Scientific Foundations of Audiology

Perspectives from Physics, Biology, Modeling, and Medicine

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INTRODUCTION

This is not your typical textbook in audiology; rather, it represents a compendium of state-of-the-art chapters on unique topics dealing with hearing, vestibular, and brain science, the majority of which are not found in standard texts but are highly pertinent to the field. The underlying theme is that audiology is the primary "translational interface" between basic science and clinical concerns. Trained primarily as clinicians and clinical scientists, audiologists are situated in a unique position to implement breakthroughs in engineering, molecular biology, neuroimaging, genetics, medicine, nanobioscience, etc., and deliver them to the clinic. However, the underlying advancements require a fundamental understanding of advanced concepts and materials. Therefore, our intent is to provide a foundation for doctoral students in audiology, physics, neurobiology, and engineering and residents in various medical specialties (otolaryngology, neurology, pediatrics, and neurosurgery) with the background and concepts necessary to facilitate understanding in these different areas.

Of the "Current issues" subsumed within this book, we focus on topics that have practical, experimental, and theoretical value. The practical information is clearly apparent and is directly applicable to clinical situations. However, within this material, we also provide insight into basic areas of research where technical information is developing, where our understanding is incomplete, where theory has *not* been applied in a rigorous manner, and where experimental models can be improved upon to validate our concepts in complex areas. We hope that the end result will inspire new investigators to fill in the gaps and advance the field.

Moreover, it should be obvious that after viewing the table of contents, the topics being covered are expansive. They range from areas of basic science (anatomy, physiology, genetics, gene expression, molecular biology, neurochemistry) and clinical concerns (peripheral and central otopathology) to other relevant domains in assessment and treatment. They cover physical principles of middle ear and inner ear function (auditory, vestibular, balance), molecular and neural substrate underlying normal and pathologic activity in afferent and efferent pathways, implanted devices (cochlear and midbrain implants), mechanisms of speech perception associated with electrical stimulation, to the cortical processing of sound (normal and pathological) using noninvasive methods vis-à-vis magnetic resonance imaging (MRI).

We also consider "Future perspectives" in a similar context to those areas described above. However, these particular areas will no doubt be transformative in nature, where advancements are motivated by the ingenuity of the investigators and where the potential to produce large dividends (successful treatments and potential cures) is on the horizon. One area of interest concerns the combined use of manganese-enhanced MRI (MEMRI), gene expression, and functionalized nanoparticles to treat noise-induced tinnitus. Another very exciting domain concerns novel approaches for the protection and restoration of hearing. This highly fluid area is expected to have substantial impact on the field, where future developments remain extremely bright.

It is our hope that information derived from these topics expands one's knowledge base but also provides the incentive to improve the status quo. However, this is not an easy task. To succeed in this ambitious undertaking, we have assembled a stellar array of international world-class scientists, clinicians, and scholars to ensure that state-of-the-art technical information is explicated in an understandable, logical, and cohesive manner. The authors of these chapters have taken this task very seriously and share the common responsibility for giving an exposé on potential gaps in knowledge that currently exist in a thoughtful and unselfish manner. We are extremely grateful for their efforts and contributions.

To summarize, we believe that this book will have many beneficiaries. They will be independent of geographical boundaries but will have in common the desire to learn and apply new and advanced concepts to everyday situations. This includes a broad spectrum of individuals from multiple scientific disciplines, including medicine (otolaryngology, pediatrics, neurology, neurosurgery), engineering (biomedical, mechanical, electrical, chemical), basic science (neuro/molecular biology and neurochemistry), rehabilitation, physics, psychology, and of course audiology, where each group will have specific domains-of-interest and applications. We also believe that having a literary source in one book that contains a repository of diverse and highly technical information, presented in a coherent manner, should be extremely valuable to a wide range of individuals, but to our knowledge, such a document does *not* yet exist. Therefore, this book should fill an important void in the scientific literature as a combined reference text, research guide, and educational tool.

As science in this area evolves, the profession of audiology is in a unique position to integrate advanced technologies developed by clinicians, engineers, and basic scientists and apply them to the clinic. Consequently, audiologists and others in related fields like medicine and engineering represent the "translational interface" between basic science and current clinical concerns. It is a big responsibility to integrate new ideas and concepts into the clinic but it is one that encompasses the technical skills and educational background of those individuals already working in this field.

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—Pim van Dijk

CHAPTER 1

Middle-Ear Reflectance: Concepts and Clinical Applications

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The middle ear is a complex sound transmission system that converts airborne sound into cochlear fluid-born sound, in a relatively efficient way, over the bandwidth of hearing (about 0.1–15 kHz). The middle ear is the gateway to the auditory system, and it is involved in nearly every audiologic test. It is therefore critical to assess middle-ear status in any audiologic evaluation and, in the case of abnormal middle-ear function, pinpoint the source of pathology to enable an appropriate medical intervention. By the use of wideband acoustic measurements, the middle-ear structures can be noninvasively probed across the wide frequency range of hearing, allowing clinicians to make nuanced interpretations of hearing health. The term *wideband acoustic immittance* (WAI) has recently been coined as an umbrella term to identify a variety of acoustic quantities measured in the ear canal (Feeney et al., 2013). Here we focus primarily on wideband reflectance, from which other WAI quantities may be derived. The *reflectance* is defined as the ratio of reflected to forward pressure waves.

A middle-ear reflectance measurement involves inserting an acoustic measurement probe into the ear canal, fitted with an ear tip designed to create a sealed ear-canal cavity (Figure 1–1). A hearing aid loudspeaker in the probe transmits wideband sound into the ear canal. Any reflected sound, related to structures of the middle ear, is measured by the probe microphone. This probe is calibrated in such a way that the absorbed and reflected pressures in a cavity may be determined.

Reflectance measurements are clinically practical to make: The measurement takes less than a minute and the ear does not require pressurization. The

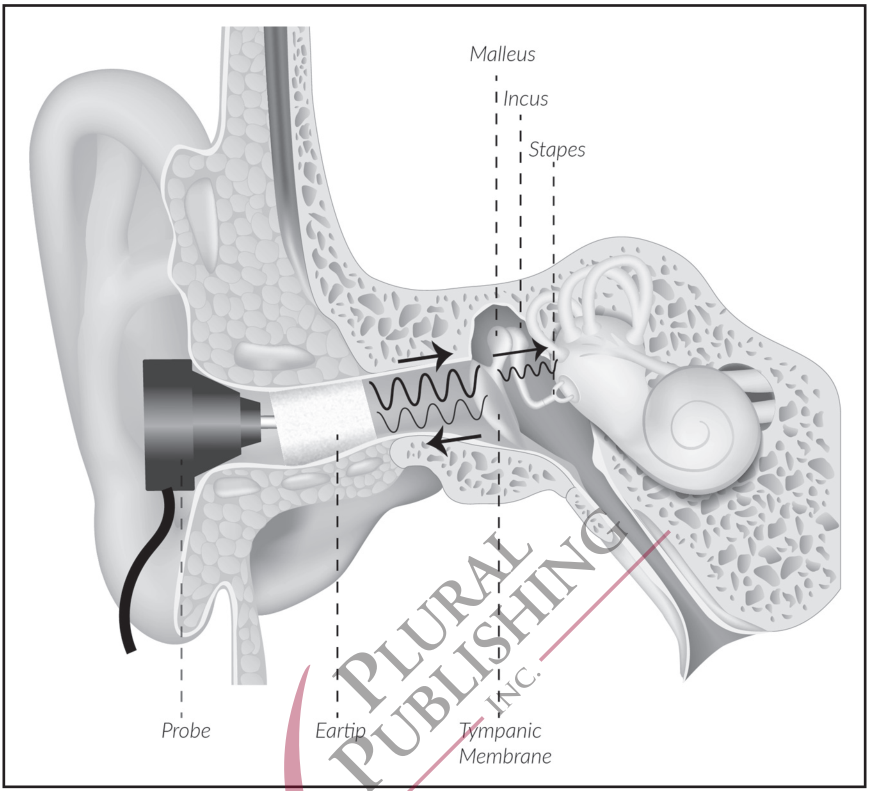

Figure 1–1. Probe configuration in the ear canal to measure middle-ear reflectance, showing the acoustic signal traveling down the ear canal until it reaches the TM. At the TM, the sound is partially reflected back into the ear canal and partially absorbed into the middle ear.

same probe can be used for other audiologic tests, such as otoacoustic emission (OAE) tests and pure-tone hearing threshold testing. Such testing, when a microphone is used in the ear canal, is known as *real-ear* testing. Given knowledge of the reflectance, it is possible to correct for troublesome ear canal standing waves, which can produce large artifacts in the real-ear calibrations. Alone, or together with other audiologic measurements, middle-ear reflectance measurements can help identify many abnormal conditions which may lead to conductive hearing loss (CHL), including degrees of otitis media, tympanic membrane (TM) perforations, otosclerosis, and ossicular disarticulation. The method is noninvasive, fast, and clinically available.

In this chapter, we cover the theoretical principles of middle-ear reflectance. We then move to clinical applications, showing how normal middle ears behave and how abnormal middle ears differ. We offer advice on how to make quality measurements and provide suggestions for future research.

Background to Middle-Ear Assessment

Noninvasive assessment of middle-ear status is of great importance in hearing health care. An early approach to middle-ear assessment is that of *tympanometry* (e.g., Feldman, 1976; Shanks, 1988), and it is still the clinical gold standard. The method relies on measurements at low frequencies (e.g., probe tones at 226 Hz and 1,000 Hz are commonly used) and provides no information on the status of the middle ear at higher frequencies relevant to speech perception (e.g., 0.2–8.0 kHz). The methods employed in tympanometry were developed prior to the introduction of digital technology, and these methods reflect the limitations of that era.

Reflectance of sound from the TM and the acoustic impedance of the middle ear are different facets of the same underlying mechanism. Historically, acoustic impedance of the ear was the first to be measured and studied (West, 1928). There is a substantial body of research on the acoustic impedance of the ear. Metz (1946) developed the first clinical instrument for measuring the acoustic impedance of the ear. This instrument was not easy to use and clinical measurement of acoustic impedance proceeded at a slow pace until more practical instruments were developed (Møller, 1960; Terkildsen & Nielsen, 1960; Zwislocki & Feldman, 1970). Tympanometry, the measurement of the middle-ear acoustic impedance as a function of static pressure in the ear canal, provided useful clinical data. Thus, practical instruments were developed for measurements of this type. The 1970s saw a rapid growth in the use of tympanometry, which is widely used today in audiologic evaluations (Jerger, 1970).

The introduction of small, inexpensive computers in the mid-1980s paved the way for a new generation of digital test equipment with capabilities well beyond that of conventional electronic instrumentation. It also facilitated new ways of thinking about audiologic measurement, resulting in the development of innovative wideband techniques. The evolution of wideband reflectance measurement allows for more detailed diagnostic assessment of the middle-ear status than the previous approach based on tympanometry. Early reflectance studies were conducted by Keefe, Ling, and Bulen (1992); Keefe, Bulen, Arehart, and Burns (1993); and Voss and Allen (1994).

The use of reflectance measurements in a computer-based system does not preclude the use of acoustic impedance data, where appropriate. Acoustic reflectance and acoustic impedance are both WAI quantities; different facets of the same underlying mechanism. If one is known, the other can be computed by means of a mathematical transformation. This mathematical transformation can be implemented conveniently in a computer-based instrument.

Acoustics of the Outer and Middle Ear

When a sound wave travels down the ear canal toward the TM, the acoustic power is continuous until it reaches an *impedance discontinuity*, such as the

Propagation of Sound: The Basics

Many of the concepts in WAI, including reflectance, are defined in mathematical or physics terms. This creates a problem for clinicians and others without the necessary background. Here we explain some acoustical concepts in lay terms.

The transmission of sound in the ear canal can be approximated quite well by a tube with a fixed diameter equal to that of the average adult ear canal. The tube is terminated at one end by a loudspeaker that delivers an acoustic signal in the frequency range up to at least 10,000 Hz. One may imagine that the air in the tube is partitioned into a very large number of infinitesimally thin discs (Beranek, 1949); each disc can be thought of as consisting of a layer of air particles. These discs of air are compressed or expanded by an applied force, such as a change in air pressure (air molecules will spread out from an area of high pressure to an area of lower pressure), and will return to their original volume once the applied force is removed.

Consider now what happens when the loudspeaker at one end of the tube generates an acoustic signal. When the speaker diaphragm moves inward, it displaces and compresses the adjacent discs of air, which then displace and compress the next layer of air, and so on. By this means, the in and out movements of the transducer diaphragm create a pressure wave that travels down the tube at the speed of sound, about 343 m/s at 20°C. The velocity of each disc of air about its quiescent position (the position of the disc at rest) multiplied by its cross-sectional area is known as the *volume velocity*, as the product of velocity and cross-sectional area encompasses a moving volume.

The air in the tube opposes being displaced and compressed by the transducer diaphragm. The force exerted by the transducer diaphragm is equal to the pressure times the area of the diaphragm. The *work* done by the force is equal to force times the displacement, and is stored as energy in the air as it travels along the tube. The *acoustic power*, $P(f)$ (the force times the volume velocity, often expressed in watts), inserted into the tube is equal to the rate of work done. The power propagated down the tube is transmitted without significant loss through the tube via the air.

TM. Impedance discontinuities result in frequency-dependent reflections of the sound wave, which we quantify using wideband reflectance.

The acoustic variables discussed in this section may be defined either in the time or frequency domain. It is important to always be aware of which domain is under consideration. In this chapter, we work almost exclusively in the frequency domain, where all variables are functions of frequency, f. These variables are also a function of location. For measurements in the ear canal, we define $x = 0$ as the measurement probe location and $x = L$ the TM location.

Pressure and Volume Velocity Waves

We denote the forward traveling pressure wave as $P_+(f,x)$ [Pa], using the plus sign subscript to signify the forward direction (toward the TM). This wave is a function of both frequency f (in Hz) and location and has units of Pascals. Similarly, the reflected, backward traveling *retrograde* pressure wave is denoted $P_-(f,x)$. At any location in the ear canal, the total pressure $P(f,x)$ is defined as

$$P(f,x) = P_+(f,x) + P_-(f,x). \tag{1}$$

The pressure is a scalar quantity (it has no direction). Any change in the pressure results in a force, which is a vector quantity (it has direction); this force leads to the motion (velocity) of air molecules in the direction of the force.

The corresponding acoustic *volume velocity* $U(f,x)$ may be decomposed into forward $U_+(f,x)$ and reverse $U_-(f,x)$ traveling portions, as

$$U(f,x) = U_+(f,x) - U_-(f,x). \tag{2}$$

The volume velocity is a vector quantity, which accounts for the change in sign of Equation 2 (here positive U_- values indicate propagation of the retrograde wave toward the probe, and positive U_+ values indicate propagation of the forward wave toward the TM).

The *complex acoustic reflectance*, which we represent using the uppercase Greek letter "Gamma," is defined as the ratio of retrograde to forward traveling pressure (or velocity) waves

$$\Gamma(f,x) = \frac{P_-(f,x)}{P_+(f,x)} = \frac{U_-(f,x)}{U_+(f,x)}. \tag{3}$$

Since $\Gamma(f,x)$ is complex, it may be expressed either as the sum of real and imaginary parts, or in terms of a magnitude and phase. The utility of the complex reflectance (as compared to other WAI quantities, such as impedance and admittance) is that the acoustic power is proportional to the square of the pressure. Thus, the squared magnitude of the reflectance describes the ratio of reflected to incident power (a value ranging between 0 and 1) as a function of frequency, while the reflectance phase codifies the latency of the reflected power (e.g., the depth at which the reflection occurs). Additionally, power absorbed by ear (potentially including the ear canal, middle ear, and inner ear) may be quantified as one minus the ratio of power reflected. The *power reflectance* at the probe may be defined as $|\Gamma(f,0)|^2$; thus, the power absorbed by the ear is $1 - |\Gamma(f,0)|^2$. These properties of reflectance are more intuitive than impedance for formulating diagnoses of middle-ear pathologies.

For reference, the *complex acoustic impedance* is defined as the total pressure over the total volume velocity

$$Z(f,x) = \frac{P(f,x)}{U(f,x)}. \tag{4}$$

The *complex acoustic admittance* is given by $Y(f,x) = \frac{1}{Z(f,x)}$ and various other WAI quantities may be calculated from $Z(f,x)$ and $Y(f,x)$, as outlined in Appendix 1–A. This variety of immittance quantities can be confusing, so it is important to remember that they may all be derived from the complex acoustic reflectance. Specifically, the complex impedance is related to the reflectance via

$$Z(f,x) = r_0\frac{1+\Gamma(f,x)}{1-\Gamma(f,x)}, \tag{5}$$