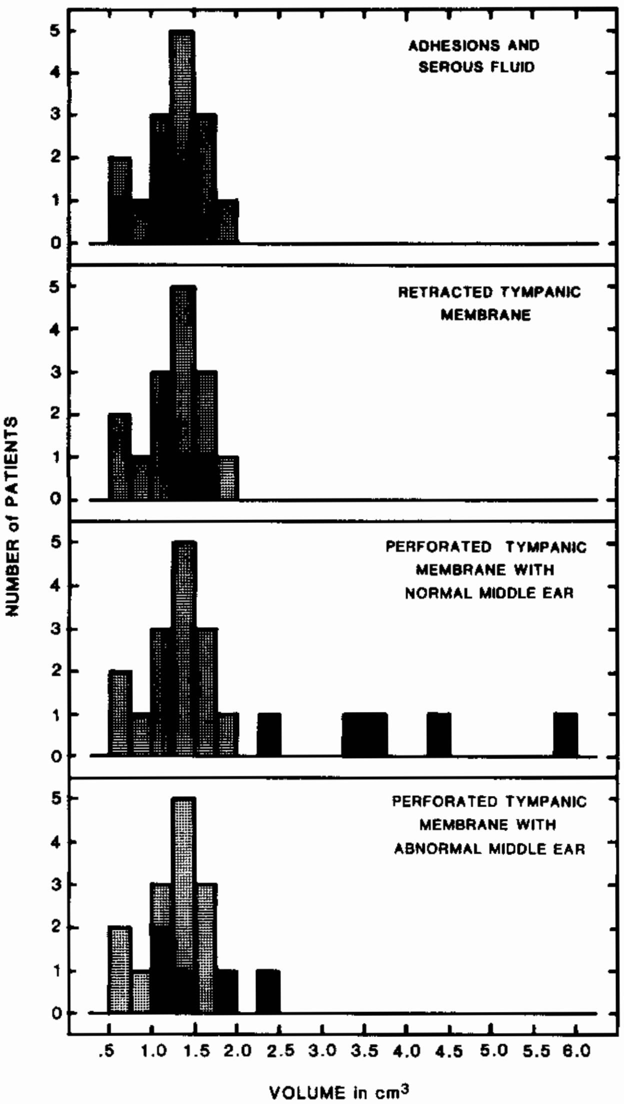


FIGURE 8.14. Tympanometric estimates of normal ear canal volumes (shaded bars) and four groups of patients with surgically confirmed middle ear pathologies (filled bars).

Developmental abnormalities. Developmental problems of the ear range from subtle abnormalities in the size, shape, or position of structures that do not disturb function to total absence of the middle ear. Since these disorders are present in early life, they are seldom first detected by an audiologist. There are exceptions, however, and the audiologist should not assume that a developmental defect has been subjected to appropriate medical attention.

Mechanical disturbances. Mechanical problems of the middle ear include space-occupying lesions such as invading tumors, conditions that interfere with ossicular vibration such as lateral sclerosis, tympanosclerosis, and otosclerosis, and ossicular interruption.

Middle ear infections. These include a wide variety of primary and secondary infections of the middle ear that result from many different pathogens that produce the various forms of acute and chronic otitis media. Audiologists are frequently in a position to recognize these conditions and make the appropriate referral. Several excellent reviews of the history, sequelae, and pathology of middle ear infections are available in the otologic literature (Goodhill, 1979; Schuknecht, 1974).

Secretory otitis media (SOM). SOM is a noninfectious condition of the middle ear that usually results from upper respiratory infection, allergic reaction, or a mechanical disturbance of the eustachian tube (Goodhill, 1979). The primary symptoms are middle ear effusion and negative middle ear pressure, while hearing loss exceeding the conventional "normal limits" occurs in a minority of cases. With regard to medical referral, this condition must be approached differently from the previously mentioned diseases. While developmental abnormalities, mechanical disturbances, and infections of the middle ear require medical attention in all cases, SOM does not always call for a medical referral. Consequently, it is necessary to establish referral criteria that assure the proper medical attention to those who need it, while keeping the over-referral rate to a minimum. To be effective, referral criteria must be based on a knowledge of the natural course of the condition—what happens if it is not treated. Several intensive prospective studies of the epidemiology of secretory otitis media have provided important information regarding the natural course of this condition (see Fiellau-Nikolajsen, 1983; Lidén & Renvall, 1980; and Thomsen, Tos, & Hancke, 1982, for reviews). These studies demonstrated that SOM is a condition that affects most children and from which most children recover without treatment. SOM appears to be rare in neonates (Poulsen & Tos, 1978), increases in prevalence during the first year of life, peaks during the preschool years, and remains high into early school age. Exact prevalences are difficult to determine due to varying identification criteria, but some representative figures may be instructive.

Tympanometric studies of neonates suggest that SOM is essentially absent in neonates. The middle ear appears to be air-filled within a few hours after birth and high negative intratympanic pressures are rare (Bennett, 1975; Himelfarb, Popelka, & Shanon, 1979; Keith, 1973, 1975; Poulsen & Tos, 1978). In a study of infants through the first 6 months of life, Poulsen and Tos found that the prevalence of SOM, defined as tympanometric peak pressure less than −200 daPa or a flat tympanogram, increased from 0% at age 2 to 4 days, to 2% at age 3 months, to 10% at age 6 months. By age 1 year, the prevalence of tympanometrically identified SOM is 10 to 20% depending on criteria, and remains at that high level into early school age (Fiellau-Nikolajsen, 1983; Thomsen, Tos, Hanke, & Melchiors, 1982; Tos, Poulsen, & Borch, 1978). By age 10 years, the prevalence has dropped to about half of the preschool age prevalence (Gimsing & Bergholtz, 1983; Renvall, Lidén, Jungert, & Nilsson, 1973). While the prevalence of SOM is roughly stable from 1 to 7 years of age, the individuals that comprise the affected group are by no means stable. Instead, most children are affected at least once during this period, and many experience repeated bouts of SOM with a strong tendency toward spontaneous remission. Several studies have demonstrated that the majority of children with abnormal tympanograms show evidence of normalization without medical intervention when tested 3 to 6 months later. Renvall, Lidén, Jungert, and Nilsson (1975) reported that 60% of the affected ears of 7–year–old children with tympanometric peak pressure less than −100 daPa or flat tympanograms had normal tympanograms when tested 6 to 12 months later. Tos, et al. (1978) retested 508 ears of 2–year–old children 3 months after the original measurements. About half of the ears with tympanometric peak pressure less than −200 daPa or flat tympanograms were improved at retest. Tos (1980) demonstrated that of 51 ears of 2–year–old children with flat tympanograms at the initial test, 47% had flat tympanograms 3 months later, 41% at the 6–month retest, and only 16% at 9 months. Considering the total number of spontaneously improved ears in children with SOM, Fiellau–Nikolajsen (1983) gives the combined rate of permanent and transient spontaneous normalization at 70 to 80% and the average duration of SOM as 3 months. In a group of children followed from birth to age 4 years, 80% had flat tympanograms or tympanometric peak pressure ≤ −200 daPa at least once (Thomsen et al., 1982). Many children have repetitive occurrences of SOM that normalize without treatment. A small proportion do not recover spontaneously; instead they progress to acute and chronic conditions that require medical and/or surgical intervention. The investigators who have studied the epidemiology of SOM consistently agree that all cases with the condition should not be referred to a physician. Instead, those cases for which the probability of spontaneous normalization is low, those that result in significant communicative dysfunction, and those that progress to acute and chronic otitis media need to be identified within the much larger group of children with self–correcting, noninfectious ear disease. The substantial body of literature relating audiometric, tympanometric, and otoscopic findings to the natural course of otitis media provides a basis for establishing effective referral criteria.

8.5.2 Types of Criteria

Criteria for medical referral available to audiologists are of three types: test results, case history, and visual inspection of the ear.

Test Results

Three types of audiologic tests have been used to detect middle ear abnormalities: audiometry, tympanometry, and acoustic reflex measurements.

Puretone audiometry. Puretone audiometry has proved to be essential in the detection of auditory dysfunction among subjects of all ages. The sensitivity of threshold and screening audiometry to middle ear disease is unsatisfactory, however, because many pathological conditions of the middle ear do not produce auditory threshold shifts sufficient to be detected by conventional audiometric methods. The insensitivity of threshold audiometry to conditions of the middle ear was demonstrated in the "Pittsburgh study" (Eagles, Wishik, & Doerfler, 1967). Eagles et al. classified children into groups based on otoscopic findings and followed the subjects audiometrically for 5 years. The majority of children with otitis media—varying in severity from mild SOM to adhesive otitis media—had clinically normal hearing, adequate to pass conventional audiometric screening tests. Several investigators have noted that subjects with abnormal tympanograms frequently have normal or near–normal hearing (e.g. Brooks, 1974; Gimsing & Bergholtz, 1983; Harker & Van Wagoner, 1974; Lidén & Renvall, 1980; Renvall et al., 1975). Audiometry is essential in evaluating the potential communicative dysfunction associated with middle ear disease. Thus, abnormal audiometric thresholds are sufficient cause for medical referral, but not adequately sensitive to rule out the existence of medically significant ear pathology.

Tympanometry. On the other hand, tympanometry is extremely sensitive to alterations in the state of the middle ear. Instead of being inadequately sensitive to ear disease, tympanometry can be viewed as overly sensitive, with many tympanometric abnormalities occurring in subjects who should not be referred to a physician. Many studies have attempted to relate tympanometric patterns to otoscopic and audiometric findings. Three characteristics of the tympanogram have been studied in relation to middle ear dysfunction: tympanometric shape, tympanometric peak pressure, and static acoustic impedance.

The relationship between tympanometric shape and middle ear function is complex. A patient with otosclerosis may have a normal tympanometric pattern with a 40 to 60 dB conductive hearing loss (Jerger et al., 1974), while a patient with a monomeric tympanic membrane may have a grossly abnormal tympanogram with normal hearing. In otitis media, flat tympanograms are more likely to be associated with conductive loss than tympanograms with peaks, but exceptions are sufficiently frequent that one cannot be predicted from the other. Tympanometric shape is related to the amount, but not the viscosity, of middle ear effusion (Fiellau–Nikolajsen, 1983). The presence of a tympanometric peak indicates the presence of air in the middle ear, with or without effusion. The presence of air in the middle air is a positive prognostic sign that indicates a high probability of spontaneous recovery. In patients with secretory otitis media a flat tympanogram indicates a relatively large quantity of middle ear effusion, possibly completely filling the middle ear space. Fiellau–Nikolajsen (1983) concluded that "children who consistently reproduce flat tympanograms from test to test . . . represent the group having the most severe hearing loss and the poorest long–term prospects" (p. 44). At the same time, he cautioned that if all children with flat tympanograms were referred to a physician, "the consequence would be massive over–treatment, as about three–quarters of the children would improve spontaneously in the course of 6 months" (p. 37).

Another aspect of tympanometric shape that has been used as a criterion for medical referral is the gradient. Originally described by Brooks (1968), the gradient is the immittance change in the pressure interval ±50 daPa surrounding the peak. This measure is thought to provide important information regarding the disease state of the middle ear (Brooks, 1969; Paradise, Smith, & Bluestone, 1976). Unfortunately, the quantification of tympanometric gradient has been performed on tympanograms expressed in "arbitrary compliance units." Since the magnitude of an arbitrary compliance unit is not constant within or among individuals (Thelin & Thelin, 1976), arithmetic manipulations are not legitimate. The mean gradient value, calculated on undefined units, is not a meaningful expression of central tendency. Feldman (1975) demonstrated that the gradient obtained from the same ear with two different instruments can be widely disparate. On the other hand, gradient values obtained from different instruments calibrated in the same physical units should be comparable and amenable to statistical examination. A recent effort in that direction was reported by de Jonge (1983). He calculated tympanometric gradients from tympanograms of normal adult subjects recorded in acoustic admittance units. De Jonge also explored an alternative method of calculating the gradient. Instead of defining the gradient as the immittance change in the interval ±50 daPa around the peak as Brooks (1968) originally proposed, de Jonge defined the gradient as the pressure interval required for a 50% decrease in admittance on either side of the peak. This new measure exhibited some promising properties in comparison to other gradient measures obtained from preschool children (Koebsell & Margolis, 1985). At this point, the tympanometric gradient should be viewed as a potentially useful concept that has not been adequately explored. Future investigations may provide guidelines for appropriate interpretation of gradient data.

Referral criteria have also employed tympanometric–peak pressure (TPP) as an index of middle ear dysfunction (e.g. ASHA, 1978). The relationship between TPP and the condition of the middle ear is complex. While there is a tendency for negative TPP to be associated with middle ear effusion, ears with high negative TPPs may not contain fluid (Fiellau–Nikolajsen, 1983). If the tympanogram is otherwise normal, a negative TPP indicates that a negative middle ear pressure exists and that the mechanical condition of the middle ear is normal when the ear canal is pressurized to equalize the pressure on either side of the eardrum. The majority of such cases do not develop acute and chronic conditions that require medical attention (Fiellau–Nikolajsen, 1983; Renvall et al., 1975, 1978; Thomsen et al., 1982). When middle ear effusion begins to interfere with middle ear mechanics, a change in tympanometric peak height, and thus static acoustic immittance will result. The peak height, or static immittance, is a more effective criterion than TPP for detecting medically significant ear pathology. Negative TPP (less than −150 daPa) warrants follow–up evaluations but, by itself, is not sufficient cause for a medical referral.

Several investigators have concluded that static acoustic immittance measures are not useful in the clinical interpretation of tympanometric data (Jerger et al., 1974; Lidén & Renvall, 1980). This pessimistic view of the usefulness of quantitative data is probably the result of several methodological problems. If qualitative inspection of tympanometric shape is useful but the quantitative expression of the same data is not, then the methods for obtaining and interpreting the quantitative data must be faulty. Perhaps the tympanometric characteristics that are qualitatively useful have not been properly quantified. The lack of norms and standard calibration methods, the variety of tympanometric measurement units, and the absence of standard clinical methods, have contributed to the perception that static immittance measurements are not useful for evaluating middle ear function. Controlled investigations of the immittance characteristics of normal and abnormal ears (e.g. Margolis et al., 1978; Zwislocki, 1957) suggest that normal and pathological populations distribute into distinct groups based on quantitative immittance measurement. Tympanometric characteristics that are judged qualitatively, like tympanometric peak height, can be more reliably determined by the use of a quantitative criterion. Peaked and flat tympanograms, an important distinction for the purpose of medical referral, should be differentiated on the basis of such a criterion. Recent efforts to explore measurement procedures and determine normative values have provided the information necessary to use static immittance values for making clinical decisions. These efforts led to the guidelines and norms for static acoustic immittance discussed in Chapter 6.

Acoustic reflex measurements. Acoustic reflex measurements have also been used as a criterion for medical referral in patients with suspected middle ear disease (ASHA, 1978; Brooks, 1969, 1971, 1974; Harford, Bess, Bluestone, & Klein, 1978; McCandless & Thomas, 1974). While acoustic reflex thresholds are effective in detecting sensorineural hearing loss in patients with normal middle ear function (Popelka, 1981), the efficacy of acoustic reflex measurements for detecting middle ear disease is limited. An absent acoustic reflex may result from (a) a reduction in input to the reflex mechanism due to middle ear disease; (b) a reduction in transmission through the afferent pathway due to sensorineural hearing loss; (c) abnormal function of the efferent portion of the reflex arc; or (d) a mechanical disturbance in the middle ear which reduces or eliminates the impedance change that normally results from muscle contraction. Often a combination of these factors operates. In evaluating patients with high impedance abnormalities, the acoustic reflex measurement is an indirect index of the status of the middle ear which is more directly assessed with tympanometry. These considerations and their extensive examination of screening programs led Renvall et al. (1975) to abandon acoustic reflex measurements in favor of puretone audiometric screening and tympanometry for detecting middle ear disease in children.

Case History

Obtaining a small amount of case history information can save time and money in programs that are designed to identify potential medical problems. Certain aspects of the case history are, in and of themselves, sufficient to warrant a medical referral. These include otalgia (ear pain) and otorrhea (discharge from the ear). Ideally, a thorough case history would be obtained before the appropriateness of a medical referral is ruled out. However, when this is impractical, such as in screening programs, the inclusion of a brief case history, particularly regarding otalgia and otorrhea, is advisable.

Visual Inspection

Visual inspection of the ear is essential in the determination of the appropriateness of medical referral. Otoscopy is a skill that should be in the armamentarium of the clinical audiologist. Although diagnosis of ear disease is not the realm of the audiologist, we should be sufficiently skilled observers to detect visual evidence of medical problems. In some cases the signs of disease can be observed by the unaided inspection of the external ear area. In other cases, the skilled otoscopist can detect signs that call for medical referral which are not detected by our clinical tests. In interpreting visual evidence of ear disease, it is important to distinguish between infectious processes that require medical attention in all cases, and the noninfectious condition of secretory otitis media which does not always warrant medical referral. Any of the visual observations listed in Table 8.3 require medical referral.

Visual inspection of the ear should always precede tympanometry. Aside from the detection of signs of disease, the interpretation of tympanograms requires that an air column exists between the probe tip and the tympanic membrane. In addition, the occurrence of any of the above-mentioned visual signs of ear disease obviates the need for tympanometry to decide whether a patient should be referred. The advisability of tympanometry in the presence of infectious conditions of the middle ear is questionable. We recommend that tympanometry not be performed in the presence of known external or middle ear infection, unless specifically requested by a physician.

TABLE 8.3. Visual observations requiring medical referral.

Evidence of a developmental defect
Discharge from the ear (otorrhea)
Blood or effusion in the ear canal
Occlusion of the ear canal
Foreign bodies in the ear canal
Eardrum abnormalities including:
- perforation
- bulging eardrum
- inflammation
- retraction

8.5.3 Recommended Criteria

Table 8.4 lists criteria for medical referral that can be implemented in a screening program or in the more complete audiologic evaluation. The characteristics of clinical programs and populations, the availability of medical personnel, and the number and training of the staff that implements the program may call for modifications in this recommendation.

TABLE 8.4. Criteria for medical referral.

I. Test results
  A. Audiometry
    1. Air conduction thresholds $\geqslant$ 20 dB HL at two or more of the following frequencies: 500, 1000, 2000, 3000, 4000 Hz
    2. Air–bone gap $\geqslant$ 10 dB at two or more of the following frequencies: 500, 1000, 2000, 3000, 4000 Hz
  B. Tympanometry: flat tympanograms ($|Z| \geqslant 4000$ acoustic ohms at 226 Hz) on two successive recordings in a 2 to 3 month interval

II. Case history
  A. Otalgia
  B. Otorrhea

III. Visual inspection: any of the findings listed in Table 8.3

These criteria should result in a more tolerable over-referral rate than previously recommended screening criteria that were based on acoustic impedance results alone (e.g. ASHA, 1978; Harford et al., 1978). The inclusion of audiometric data, case history, and visual inspection should improve both the sensitivity (hit rate) and specificity (false positive rate) of audiologic programs for determining the need for medical consultation.

Chapter 9

Tympanometric Pattern Recognition

In this chapter a variety of normal and abnormal tympanograms are presented in order to illustrate the various patterns. Because nearly all tympanograms recorded with a 220–Hz probe frequency have the same 1B1G/1Y1φ shape, only 660–Hz tympanograms are presented here. Figures 9.1 to 9.40 provide an opportunity to observe the relations among the various tympanometric quantities recorded from the same normal and abnormal ears. In the examples, the ordinate susceptance, conductance, and admittance values are given in nanoSiemens (1 nS = 0.1 acoustic mmhos) and the abscissa ear–canal pressures are expressed in dekapascals (1 daPa = 1.02 mm H_2O). The reader should review Chapters 2, 7, and 8 in order to understand the tympanometric categories illustrated below.

These tympanograms were obtained using two different immittance instruments: a Grason–Stadler Model 1720 otoadmittance meter or an experimental Amplaid VC01 instrument tuned to 660 Hz. Both instruments measured simultaneously the susceptance B_1 and the conductance G_1 at the tip of the probe (Figure 9.1a,b). The ear–canal pressure was obtained from a piezo–resistant pressure transducer located near the probe. The electrical phase angle (Figure 9.1d) between the driver and microphone signals was determined with a laboratory–constructed phase–angle meter. The admittance at the probe tip Y_1 (Figure 9.1c) was computed from the susceptance and conductance data (Equation 1.45). Further details of the experimental set–up can be found in Van Camp et al. (1983).

Our interpretation of the figures is given at the end of the chapter so that the reader can compare with his own. The most probable conditions of the ears producing each set of tympanograms is given for each. Remember from Sections 7.3.1 and 7.3.2 that:

1. the common features of all normal low impedance patterns are sharp peaks and narrow interpeak intervals, and
2. the features of abnormal low impedance patterns are broad peaks and wide interpeak intervals, with high admittance and high admittance component values.

FIGURES 9.1 to 9.40. Simultaneous recordings of (a) the susceptance B_1, (b) the conductance G_1, (c) the computed admittance Y_1, and (d) the electrical phase angle φ_e. A 660–Hz probe frequency was used for all measurements. In each set the ordinal values (in nanoSiemens) for susceptance, conductance, and admittance are scaled identically but the scale values change from case to case. The phase–angle scaling is arbitrary and not indicated. Because all four immittance components were obtained simultaneously, the pressure axes and calibration are identical for all components.

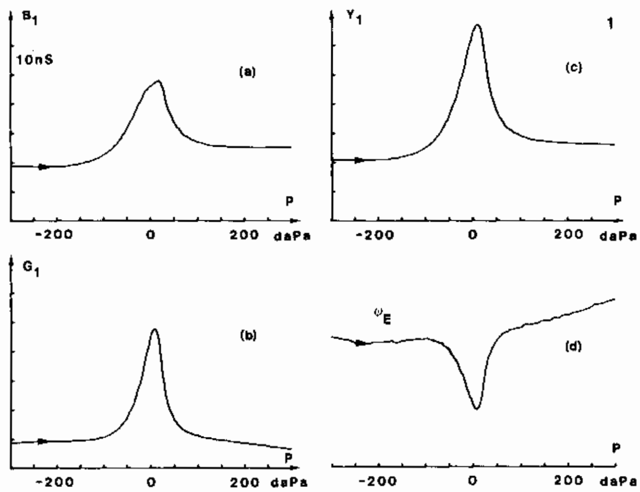


FIGURE 9.1.

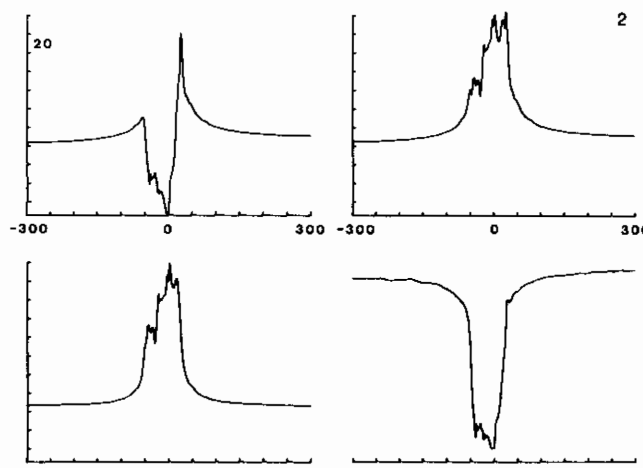


FIGURE 9.2.

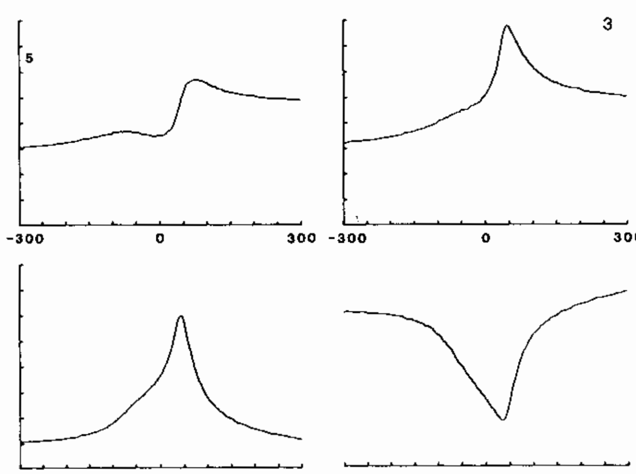


FIGURE 9.3.

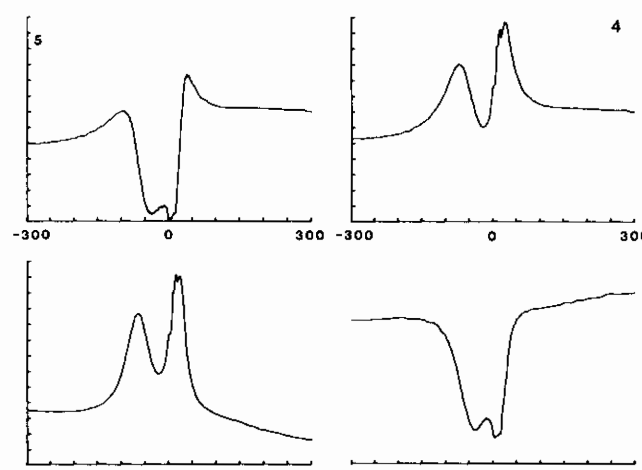


FIGURE 9.4.

FIGURES 9.1 to 9.40. Simultaneous recordings of (a) the susceptance B_1, (b) the conductance G_1, (c) the computed admittance Y_1, and (d) the electrical phase angle φ_e. A 660–Hz probe frequency was used for all measurements. In each set the ordinal values (in nanoSiemens) for susceptance, conductance, and admittance are scaled identically but the scale values change from case to case. The phase–angle scaling is arbitrary and not indicated. Because all four immittance components were obtained simultaneously, the pressure axes and calibration are identical for all components.

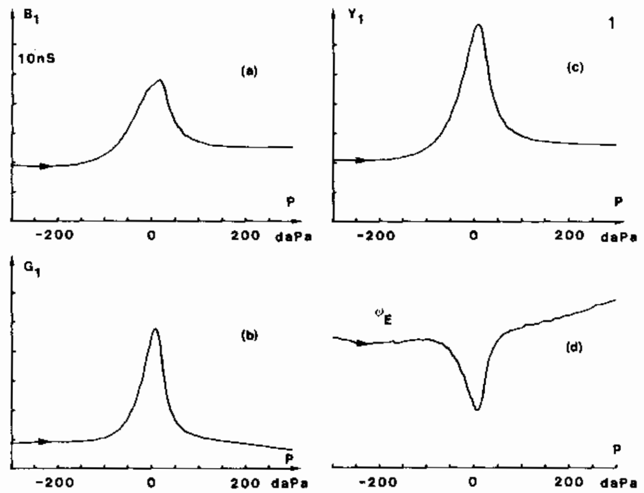


FIGURE 9.1.

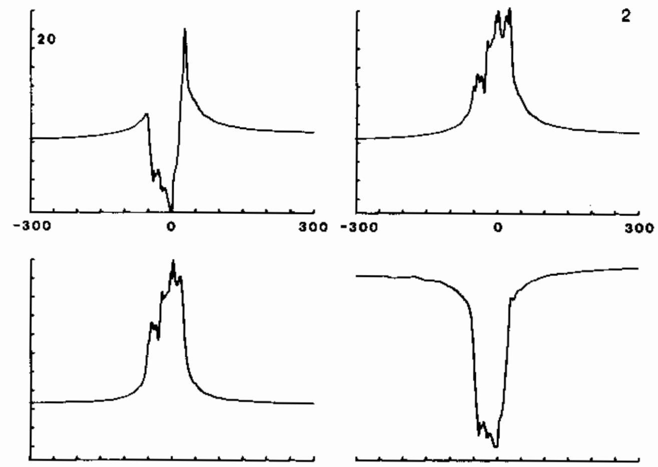


FIGURE 9.2.

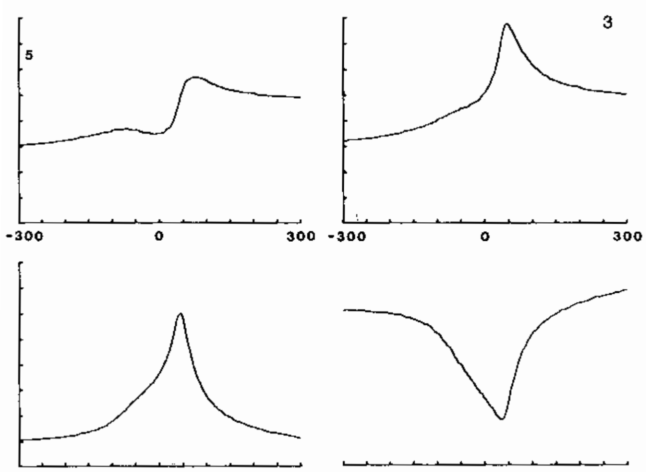


FIGURE 9.3.

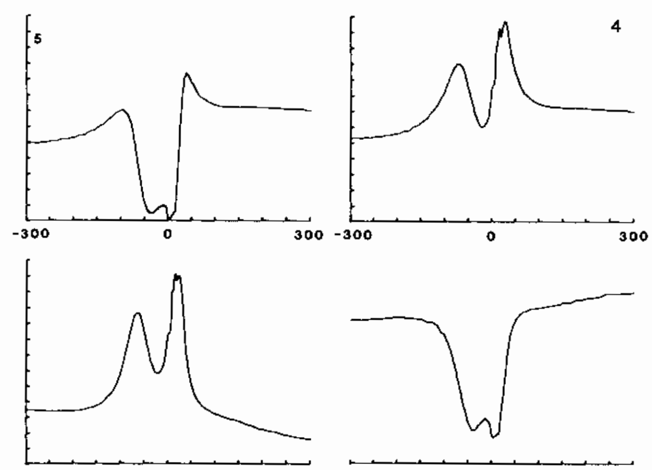


FIGURE 9.4.

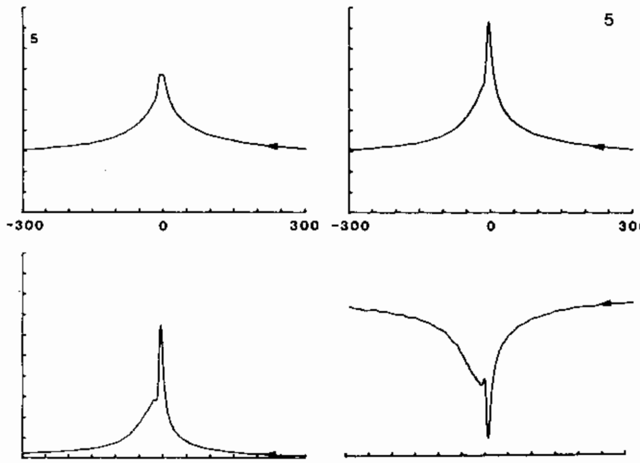


FIGURE 9.5.

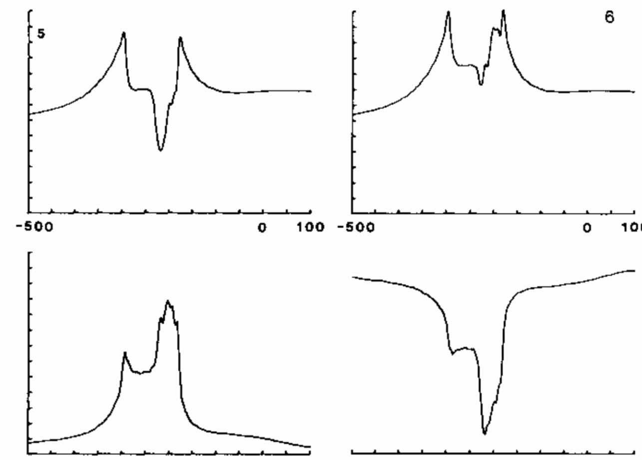


FIGURE 9.6.

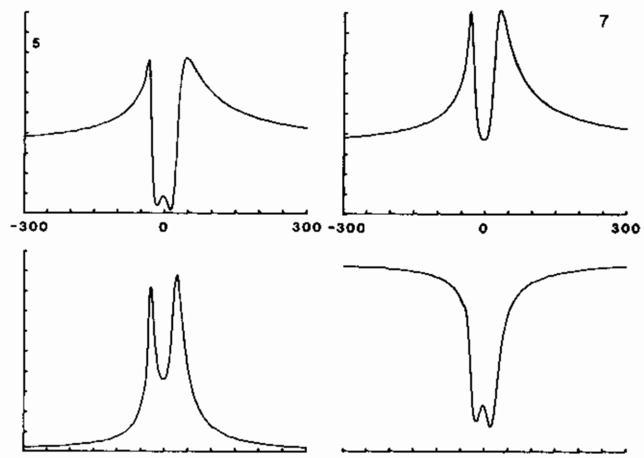


FIGURE 9.7.

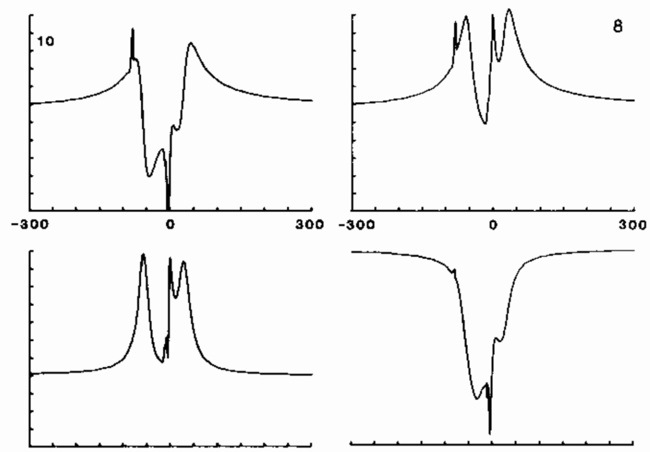


FIGURE 9.8.

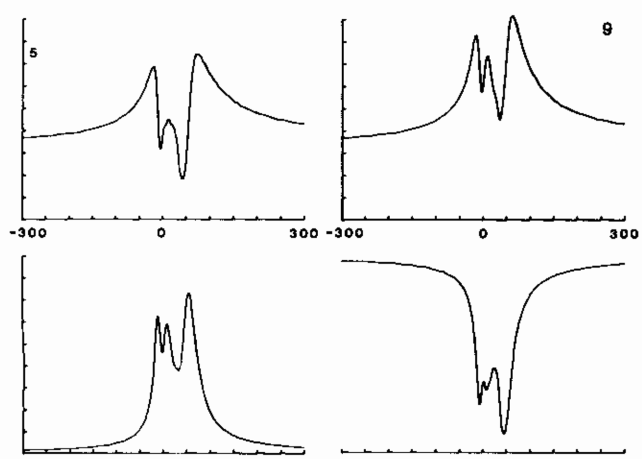


FIGURE 9.9.

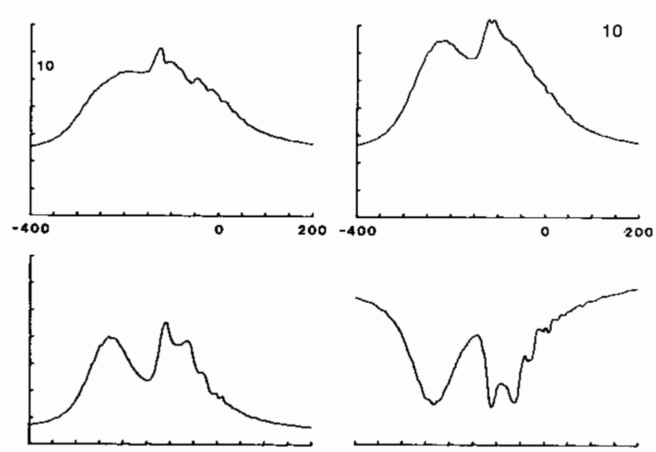


FIGURE 9.10.

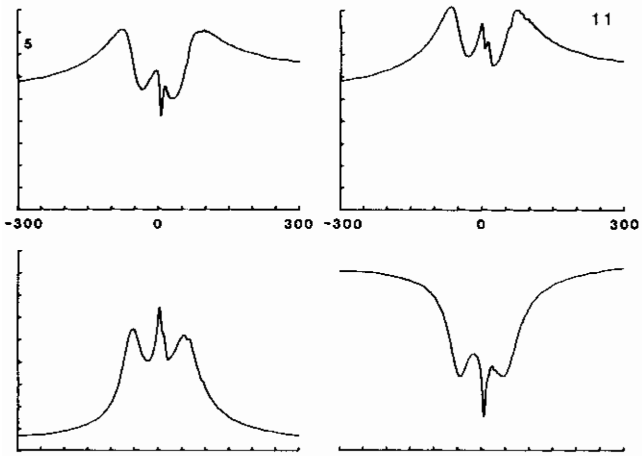


FIGURE 9.11.

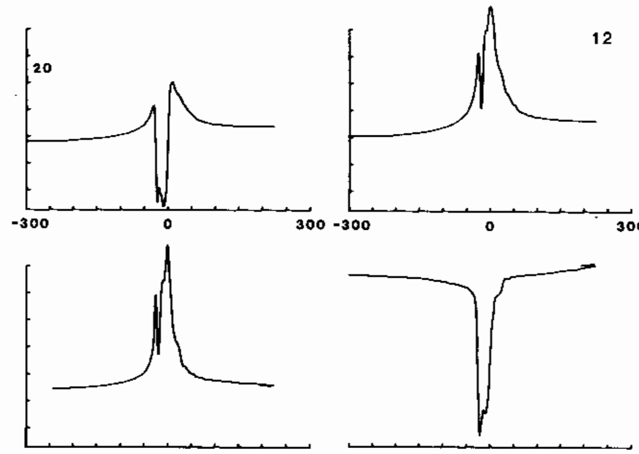


FIGURE 9.12.

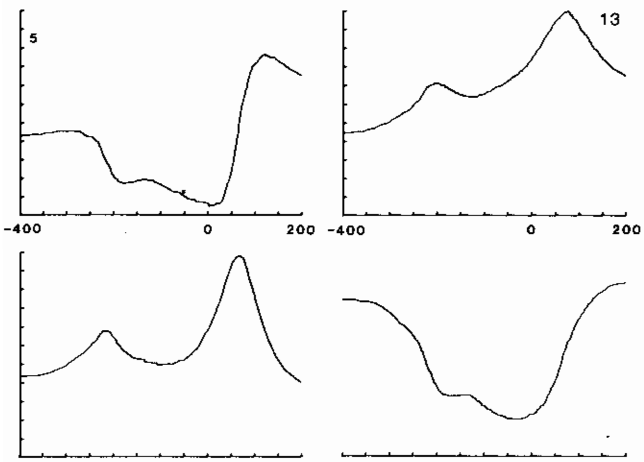


FIGURE 9.13.

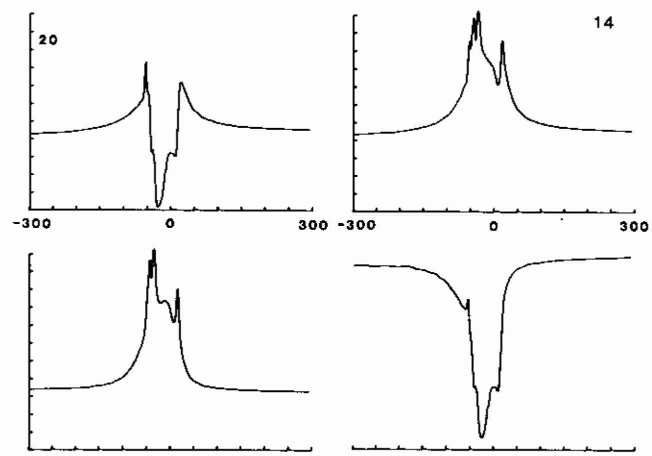


FIGURE 9.14.

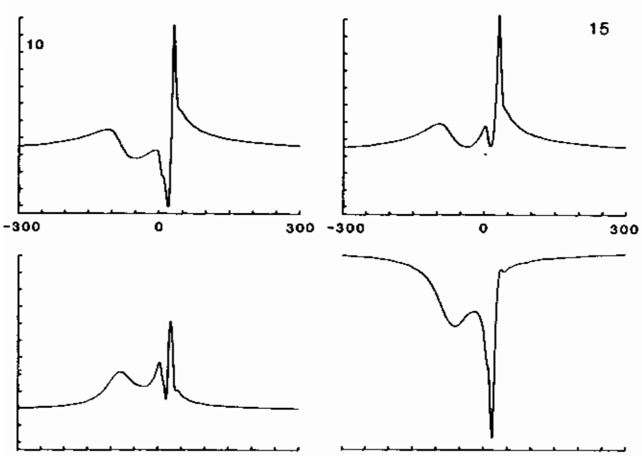


FIGURE 9.15.

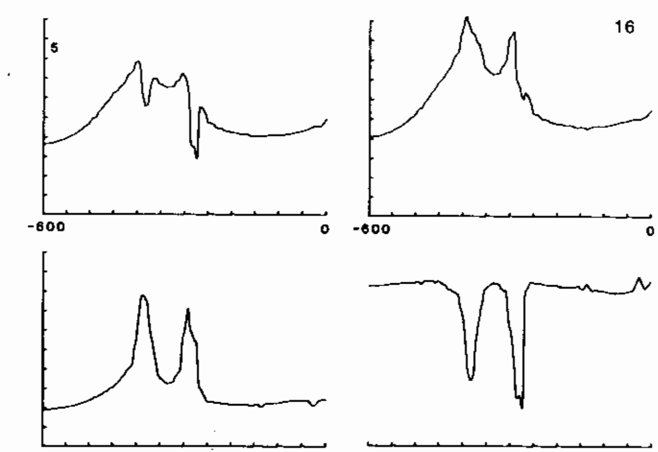
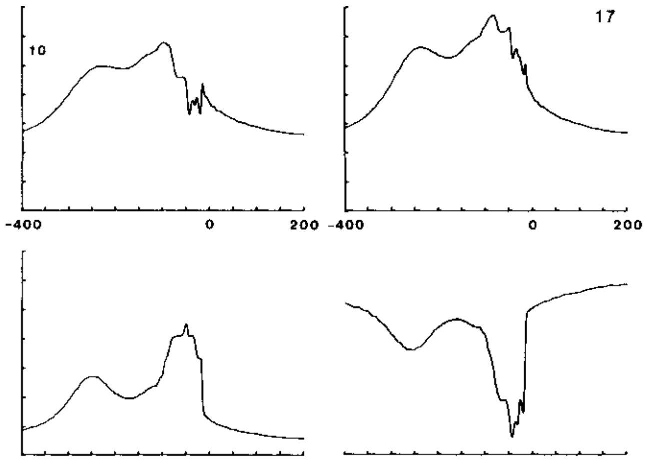


FIGURE 9.16.



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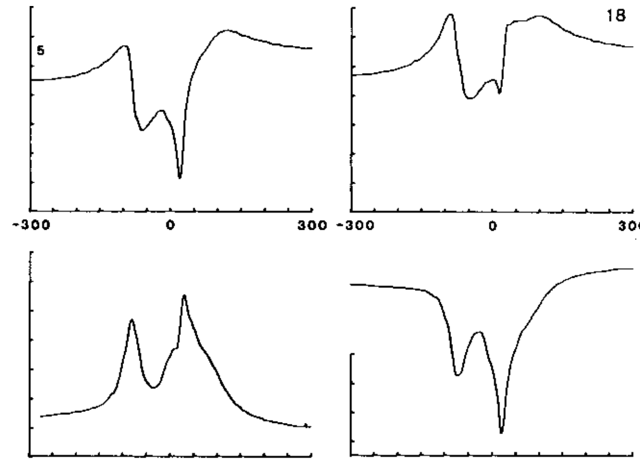

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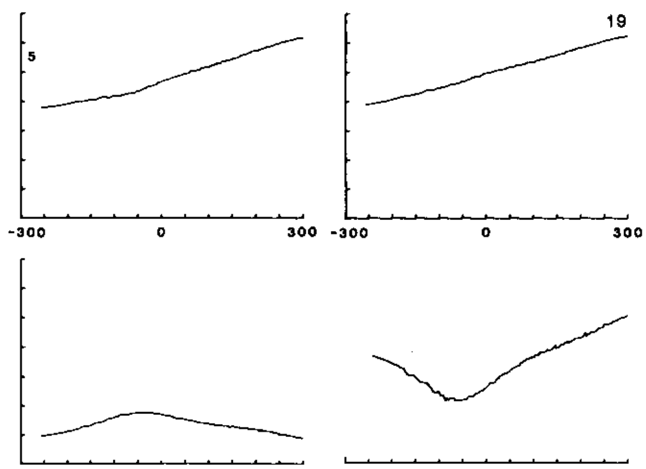

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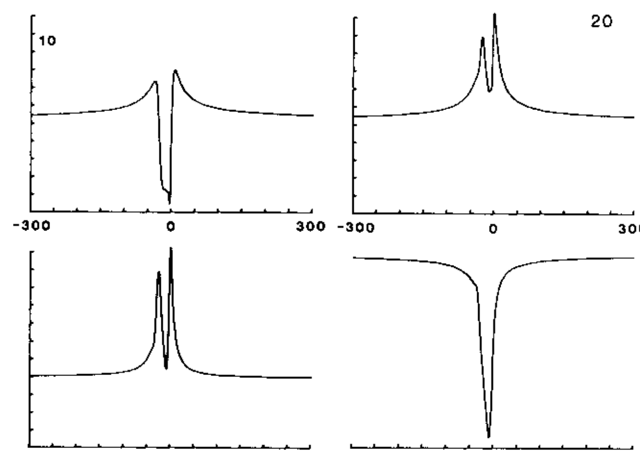

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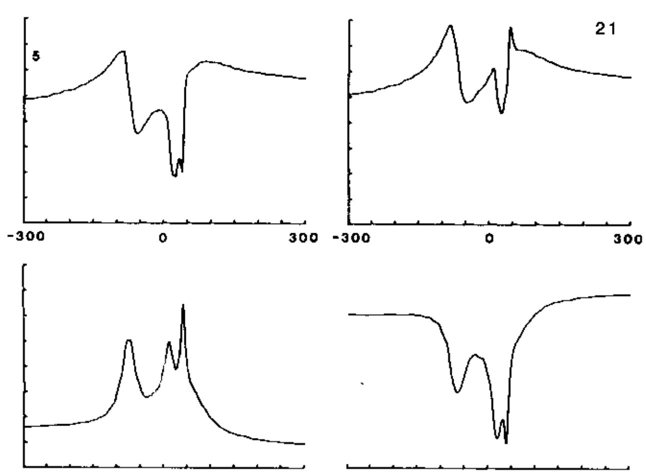

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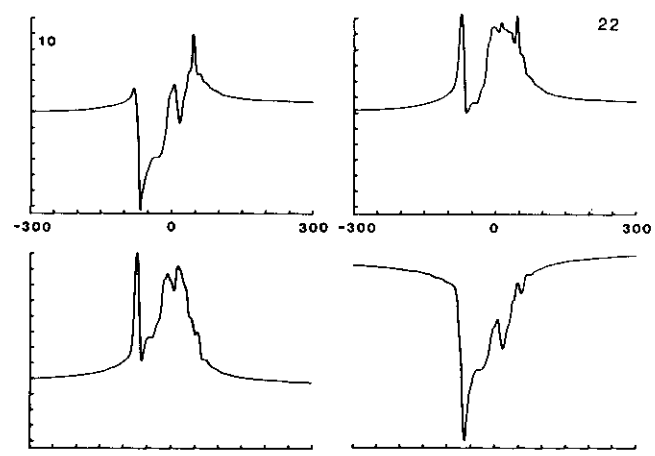

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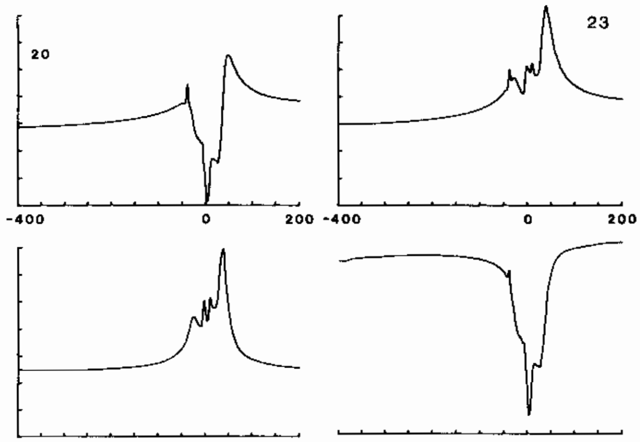

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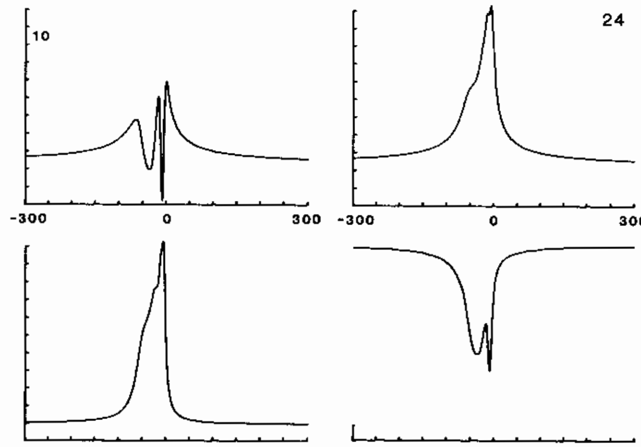

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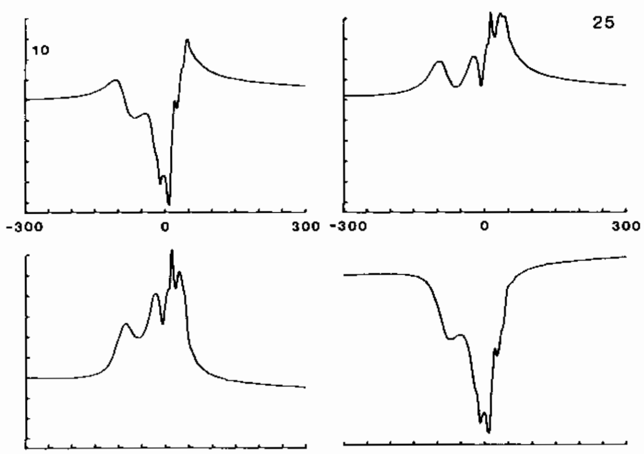

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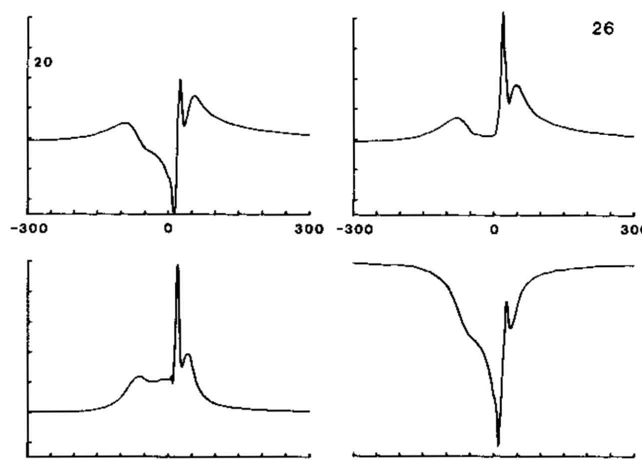

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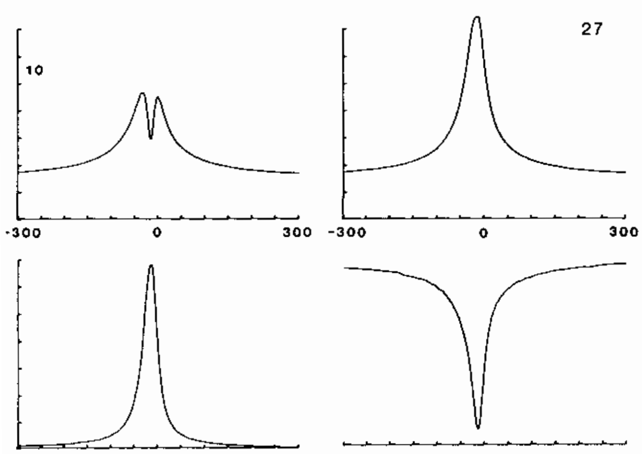

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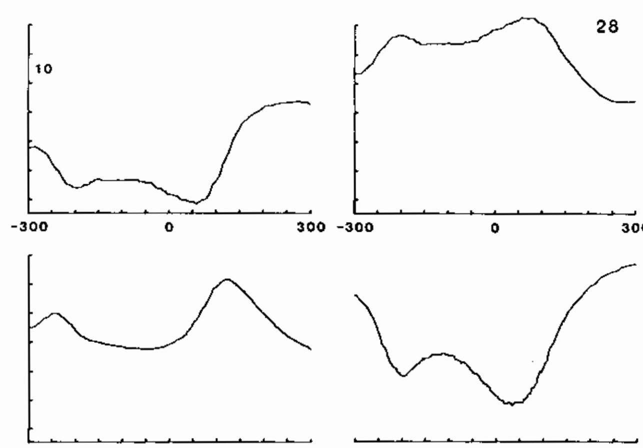

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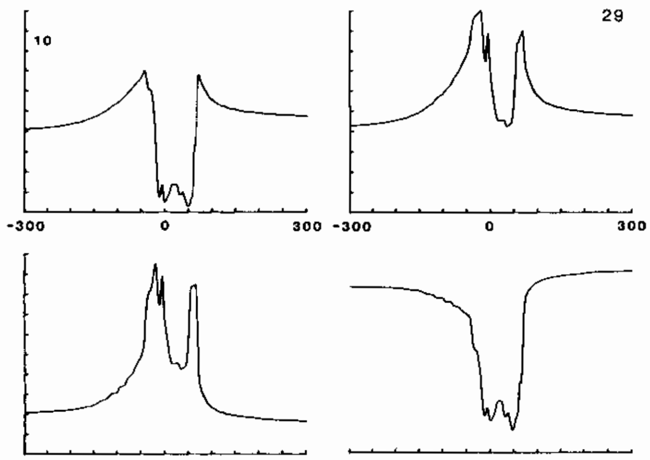

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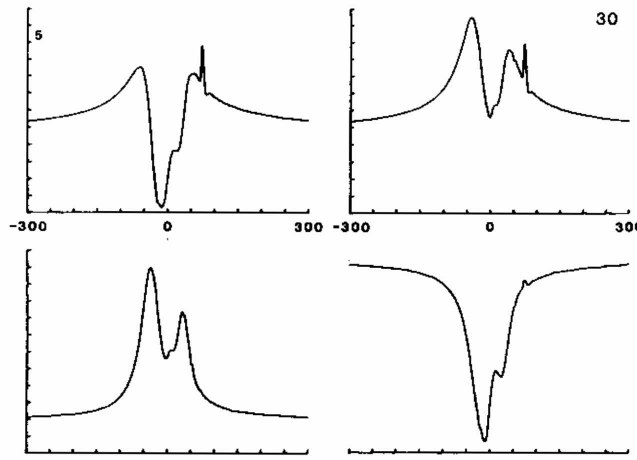

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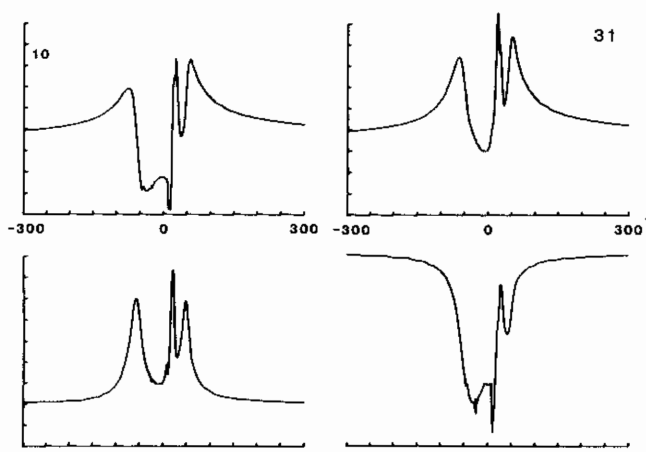

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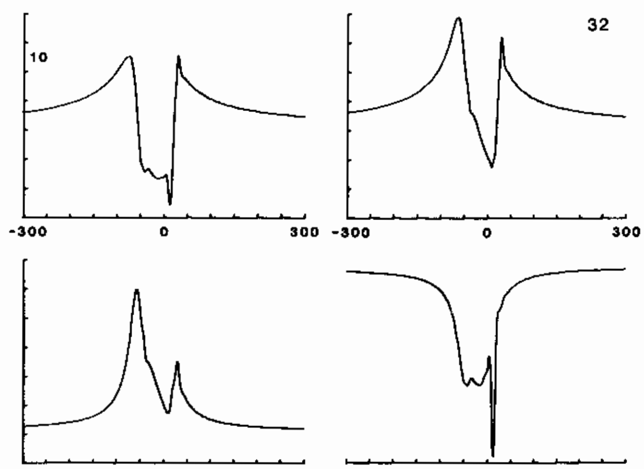

FIGURE 9.32.

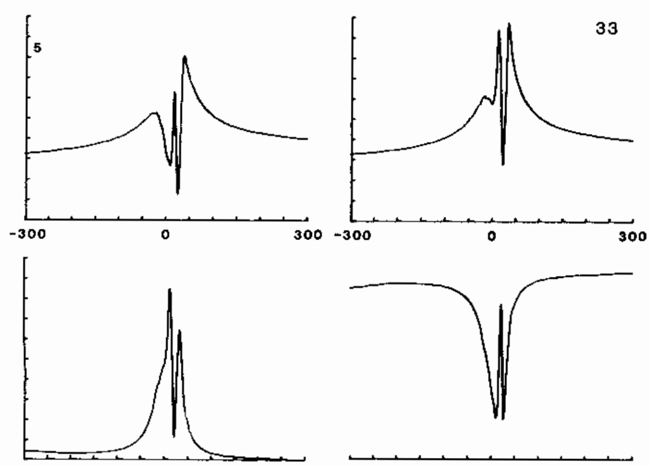

FIGURE 9.33.

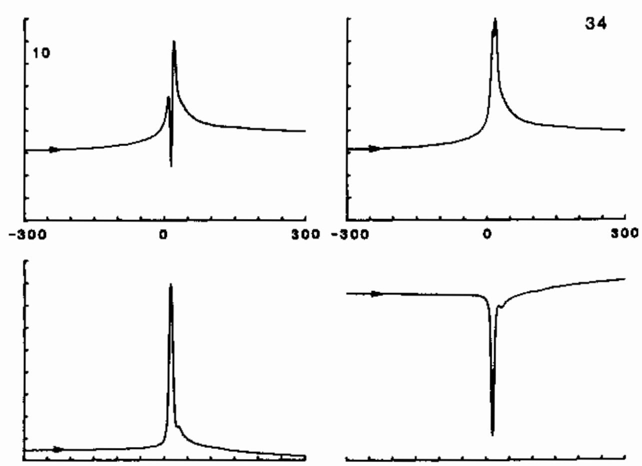

FIGURE 9.34.

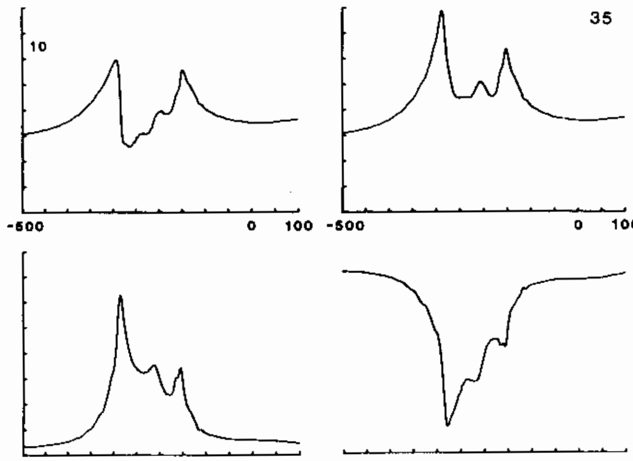

FIGURE 9.35.

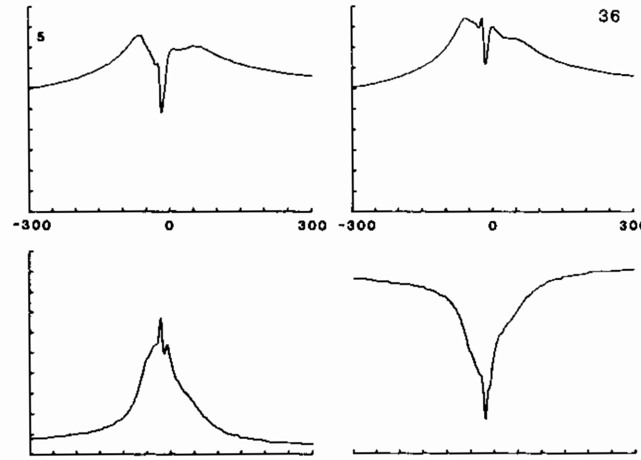

FIGURE 9.36.

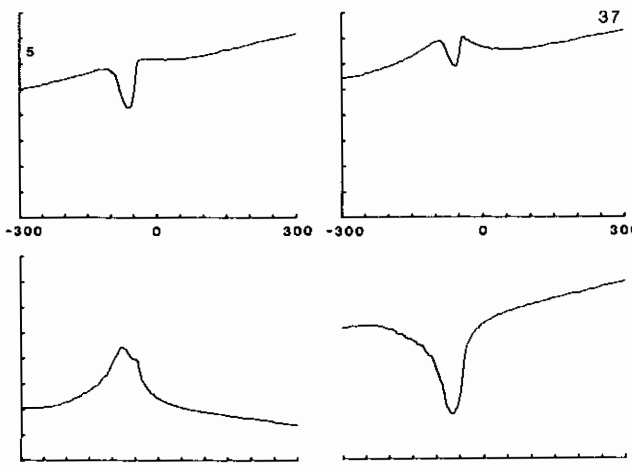

FIGURE 9.37.

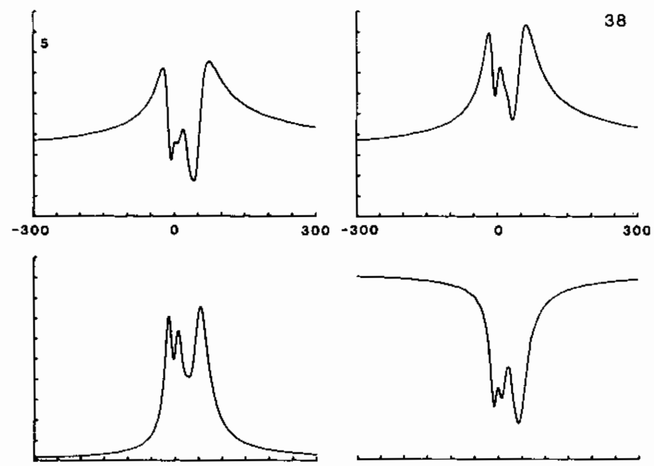

FIGURE 9.38.

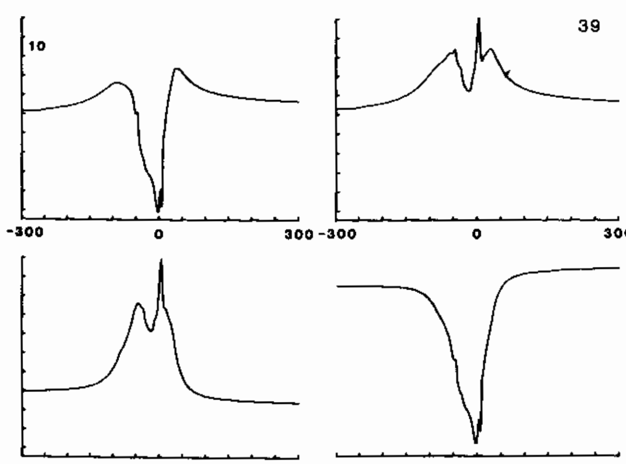

FIGURE 9.39.

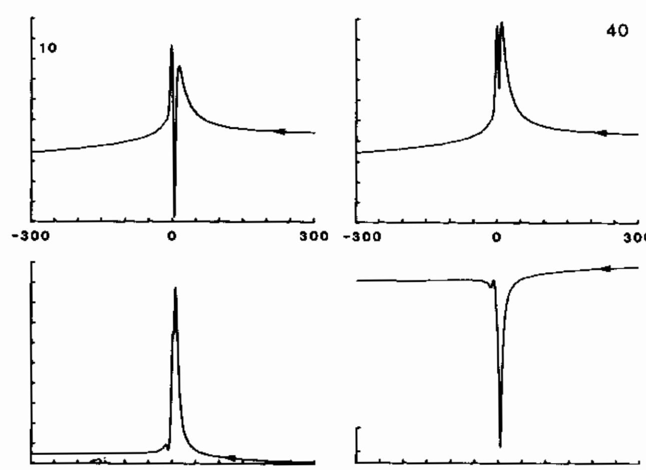

FIGURE 9.40.

FIGURE 9.1. A regular 1B1G, 1Y1φ set of tympanograms. Normal middle ear.

FIGURE 9.2. Irregular multipeaked tympanograms, in the (B,G) and in the (Y,φ) approach. Ossicular or severe eardrum abnormality.

FIGURE 9.3. Regular, broad, 3B1G, 1Y1φ set of tympanograms. Mild otitis media or external otitis.

FIGURE 9.4. Regular, broad 5B3G, 3Y3φ set of tympanograms with a small, insignificant irregularity on the conductance and admittance recordings. Ossicular or severe eardrum abnormality.

FIGURE 9.5. Normal 1B1G, 1Y1φ set of tympanograms, with a small irregularity in the conductance and the phase angle, probably due to a slow response of the AGC. Direction of pressure change was (+/−). Normal middle ear.

FIGURE 9.6. Irregular, multipeaked tympanograms, in the (B,G) and in the (Y,φ) approach. Ossicular or severe eardrum abnormality.

FIGURE 9.7. Regular 5B3G, 3Y3φ set of tympanograms. Most likely eardrum abnormality but possibly normal middle ear or ossicular abnormality.

FIGURE 9.8. Irregular, multipeaked tympanograms, in the (B,G) and in the (Y,φ) approach with a supplementary instrumental artifact (due to a faulty susceptance multiplier) clearly visible at the low pressure side in the susceptance and the admittance recordings. Ossicular or severe eardrum abnormality.

FIGURE 9.9. Irregular, multipeaked set of tympanograms. These sets are irregular because 5B5G, 5Y5φ do not fit in the Vanhuyse et al. (1975) model. Ossicular or severe eardrum abnormality.

FIGURE 9.10. Broad, irregular set of tympanograms. Ossicular abnormality.

FIGURE 9.11. Irregular, multipeaked set of tympanograms. These sets are irregular because 7B5G, 7Y5φ do not fit in the Vanhuyse et al. model (1975). This set can be explained as a sharp W–notch near zero pressure in a broad 3B3G, 3Y3φ (see Section 7.3.2: Type W–in–W). Ossicular or severe eardrum abnormality.

FIGURE 9.12. Normal, sharp 5B3G, 3Y3φ set of tympanograms. Mild eardrum abnormality.

FIGURE 9.13. Irregular, broad 5B3G, 3Y3φ set of tympanogram recordings. Ossicular abnormality.

FIGURE 9.14. Irregular, multipeaked tympanograms, in the (B,G) and in the (Y,φ) approach. Ossicular or severe eardrum abnormality.

FIGURE 9.15. Irregular, multipeaked set of tympanograms. These sets are irregular because 5B5G, 5Y3φ do not fit in the Vanhuyse et al. (1975) model. Ossicular or severe eardrum abnormality.

FIGURE 9.16. Irregular, multipeaked set of tympanograms. These sets are irregular because 7B5G does not fit in the Vanhuyse et al. (1975) model. In the (Y,φ) approach, the picture is not so clear because the mere counting of the number of extrema yields a broad 3Y3φ. The sequence of the extrema is, however, scrambled: the φ–minimum at positive pressure side is located outside the pressure interval defined by the admittance maxima (see Table 2.2). Most likely ossicular abnormality.

FIGURE 9.17. Irregular and very broad multipeaked tympanograms, in the (B,G) and in the (Y,φ) approach. Most likely ossicular abnormality.

FIGURE 9.18. Irregular, multipeaked set of tympanograms. These sets are irregular because 5Y3φ do not fit in the Vanhuyse et al. (1975) model. The B,G tympanograms do not reveal the irregularity because they can be classified as a broad 5B3G. The interpretation is much easier in the (Y, φ) than in the (B,G) approach. Ossicular or severe eardrum abnormality.

FIGURE 9.19. High impedance abnormal (glue ear), classified as 0B1G, 0Y1φ set of tympanograms (see Section 2.4, Figure 2.16).

FIGURE 9.20. Regular 3B3G, 3Y1φ set of tympanograms (on the borderline of a 5B3G pattern). Normal middle ear or mild eardrum abnormality.

FIGURE 9.21. Irregular, multipeaked set of tympanograms. These sets are irregular because 5B5G, 5Y5φ do not fit in the Vanhuyse et al. (1975) model. Ossicular or severe eardrum abnormality.

FIGURE 9.22. Irregular, multipeaked tympanograms, in the (B,G) and in the (Y,φ) approach. Ossicular or severe eardrum abnormality.

FIGURE 9.23. Irregular, multipeaked tympanograms, in the (B,G) and in the (Y,φ) approach with a supplementary instrumental artifact (due to a faulty susceptance multiplier) clearly visible at the low pressure side in the susceptance tympanogram. Ossicular or severe eardrum abnormality.

FIGURE 9.24. Irregular, multipeaked set of tympanograms. These sets are irregular because 5B1G, 1Y3φ do not fit in the Vanhuyse et al. (1975) model. Probably eardrum abnormality.

FIGURE 9.25. Irregular, multipeaked tympanograms, in the (B,G) and in the (Y,φ) approach. Ossicular or severe eardrum abnormality.

FIGURE 9.26. Irregular, multipeaked set of tympanograms. These sets are irregular because 5B5G, 5Y3φ do not fit in the Vanhuyse et al. (1975) model. This set can be explained as a sharp W–notch near zero pressure in a broad 3B3G, 3Y1φ (see Section 7.3.2: Type W–in–W). Ossicular or severe eardrum abnormality.

FIGURE 9.27. Regular, sharp 3B1G, 1Y1φ set of tympanograms. Normal middle ear.

FIGURE 9.28. Extremely broad, 5B3G, 3Y3φ set of tympanograms. Most likely ossicular abnormality.

FIGURE 9.29. Irregular, multipeaked tympanograms, in the (B,G) and in the (Y,φ) approach. Ossicular or severe eardrum abnormality.

FIGURE 9.30. Regular but broad 3B3G, 3Y3φ set of tympanograms with a supplementary instrumental artifact (due to a faulty susceptance multiplier) clearly visible at the positive pressure side in the susceptance and admittance recordings. Ossicular or severe eardrum abnormality.

FIGURE 9.31. Irregular, multipeaked tympanograms, in the (B,G) and in the (Y,φ) approach. At closer examination it can be interpreted as a W–in–W (see Section 7.3.2; compare with Figure 9.11). Ossicular or severe eardrum abnormality.

FIGURE 9.32. Neglecting the small irregularities between −50 and 0 daPa, the set seems to be a regular, broad 3B3G. The phase angle recording, however, shows that a sharp notch is superimposed on a nearly regular broad 3Y1φ (see Section 7.3.2: Type W–in–W). The irregularity is more apparent in the (Y,φ) than in the (B,G) approach. Ossicular or severe eardrum abnormality.

FIGURE 9.33. Although this set of tympanograms seems a regular 5B3G, 3Y3φ at first glance (except for an extremely small irregularity in the admittance at the negative pressure side), this set must be considered as irregular because the central maximum of the susceptance is clearly above the tail values (see Section 2.3.1, comments after Type 5B3G). Most probably eardrum abnormality.

FIGURE 9.34. Regular, sharp 3B1G, 3Y1φ set of tympanograms, with a small bump in conductance and phase probably due to AGC problems. Normal middle ear.

FIGURE 9.35. Irregular, multipeaked tympanograms, in the (B,G) and in the (Y,φ) approach. Ossicular or severe eardrum abnormality.

FIGURE 9.36. Mere counting of the number of extrema in the susceptance and the conductance tympanograms should lead to classification as a normal 3B3G. At closer examination and taking into account the sudden slope changes, it is in fact a 3B1G with a sharp supplementary notch near zero pressure. This notch is especially clear in the conductance and admittance recordings. The measurements were done on a temporal bone with an experimentally produced ossicular abnormality.

FIGURE 9.37. Regular, sharp 3B1G, 3Y1φ set of tympanograms. Large ear–canal volume change together with indistinct susceptance maxima creates an unusual shape. Nearly a 4B1C type (see Section 2.4 and Figure 2.17). Normal middle ear.

FIGURE 9.38. Irregular, multipeaked set of tympanograms. These sets are irregular because 5B5G, 5Y5φ do not fit in the Vanhuyse et al. (1975) model. Ossicular or severe eardrum abnormality.

FIGURE 9.39. Irregular, multipeaked set of tympanograms. These sets are irregular because 5Y3φ do not fit in the Vanhuyse et al. (1975) model. This set can be explained as sharp W–notch near zero pressure in a broad 3B3G, 3Y1φ (see Section 7.3.2: Type W–in–W). The interpretation is much easier in the (Y,φ) than in the (B,G) approach. Ossicular or severe eardrum abnormality.

FIGURE 9.40. Normal sharp 3B3G, 3Y1φ set of tympanograms (limit case), with a small bump due to AGC problem (+/− pressure direction). Normal middle ear or mild eardrum abnormality.

Appendix A

Power Transfer and the Concept of Impedance

The concept of impedance, developed by Heaviside in 1886, is a useful means of characterizing a physical system because it is directly related to the power transfer or power consumption of the system for which the impedance is assessed.

The acoustic input impedance at the drum determines the available power at the input to the middle–ear system. However, this input impedance does not tell us how much energy is transmitted through the middle–ear system into the cochlea or how much energy is dissipated or lost in the middle ear itself. The relation between the acoustic input impedance and the power available at the drum is developed below.

In mechanics it is known that the instantaneous power (P_i) transferred through a system by the instantaneous force (F_i) producing an instantaneous velocity (v_i) is given by

$$P_i = F_i v_i. \tag{A.1}$$

If F_i and v_i are colinear (i.e., the force and displacement occur in the same direction), the product $F_i v_i$ is positive. When the force and displacement occur in opposite directions, the product $F_i v_i$ is negative. For an acoustical system Equation A.1 is transformed by substituting for F_i and v_i the analogous acoustical quantities:

$$P_i = p_i U_i \tag{A.2}$$

where p_i and U_i are the instantaneous sound pressure and volume velocity, respectively. For a sinusoidally varying sound pressure, the situation is somewhat complicated. We are interested in an average power transfer so that for p and U, being sinusoidally varying quantities, the phase angle between the two quantities must be taken into account. If the sound pressure is written as (see Equation 1.2)

$$p(t) = p_o \sin(2\pi f t + \varphi_z), \tag{A.3}$$

the resulting volume velocity can be expressed by (see Equation 1.3)

$$U(t) = U_o \sin 2\pi f t. \tag{A.4}$$

One can prove now that the average power transfer is given by

$$P_{av} = \frac{1}{2} p_o U_o \cos\varphi_z. \tag{A.5}$$

A convenient method of characterizing time–varying quantities is the root mean square (rms) value. The rms pressure p_{rms} and the rms volume velocity U_{rms} can be substituted into Equation A.5 to produce

$$P_{av} = p_{rms} U_{rms} \cos\varphi_z, \tag{A.6}$$

because

$$p_{rms} = p_o/\sqrt{2} \quad \text{and} \quad U_{rms} = U_o/\sqrt{2} \tag{A.7}$$

for sinusoidal quantities. Readers who wish to obtain more information are referred to electronics textbooks on alternating currents, remembering that sound pressure is analogous to electrical voltage and volume velocity is analogous to electrical current. From the polar definition of the acoustic impedance (Equation 1.6) we obtain

$$|Z_a| = \frac{p_o}{U_o} = \frac{p_a\sqrt{2}}{U_a\sqrt{2}} = \frac{p_{rms}}{U_{rms}}. \tag{A.8}$$

Substitution of Equation A.8 in Equation A.6 leads to

$$P_{av} = p_{rms}^2 \frac{U_{rms}}{p_{rms}} \cos\varphi_z \tag{A.9}$$

or

$$P_{av} = \frac{p^2}{|Z_a|} \cos\varphi_z. \tag{A.10}$$

Equation A.10 states the relationship between power and impedance. Since P_{av} and $|Z_a|$ are inversely proportional, the larger $|Z_a|$, the smaller the power transfer. Equation A.10 clearly indicates the importance of the phase angle. Even for a very low absolute value of the acoustic impedance $|Z_a|$, there will be no power transfer if $\varphi_z = +90°$ or $-90°$ since $\cos 90° = \cos -90° = 0$. Only a complete definition of the impedance $|Z_a| \angle \varphi$ enables computation of the power transfer.

The concept of admittance can be similarly determined. Combining Equation A.8 and the polar definition of admittance (Equation 1.7) results in:

$$P_{av} = p_{rms}^2 |Y_a| \cos\varphi_y. \tag{A.11}$$

From this equation it follows that P_{av} and $|Y_a|$ are directly proportional: the larger the absolute value of the admittance $|Y_a|$, the larger the power transfer (for a constant φ_y). Note that introducing $\varphi_y = -\varphi_z$ does not result in an inversion of the sign of P_{av} defined by Equation A.10 or A.11 because for all angles $-90° < \varphi < +90°$, $\cos(\varphi_y) = \cos(-\varphi z) > 0$. Average power transfer is always positive (or zero) as all terms in (Equation A.11) are positive (or zero). Equation A.9 also explains why the following equation is used for decibel (dB) computations:

$$dB = 20 \log_{10} \frac{p^2_{rms}}{p^2_{rms}\,(ref)}, \qquad (A.12)$$

although the definition of decibel is

$$dB = 10 \log_{10} \frac{p^2_{av}}{p^2_{rms}\,(ref)}. \qquad (A.13)$$

From Equation A.13 one deduces indeed

$$dB = 10 \log_{10} \frac{P_{av}}{P_{av}\,(ref)} = 10 \log_{10} \frac{p^2_{rms}}{p^2_{rms}\,(ref)} \times \frac{|Z_a|}{|Z_a|} \times \frac{\cos \varphi_z}{\cos \varphi_z} \qquad (A.14)$$

or

$$dB = 10 \log_{10} \frac{p^2_{rms}\,(ref)}{p^2_{rms}\,(ref)} = 20 \log_{10} \frac{p^2_{rms}\,(ref)}{p^2_{rms}\,(ref)} \qquad (A.15)$$

because:

$$\log a^n = n \log a.$$

Appendix B

Conversion Formulas

Because the phasor representation of any impedance is a right triangle, one can apply a few well known general trigonometric definitions and equations leading to the conversion formulas of Table 1.1. These definitions are:

APPENDIX B.1. Basic trigonometric equations.

Pythagoras	The sum of squares of the rectangular sides of a right triangle equals the square of the hypotenuse
Definition of a sine	Side opposite/hypotenuse
Definition of a cosine	Side adjacent/hypotenuse
For any angle $\propto$	$\sin \propto = -\sin(-\propto)$ $\cos \propto = \cos(-\propto)$

Application of the definition of a cosine on the phase angles φ_z and φ_y in Figure 1.3 leads to:

$$\cos\varphi_z = \frac{R}{|Z|} \quad \text{or} \quad R = |Z|\cos\varphi_z, \tag{B.1}$$

and

$$\cos\varphi_y = \frac{G}{|Y|} \quad \text{or} \quad G = |Y|\cos\varphi_y. \tag{B.2}$$

Similarly, the definition of a sine results in:

$$\sin\varphi_z = \frac{X}{|Z|} \quad \text{or} \quad X = |Z|\sin\varphi_z, \tag{B.3}$$

and

$$\sin\varphi_y = \frac{B}{|Y|} \quad \text{or} \quad B = |Y|\sin\varphi_y. \tag{B.4}$$

The Theorem of Pythagoras leads to:

$$|Z| = \sqrt{R^2 + X^2} \tag{B.5}$$

and

$$|Y| = \sqrt{B^2 + G^2}. \tag{B.6}$$

The relations between admittance and impedance components can be derived with Equations B.1 through B.6 together with general trigonometric equations. From

$$|Z| = 1/|Y| \tag{B.7}$$

and Equation B.1 it follows that

$$R = \frac{1}{|Y|}\cos\varphi_z. \tag{B.8}$$

Because $\cos\varphi_z = \cos\varphi_y = G/|Y|$ one obtains:

$$R = \frac{1}{|Y|} \times \frac{G}{|Y|} = \frac{G}{B^2 + G^2}, \tag{B.9}$$

and similarly

$$X = \frac{1}{|Y|} \times \frac{-B}{|Y|} = \frac{-B}{B^2 + G^2}. \tag{B.10}$$

Analoguously one can deduce the inverse equations

$$G = \frac{R}{X^2 + R^2} \quad \text{and} \quad B = \frac{-X}{X^2 + R^2}. \tag{B.11}$$

Appendix C

History of the Development of Tympanometry

The basic principles that led to the development of tympanometry have their origins in three distinct areas of inquiry. In the 19th and early 20th centuries, a number of investigators made informal observations of the effect of air pressure on the auditory system. The application of these observations to the diagnosis of ear disease was the precursor to the clinical use of tympanometry. Acoustic impedance measurement techniques were derived from the concept of electrical impedance and were applied to electroacoustic systems by the early telephone engineers. These diverse areas of inquiry were brought together by the developers of tympanometry to produce the aural acoustic impedance measurements with ear–canal pressure changes that have become essential components of the audiologic and otologic evaluations.

When one considers that the early investigators designed and built the apparatus required to make their observations, the effort and creativity that went into those early studies seem heroic. Lucae's interference otoscope, with which he compared the impedances of his patients' two ears; Van Dishoeck's pneumophone, used to determine the ear–canal air pressure that maximized loudness; and Békésy's acoustic bridges, capable of measuring the complex acoustic impedance of human ears, are precursors of the current electroacoustic–integrated circuit devices. The awesome complexity of the current technology seems, somehow, unnecessary when one views the elegant simplicity of the early instruments. In the following paragraphs the development of tympanometry is traced from its preelectric beginnings to the present–day clinical techniques. For a comprehensive review of the history of the study of middle–ear function see Shallop (1976).

OBSERVATIONS OF THE EFFECTS OF AIR PRESSURE ON HEARING

Perhaps the first observation that led to the development of tympanometry was made by Wollaston (1820). He noted that negative middle–ear pressure reduced hearing sensitivity and increased the tension of the tympanic membrane. A few years later, in a classic paper entitled "Experiments on Audition," Sir Charles Wheatstone (1802–1875) reported six not–so–closely–related observations including the frequency dependence of the head shadow effect, the occlusion effect, and the effect of middle–ear pressure on auditory sensitivity (Wheatstone, 1827). He also noted a decrease in sensitivity when the ear–canal air pressure was increased by pressing his cupped hand over the pinna to compress the air in the external ear. This is probably the first observation of the effect of ear–canal air pressure on middle–ear function. It is a remarkable coincidence that Wheatstone later published the first description of the electrical bridge circuit that bears his name (Wheatstone, 1843). Actually invented and reported ten years earlier by Wheatstone's colleague, S. H. Christie (1833), the Wheatstone bridge was developed for electrical resistance measurements used in the pioneering work of these engineers in the development of the printing telegraph (Hubbard, 1965). The Wheatstone bridge, then, not invented by Wheatstone, led to the popular use of the term "impedance bridge" to describe tympanometry instruments, most of which are not based on bridge circuitry at all.

These early observations on the effect of middle–ear pressure led to the important works of Toynbee (1865) and Politzer (1869), whose systematic studies of middle–ear function, pathology, and treatment are the origins of otology. Their understanding of the importance of middle–ear pressure led to several attempts to measure and alter the pressure behind the tympanic membrane. Fowler (1920), for example, measured and altered the middle–ear pressure by determining the pressure applied to the nasopharynx necessary to "center" the otoscopically observed tympanic membrane. Fowler observed that the normal condition of the middle ear was characterized by negative pressure ranging from very slight to -20 mm Hg (-266 daPa). Fowler also measured the effect of middle–ear pressure on the time to inaudibility of air–conducted signals generated by tuning forks, and noted the frequency dependent effect of middle–ear pressure on auditory sensitivity, an observation that was later confirmed by several investigators who had more sophisticated means at their disposal.

Other investigators sought to measure the middle–ear pressure by determining the effects of ear–canal air pressure on loudness and auditory thresholds. The assumption, still widely accepted, was that the listener would experience maximal loudness when the pressure difference across the eardrum was zero. Perhaps most notable among these psychophysical determinations of middle–ear pressure are the classic papers of Pohlman and Kranz (1923, 1925). They sealed an electroacoustic transducer in the ear canal of their normal subjects and measured loudness and thresholds for various ear–canal air pressures. Their measurements were, in a sense, psychophysical tympanograms, and predate the first physical tympanograms by 35 years.

A clinical technique for the psychophysical determination of middle–ear pressure was developed by Van Dishoeck (1937). Van Dishoeck's "pneumophone" consisted of a manually operated air pump which, along with the acoustic output of an audiometer, was coupled to the ear canal by a tube. The ear–canal air pressure required for maximal loudness was determined. Remarkably, the pneumophone was used in the first attempt to screen school children for middle–ear disease by van den Borg (1942) who tested 500 children with Van Dishoeck's device.

ACOUSTIC IMPEDANCE MEASUREMENTS AT AMBIENT EAR–CANAL AIR PRESSURE

Lucae (1867) developed his interference otoscope to provide a psychophysical comparison of the acoustic impedance of a patient's two ears (see Shallop, 1976, Figure 2.3, p. 20). A sound ("probe tone") was delivered to the ears via identical coupling tubes. Another tube allowed the examiner to listen to the sound that was delivered, first to one ear, then to the other. To the extent that the examiner could detect loudness differences, Lucae's ingenious device provided a method for detecting interaural differences in acoustic impedance. The sensitivity of such an instrument, of course, is limited by the differential sensitivity to intensity of the observer, a serious limitation that would be overcome by replacing the observor with electroacoustic instrumentation. The underlying principle governing the interference otoscope was precisely the same as the one exploited by our modern microprocessor tympanometry devices—acoustic impedance.

The concept of impedance (the complex ratio of a force–like quantity to a velocity–like quantity) has been useful in the study of a wide variety of physical systems. Electrical, mechanical, acoustical, and thermodynamic systems can be analyzed with the unifying concept of impedance. Oliver Heaviside (1850–1925[25]) is credited with developing the concept and mathematics of impedance in his pioneering work in electrical engineering. Heaviside was the nephew of Sir Charles Wheatstone, and wrote extensively on the "Wheatstones bridge," among other topics. Much of his work was published in the British trade journal, *The Electrician* and a collection of those papers was published in two volumes in the year of his death with annotations by Heaviside himself. Heaviside lived a life of self–imposed seclusion. As a self–educated scientist whose theories were, at times, in conflict with those of the more established members of the Royal Society, Heaviside lived, worked, and published outside of conventional circles. His conflicts with colleagues are evident in the Forward to his collected papers (Heaviside, 1925) when he commented on the editors of the prevailing scientific publications. The editors, he wrote, "thought that official views were so much more likely to be right that it was safe to decline the discussion of novel views in such striking opposition thereto" (Heaviside, 1925, p. x). In fact, many of Heaviside's early manuscripts were denied access to publication by his colleagues who may have been ill–equipped to judge the importance of his work. His reclusive life style also may have been related to hearing loss (Asimov, 1982). Heaviside's intentional evasion of social and professional gatherings certainly is consistent with hearing impairment in an era that preceded the advent of effective hearing aids. If hearing loss forced an isolation that led to his prolific writings on topics that would have enormous impact on the development of instruments for diagnosis and rehabilitation of auditory disorders, Heaviside's career has to be one of the great ironies of science.

Impedance is a generalization of the concept that was introduced by the German physicist, Georg S. Ohm (1789–1854). Ohm's electrical law, inspired by the writings of Fourier on the physics of the transfer of heat (Asimov, 1982), states the relationship among voltage, current, and resistance. Heaviside generalized the relationship to complex electrical circuits and introduced the method of expressing impedance as a vector quantity. The rudiments of his formal exposition of the concept of impedance are scattered through his early papers but the first detailed mathematical development appeared in a series of articles published in *The Electrician* in 1886. A discussion of inductive transmission lines contained the following introduction of the term impedance, complete with instructions for its pronunciation:

> Let us call the ratio of the impressed force to the current in the line when electrostatic induction is ignorable the Impedance of the line, from the verb impede. It seems as good a term as Resistance, from resist. (Put an accent on the middle e in impedance.) [Heaviside 1886a]

Later he extended the formulation to capacitive circuits (Heaviside 1886b).

The principles developed in these remarkable papers have had a profound impact on many disciplines. Due to the wide applicability of these concepts to problems in many fields, which are not solidly based in mathematics and physics, correct application has, at times, been troubled by poor understanding of the fundamental concepts. The trouble began long before audiologists started contributing to the confusion. Heaviside's frustration with his own colleagues, who had their own problems with the basic concepts, was evident in the following passage from an 1883 paper:

> As regards Ohm's law, if there is little to be said that has not been said over and over again, it is certain that a good deal of nonsense has been written about it. Perhaps no scientific law has had so much unscientific discussion, a result to be attributed in the main to its remarkable practical im-

[25]At the time of publication of his collected papers (Heaviside, 1925) the date of Heaviside's birth was apparently uncertain. The date of his death was February 3, 1925, when his age was variously given as 70, 74, and 77 years. Later accounts (Asimov, 1982; Gillispie, 1972) give his birthdate as May 18, 1850.

portance bringing it down from the professors to the multitude, which must always contain amongst the great mass who are willing to learn, and are too modest to imagine . . . that the professors are all wrong, a certain number of self–confidant paradoxers, whose peculiar conceit is that their views are necessarily right. Self confidence is, no doubt, an excellent thing in its way, but when coupled with ignorance of the fundamental truths of dynamics . . . leads to extraordinary jumbles sometimes. Did they only deceive themselves in their delusions little harm would be done, but when they take to writing books for students, then a whole body of blind followers is precipitated into the ditch of mental confusion, from which extrication is so difficult, and whose mud sticks for so long (Heaviside, 1883).

One hundred years later, similar "extraordinary jumbles" characterize the application of Heaviside's principle to the clinical examination of the ear.

The first exposition of the principles of acoustic impedance was probably that of Webster (1919) who developed the principles as they applied to new electroacoustic devices like the phonograph and the telephone. Kennelly and Kurokawa (1921) measured the mechanical impedance of a telephone diaphragm under various acoustic loads. By loading the telephone with the human ear, they were able to estimate the aural acoustic impedance. These estimates represent the first impedance measurements made on human ears and were followed by the papers of West (1928) and Inglis, Gray, and Jenkins (1932). Since these early experiments used telephone receivers that were loosely coupled to the ear, the measurements are difficult to compare with later measurements that employed probes that were hermetically sealed in the ear canal. The first measurements that employed an insert probe were probably made by Tröger (1930), with several other investigators soon to follow (Békésy, 1932; Geffcken, 1934; Waetzmann & Keibs, 1936). Although these early investigators recognized the importance of the volume of air between the probe and the tympanic membrane, a method of correcting the measurement for ear–canal volume would not be employed until Zwislocki's (1957a,b) important experiments that led to his model of the middle ear. The problem of ear–canal volume correction would render the early methods inadequate for clinical purposes. Only with the advent of tympanometry would the ear–canal volume problem be solved in a manner that made aural acoustic impedance measurements clinically useful.

The classic monograph of Otto Metz (1946) was the most important step toward application of these early impedance measurement techniques to clinical problems. A Danish otologist, Metz designed an acoustic bridge that was fashioned after Schuster's (1934) device for measuring the acoustic properties of various materials. After four years of work at the State Hospital in Copenhagen, Metz was forced to leave Denmark in 1943. He continued his work at the University of Lund in Sweden, where he resided until the end of the war. This remarkable work, more than any other, laid the foundation for our current clinical acoustic impedance methods. Metz described the physical principles underlying aural acoustic impedance measurements, and reported on the acoustic characteristics of a wide variety of normal and pathological ears. Primarily because the Metz bridge had no facility for estimating the ear–canal volume, absolute impedance measures made with this method were not sufficiently sensitive to differences among ears to make the instrument clinically useful. Still, Metz demonstrated that middle–ear pathologies produced changes in aural acoustic impedance that could be measured by a probe inserted into the ear canal. Furthermore, he pointed out the potential value of acoustic reflex measurements and discussed the possibility of evaluating eustachian tube function, applications that he elaborated in later papers (Metz, 1951, 1953).

Another line of investigation that was important to our current understanding of aural acoustic impedance was the development of middle–ear models. In the course of developing these models, several investigators made impedance measurements that have contributed significantly to the understanding of normal and pathological middle–ear function. The works of Moller (1965), Onchi (1961), and Zwislocki (1957a,b; 1962) are notable in this regard. Zwislocki's acoustic bridge (Zwislocki & Feldman, 1963) could estimate the aural acoustic impedance, corrected to the tympanic membrane by an alcohol injection method. Zwislocki and Feldman (1970) used the instrument to study a wide variety of abnormal ears.

These early measurements of the properties of normal and pathological ears employed devices that measured impedance with ambient air pressure in the ear canal. The methods were not to be widely used for clinical purposes for two reasons. First, measurements made at ambient ear–canal pressure are made with a wide range of pressure differences across the eardrum. Consequently, these measurements consistently overestimate the impedance of the ear that exists when the pressure difference is zero, and are characterized by inter– and intrasubject variability that is too high for clinical applications. Second, these methods either did not provide ear–canal volume corrections, or did so with the cumbersome procedure of filling the ear canal with fluid. A satisfactory method of ear–canal volume correction would be needed to provide a clinically feasible method of estimating the impedance at the tympanic membrane. This and other unexpected advantages would lead to the widespread use of tympanometry.

TYMPANOMETRY

Metz (1946) recognized the problem of measuring the acoustic impedance of the ear with normally varying middle–ear pressures:

> If such differences of pressure can occur on the normal ear, they may be reflected in the measured Imp. and thereby give rise to differences in the measurements, both repeated measurements on the same ear and on comparison between right and left ear. (p. 103)

He also recognized that his bridge was too cumbersome for routine clinical use and envisioned our current instrumentation:

> It would be a great advantage if it would be sufficient to connect a small apparatus (a telephone) with the ear, and make the measurements on a possibly bigger apparatus placed on a table alongside the patient. (p. 233)

Thomsen (1958), carrying on the work of Metz in Copenhagen, studied the effects of air pressure on the impedance of the ear using a pressure chamber. Earlier investigations had revealed that pressure differences across the tympanic membrane influenced the motion (Dahmann, 1929, 1930; Frenckner, 1939) and the impedance (Békésy, 1932) of the eardrum. Thomsen suggested that the minimal impedance occurs when the pressures on either side of the eardrum are equal. This work led to the development of the apparatus that Metz had anticipated. Terkildsen and Thomsen (1959) published the first impedance measurements recorded as a function of ear–canal air pressure. They used an electroacoustic device, described by Terkildsen and Scott–Nielsen (1960), that was the prototype of the first commercially available aural acoustic immittance instrument. Several features of the Terkildsen and Thomsen paper are particularly noteworthy. First, these investigators selected a low–frequency probe tone (220 Hz) "partly at random." While their initial probe frequency selection was logical at the time, the nearly exclusive availability of the low probe frequency on commercial instruments has severely limited the development of tympanometry as a clinical method. Second, these investigators pointed out that "the difference between the highest and lowest impedance volumes as obtained by variations in pressure, is thought to some extent to indicate the vibrating characteristics of the individual eardrum" (p. 414). Terkildsen and Thomsen recognized that the impedance at the eardrum could be estimated from the tympanogram, and suggested the MAX/MIN method for correcting for ear–canal volume. Third, by expressing their measurements in terms of equivalent volume of air in ml, Terkildsen and Thomsen initiated the convention of approximating the impedance of the ear as a "compliance." While this approximation is reasonable for normal adult ears at low probe frequencies, it is not reasonable for many abnormal adult ears, for normal ears at higher frequencies, or for normal neonate ears at any frequency. The failure of later investigators to recognize the limitations of the compliance analogy has led to the kind of "extraordinary jumbles" that aggravated Heaviside one hundred years ago.

During the 1960s there was very little further development of the technique named "tympanometry" by Terkildsen (1964). (Anderson, Holmgren, & Holst, 1956, had previously used the term for their measurements of the ear–canal sound pressure resulting from a vibratory signal applied by bone conduction.) Commercial instruments became available and the use of tympanometry as a screening device was pioneered by Brooks (1968, 1969). As clinicians gained experience with the new technique, a variety of tympanometric patterns began to be recognized. These were first categorized by Lidén (1969a,b) and Jerger (1970), but a framework for understanding the various tympanometric patterns would not appear until the important 1975 article by Vanhuyse, Creten, and Van Camp.

The first commercially available, two–component electroacoustic impedance instrument (Grason–Stadler, Model 1720 otoadmittance meter) provided investigators and clinicians with the opportunity to study tympanometry in the context of the complex impedance concepts originally introduced by Heaviside. Introduced in 1970, this instrument measured the rectangular coordinates of acoustic admittance (conductance and susceptance) at two probe frequencies (220 and 660 Hz). Measurements made with this instrument provided the basis for the development of the Vanhuyse model, a simple set of rules that accounted for a wide variety of tympanograms obtained from normal and abnormal ears (Vanhuyse et al., 1975). Subsequent investigations have basically confirmed the Vanhuyse model and determined its limitations (Creten et al., 1978; Lidén et al., 1977; Margolis et al., 1978; Margolis & Popelka, 1977; Margolis et al., 1985). The model was elaborated by Van Camp et al., (1978) into a mathematical framework that accounts for the complex tympanometric shapes that have been observed.

Because most of the tympanometric research since the original Terkildsen and Thomsen (1959) report was performed with commercial instrumentation, the scope of the work has been limited by decisions made by manufacturers regarding the capabilities of the instruments. The proliferation of one–component, one–frequency instruments has not been based on an understanding of the basic principles, nor on the optimization of clinical techniques. Our dependence on these instruments has limited the application of available information and restricted investigations. Hopefully, the development of tympanometry will continue without such inordinate reliance on marketing decisions made by instrument manufacturers.

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