Otoacoustic Emissions
Principles, Procedures, and Protocols

Second Edition

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Foreword

The Core Clinical Concepts in Audiology series was introduced to make learning in audiology more effective. The ongoing goal is to provide palatable and useful information to students and practitioners to develop and refine clinical skills for audiology practice.

Most textbooks available for our field provide exhaustive examination of broad topic areas. Many of them are edited texts with chapters representing rather diverse contributions from a variety of authors. Such books are certainly useful and necessary for advanced scholarship. However, we currently lack pedagogic materials that focus on basic clinical methods and knowledge. The books in this series are designed for teaching and learning.

Books in the Core Clinical Concepts in Audiology series are written for the student. The scope of practice for audiology has expanded dramatically since the inception of our field. Today's students must acquire a tremendous arsenal of clinical skills and knowledge in a very short period of time. The books of the CCC series are meant to be clear and comprehensible to students, focusing on the content necessary to achieve knowledge and skills for clinical practice. Furthermore, the books are designed to be economical in time spent in learning and in purchase price.

The Core Clinical Concepts in Audiology books are also written for the clinician. With expansion of the scope of audiology practice, currently audiologists must acquire new skill sets while continuing to serve their patients in busy clinical practices. Not a small feat. Hard-working practitioners deserve educational materials compatible with the real-world demands of fast-paced and time-limited clinical practice. In response to these needs, the books of the CCC series are informationally compact to allow readers to efficiently acquire the essential concepts and skills described in the books.

Finally, books in the Core Clinical Concepts in Audiology series are written for the instructor. Most instructors of audiology courses are familiar with the frustration of searching for materials that cover topics reflecting the learning outcomes of their courses. Especially lacking are materials designed to promote clinical learning. The books of the CCC series are designed to focus on specific areas of clinical practice. They are targeted toward the learning outcomes commonly found in audiology curricula. Due to the economical nature of the books, instructors can feel comfortable in creatively combining different Core Clinical Concepts in Audiology books to support the unique and diverse learning demands of specific courses.

These books are written for the user. The needs of the reader are our primary concerns. These books are written with the purpose of helping readers learn to be outstanding clinical audiologists. To be sure, these are lofty goals. The authors of the CCC series books have put forth their best effort to accomplish these goals.

The original *Otoacoustic Emissions: Principles, Procedures, and Protocols,* by Sumitrajit Dhar and James W. Hall III, was a readable yet comprehensive source of information on otoacoustic emissions (OAEs). The second edition of the popular book offers readers an updated review of this clinically important topic. The book begins with a succinct overview of OAEs and a fascinating historical description of their discovery and emergence as a clinical tool. A chapter is devoted to the anatomical and physiological underpinnings of OAEs, with an emphasis on the latest information necessary for understanding cochlear processing important in the generation of OAEs. Students and clinical audiologists alike will appreciate the way the authors clearly explain and concisely review current research findings on the origins of OAEs and changing perspectives on OAE taxonomy. Another chapter focuses on the important topic of OAE instrumentation and the often overlooked but critical topic of instrument calibration.

The book includes two chapters offering a detailed yet practical review of the measurement and analysis of transient and distortion product OAEs. Unfortunately, these essential topics are often overlooked in publications about OAEs. The discussion includes ample reference to screen displays and other features of modern clinical OAE devices. These chapters are followed by two others that provide an up-to-date literature review highlighting all major evidence-based clinical applications of OAEs in children and in adults. This second edition of *Otoacoustic Emissions: Principles, Procedures, and Protocols* updates and expands the review of clinical applications, reflecting information found in hundreds of new peer-reviewed publications. Another chapter explores current thinking on the usually neglected efferent auditory pathways, including the role of OAEs in evaluating this important component of the auditory system. The book concludes with an exciting glimpse into the future as the authors introduce the reader to new directions in OAE research and clinical application.

As with the other books of the CCC series, the organization and construction of the book works to provide important and necessary information in a manner consistent with the needs of readers.

James W. Hall III, PhD
Virginia Ramachandran, AuD, PhD
Series Editors

Preface to the First Edition

Thirty years ago, beginning in 1980, several groups of hearing scientists independently demonstrated that outer hair cells can elongate and contract. The rather revolutionary discovery of outer hair cell motility suggested an anatomic and physiologic explanation for the generation of otoacoustic emissions, first reported by David Kemp in 1978. Although outer hair cell motility clearly plays an important role in the production of OAEs, ongoing investigations for the past 30 years have yielded a vast amount of information, and even some controversy, as to the precise mechanisms underlying the origins of OAEs. Pursuit of an exact understanding of OAE generation and propagation profoundly will influence their clinical application.

The rather simplistic early classification of OAEs as either spontaneous or evoked has given way to a more complex taxonomy. Importantly, there appear to be major differences in the way TEOAEs and DPOAEs are generated. With the more recently proposed classification system, OAEs are categorized based on their mechanism of generation and grouped into those arising from a nonlinear mechanism and those arising from a linear reflection mechanism. A basic understanding of cochlear physiology is necessary to understand the distinction between these two modes of OAE generation. Unfortunately, the clinical audiologist is hard-pressed to find an up-to-date, straightforward, and clinically focused source of information on the mechanisms of OAE generation. With this in mind, we included in *Otoacoustic Emissions: Principles, Procedures, and Protocols* a clinically oriented review of current explanations for the generation of OAEs, including the latest thinking on the taxonomy of OAEs.

Within the past three decades, over 3,000 articles have appeared in peer-reviewed literature providing evidence in support of dozens of clinical applications of OAEs. For the first time, we summarize this vast amount of information so audiologists and other hearing health professionals can make rational decisions about why and how to use OAEs with children and adults in the clinical setting. Accumulated experience with OAEs has led to some proven procedures and protocols for clinical measurement and analysis, as suggested by the title of our book, *Otoacoustic Emissions: Principles, Procedures, and Protocols*. The vast clinical literature pertaining to OAEs in cochlear pathophysiology in children and adults is also summarized in two chapters of the book.

A book on OAEs would not be complete without a discussion of OAE suppression as a clinical tool. Also, mention must be made of advances in technology that permit the combined and integrated measurement of OAEs and other time-tested clinical techniques. We address each of these important topics in *Otoacoustic Emissions: Principles, Procedures, and Protocols*. Thirty years after their discovery, we are still learning more about the multiple mechanisms responsible for generation of OAEs and, at the same time, witnessing a consistent expansion and refinement of clinical applications. As clinical audiologists and clinical researchers, we gladly convey information and excitement about OAEs to our colleagues in the form of our book, *Otoacoustic Emissions: Principles, Procedures, and Protocols*.

Sumitrajit Dhar, PhD
James W. Hall III, PhD

Preface to the Second Edition

We are excited to complete a second edition of *Otoacoustic Emissions: Principles, Procedures and Protocols*. The preface for the original edition, republished in the front matter of this book, summarized major steps in the emergence of OAEs as a clinical tool and also stated our rationale for writing a textbook on the topic of otoacoustic emissions. In that preface, we commented, "Within the past three decades, over 3,000 articles have appeared in the peer-reviewed literature providing evidence in support of dozens of clinical applications of OAEs." Only 5 years later, a PubMed search with the keyword "otoacoustic emissions" reveals more than 5,000 peer-reviewed publications. The second edition of *Otoacoustic Emissions: Principles, Procedures, and Protocols* picks up where the earlier edition left off. We offer an update on otoacoustic emissions incorporating recently published information arising from basic investigations on the generation of OAEs and clinical research on applications in children and adults.

Both editions of *Otoacoustic Emissions: Principles, Procedures, and Protocols* are dedicated to the memory of our departed colleague and friend Roger Ruth. Roger made many important contributions to audiology as a clinician, teacher, researcher, administrator, and through his dedicated service to professional organizations such as the American Academy of Audiology, the American Auditory Society, and the International Evoked Response Audiometry Study Group. Roger also played a critical role in the genesis of *Otoacoustic Emissions: Principles, Procedures, and Protocols*. Indeed, we would not have coauthored the book without his influence. A brief explanation is warranted. Sometime back in about 2008 during one of my (JWH3) many telephone conversations with Roger, I mentioned an interest in writing an update to my *Handbook of Otoacoustic Emissions*, published in 2000. Given the steady increase in research findings, especially on the mechanisms and generation of OAEs, I really didn't want to write the book alone. Roger immediately suggested that I contact Sumit Dhar, a (relatively) young audiologist on the faculty at Northwestern University. Roger went on to offer a rave review of a presentation on OAEs that Sumit had recently given at an American Auditory Society meeting. Within a few days, at Roger's urging, I contacted Sumit about the prospect of coauthoring a book on otoacoustic emissions. The proposed textbook seemed to be a perfect fit for the Plural Publishing Core Clinical Concepts in Audiology series (see Foreword). In 2011, after numerous communications via telephone and email, a trip to Northwestern University for a face-to-face work session (plus a fun-filled Chicago Cubs game), and predictably persistent Plural Publishing prodding, the first edition of *Otoacoustic Emissions: Principles, Procedures, and Protocols* appeared in 2012.

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June 12, 2017

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Appendix

In memory of

Roger A. Ruth, PhD

September 2, 1950–June 13, 2009

Our audiology colleague, trusted mentor, and beloved friend.

1

Overview of Otoacoustic Emissions

HISTORICAL PERSPECTIVE

Introduction

Some delay between the discovery of a new technique for assessing auditory function and its first clinical application is usual and perhaps inevitable. Otoacoustic emissions (OAEs) were no exception. Approximately 5 years separated David Kemp's classic publication describing the first recording of OAEs in 1978 and the publication of peer-reviewed papers describing their use in infant hearing screening (e.g., Johnsen, Bagi, & Elberling, 1983). In the interim, an international collection of scientists and clinicians had initiated independent lines of investigation examining the physiology, biophysics, and clinical applications of OAEs.

Although every new discovery is accompanied by bold predictions of widespread utility in a variety of patient populations, in the long run, few technologies are able to live up to this initial euphoria. Even for techniques that eventually work their way into the clinical test battery, a second delay usually occurs between the first clinical application and widespread clinical acceptance. Again, OAEs were no exception. Another decade passed before OAEs were commonplace in clinical settings. By the mid-1990s, clinical audiologists could purchase an OAE device from a variety of manufacturers and, in the United States, two OAE billing codes were approved. Although David Kemp is certainly responsible for initiating the last phase of this journey to the addition of OAEs in the clinician's arsenal, the voyage began almost two centuries earlier.

Early Contributions: Tartini, Other Musicians, and Psychophysicists

A great wealth of knowledge has now accumulated about OAEs, as evident by the information in this textbook. When asked about the origins of this knowledge, most students and practitioners in the field trace the history of OAEs back to David Kemp or farther back to Thomas Gold (their contributions are discussed below). However, the knowledge that our ears generate sounds had existed much before the time of Kemp or Gold, with its first documentation dating back to the 1700s. That story begins with Guiseppe Tartini (Figure 1–1).

Tartini was born on April 8, 1692, in the town of Piran in current-day Slovenia, then a part of the Istrian peninsula in the Republic of Venice. Music historians believe that he received general musical training in his childhood but music was not the focus of his life and career until much later.

FIGURE 1–1. Statue of Giuseppe Tartini by Antonio dal Zotto, Tartini Square, Piran, Slovenia. From Wikimedia Commons. Photograph by Stephen Turner. Permission is granted to copy, distribute, and/or modify this document under the terms of the GNU Free Documentation License, Version 1.2 or any later version published by the Free Software Foundation; with no Invariant Sections, no Front-Cover Texts, and no Back-Cover Texts. A copy of the license can be viewed at http://en.wikipedia.org/wiki/GNU_Free_Documentation_License

Tartini studied law at the University of Padua and became an adept fencer during his time at the university. Tartini's early life was far removed from serious music. In fact, we would not even mention Tartini in passing if he had continued on the same path. However, everything changed when he married Elisabetta Premazone in 1710. Elizabetta was a favorite of a powerful cardinal by the name of Georgio Cornaro, who promptly charged Tartini with abduction. To escape prosecution, Tartini fled Padua and hid at the monastery of St. Francis in Assisi. It was here that Tartini became a serious student of the violin.

Tartini's skills as a violinist improved so greatly that he was appointed the Maestro di Capella at the Basilica di Sant'Antonio in Padua by 1721. Incidentally, legend has it that Tartini also was the first known owner of a violin made by Antonio Stradivari in 1715. Tartini started a violin school in 1726, which attracted students from all over Europe. Gradually, Tartini became more interested in harmony and the acoustics of music, and he published various treatises on these topics after 1750.

A signature of Tartini's music is the double stop trill where the performer plays two notes simultaneously, often in rapid succession. Considered a difficult skill to master even by modern standards, legend has it that Tartini had six fingers that allowed him to play these trills with relative ease. One of Tartini's better-known compositions is the Violin Sonata in G Minor, also known as the Devil's Trill Sonata for the frequent use of these trills. While playing these double stop trills, Tartini recognized the presence of audible notes that were not being produced by the violin. He concluded that these notes must be generated within the ear, and he started using them regularly in his compositions. Essentially, he would have the ear "fill in" to create a sensation of more sound than the violin was producing. Other musicians, such as the German organist Sorge and the French composer Romieu, recognized, researched, and used these ear-generated sounds, in their music. Among musicians and scientists interested in hearing, these extra sounds became known as the Tartini tones. What were known as Tartini tones in the 1700s are distortion product OAEs today. The reader is directed to Plomp (1976) for a detailed early history of Tartini tones.

Soon after the musicians were aware of "Tartini tones," psychoacousticians became interested in the phenomenon. Perhaps the earliest reports in this area are by Vieth in the early 1800s (Plomp, 1976). Vieth coined the term *combination tones* to describe the sensation of extra tones generated in the ear. The possibility of combination tones being generated in the inner ear was incompatible with the dominant model of auditory physiology of that time—that proposed by Hermann Ludwig Ferdinand von Helmholtz (1821–1894), a German physician and physicist.

Helmholtz postulated that the ear essentially worked as a frequency analyzer, decomposing complex signals into their constituent elements before passing them on to the brain. Because this was a linear model, it could not account for the generation of additional sounds within the ear. In order to accommodate combination tones, Helmholtz introduced an "overloading" type of nonlinear component in the middle ear based on the assumption that the displacement of any elastic body is linearly related to the incident pressure only for infinitesimally small amplitudes. Thus, for larger pressures, nonlinearities should be expected in the ear (Plomp, 1976).

Psychoacousticians continued to be interested in combination tones and used them to explore the nonlinearities of the inner ear noninvasively. Between about 1950 and 1980, psychoacousticians developed complex experimental techniques to record combination tones from human subjects and used these data to try to understand the source and characteristics of these tones (see Goldstein, 1970, for a review). It was indeed through psychoacoustic experiments that David Kemp (Figure 1–2A) became interested in this area of work and later performed the first physiological recordings of OAEs.

The Prophet Thomas Gold

> New ideas in science are not always right just because they are new. Nor are the old ideas always wrong just because they are old. A critical attitude is clearly required of every scientist. But what is required is to be equally critical to the old ideas as to the new. Whenever the established ideas are accepted uncritically, but conflicting new evidence is brushed aside and not reported because it does not fit, then that particular science is in deep trouble—and it has happened quite often in the historical past. If we look over the history of science, there are very long periods when the uncritical acceptance of the established ideas was a real hindrance to the pursuit of the new. (Gold, 1989, p. 103)

Dr. Thomas Gold (Figure 1–2B) wrote these words while chair of the Department of Astronomy at Cornell University in Ithaca, New York, more than 40 years after his innovative investigations of cochlear physiology in Cambridge, England.

The theme in this passage, however, accurately reflects the approach taken by Gold in the late 1940s when he challenged predominant theories

A B

FIGURE 1–2. David Kemp, the British physicist who discovered otoacoustic emissions (**A**) and Thomas Gold, the British physicist who in the late 1940s recognized the nonlinear nature of the cochlea (**B**).

of passive linear cochlear function espoused by Nobel Prize winner Georg von Békésy and, before him, the 19th-century scientific giant Helmholtz. Another quote from a 1948 article by Thomas Gold lays the foundation for the subsequent discovery of OAEs 30 years later by another British physicist, Dr. David Kemp.

> It is shown that the assumption of a "passive" cochlea, where elements are brought into mechanical oscillation solely by means of the incident sound, is not tenable. The degree of resonance of the elements of the cochlea can be measured, and the results are not compatible with the very heavy damping which must arise from the viscosity of the liquid. For this reason the "regeneration hypothesis" is put forward, and it is suggested that an electromechanical action takes place whereby a supply of electrical energy is employed to counteract the damping. (Gold, 1948, p. 492)

> The interposition of a feedback stage . . . makes construction possible where the nerve ending abstracts much energy from a mechanical resonator. (Gold, 1948, p. 498)

Like a good Hollywood movie, the fascinating story of Thomas Gold (see obituary in text box) has a happy ending. In the later years of Dr. Gold's highly varied and productive professional career, he witnessed not only the vindication of his then-heretical ideas about cochlear function, but also the emergence of OAEs as an important clinical tool. Dr. Kemp has priceless tape recordings of telephone conversations during which Thomas Gold relates, in his own words, his exciting discoveries and their less-than-enthusiastic reception by Dr. von Békésy. Readers, with a simple Internet search, will find a wealth of information about Dr. Gold and his many accomplishments.

David Kemp, Discoverer of OAEs

Dr. David Kemp (see Figure 1–2A) alone can be credited with the discovery of OAEs. He became involved in auditory research in a roundabout way, beginning with studies in general physics, electronics, and atmospheric physics, then industrial noise control. In the mid-1970s, Dr. Kemp conducted a series of psychoacoustic and then physiologic investigations on basic cochlear function that confirmed the presence of active mechanisms that could produce energy. In his truly classic paper on OAEs in 1978, Kemp unequivocally showed that, following stimulation with tones or clicks, additional sound could be measured with a small microphone in the external ear canal of animals, including humans.

Kemp's article is filled with meaty yet characteristically restrained passages summarizing his breakthrough discovery. For example,

> the response [OAEs] appears to have its origin in some nonlinear mechanism probably located in the cochlea, responding mechanically to auditory stimulation, and dependent upon the normal functioning of the cochlea transduction process. (Kemp, 1978, p. 1386)

And also,

> In the absence of a complete understanding of the mode of action of the sensory cells in the cochlea, it is tempting to suggest that one of the functions of the outer hair cell population is generation of this mechanical energy. If a cochlear origin is confirmed by experiments currently in progress, the technique developed in this study will provide a new avenue for investigation of the auditory system, with applications in both research and audiological medicine. (Kemp, 1978, p. 1391)

The rest, as the saying goes and as described in the remainder of this book, is history.

Evolution of OAEs as a Clinical Tool

The earliest clinical application of OAEs was newborn hearing screening. Certain advantages of OAEs as a hearing-screening tool were recognized almost immediately following the 1978 Kemp publication (Kemp, 1978). Abnormalities in OAE findings typically were associated with common causes of hearing loss in young children, namely, middle ear disorder and outer hair cell dysfunction.

Thomas Gold (1920–2004)*

Thomas Gold died on June 22, 2004, in Ithaca, New York, at the age of 84 after a long and varied academic career that included often-controversial research from the inner ear to outer space. Audiologists will remember Dr. Gold for his novel explanation of cochlear physiology in the late 1940s. During WWII, Gold worked for the British Admiralty on top-secret research projects to further develop radar technology. In the late 1940s, as a young graduate student, he conducted innovative studies of cochlear mechanics and physiology at the prestigious Cavendish Laboratory at Cambridge University in England. Gold's claim that the inner ear contained "mechanical resonators" and operated actively in the processing of auditory information and tuning of the auditory system were almost heretical at the time, and certainly at odds with much of the mainstream thinking dominated by the work of the eminent Georg von Békésy. Around 1948, Gold met with von Békésy and proceeded to expound on his novel theories. Some 50 years after the meeting, Gold recounted the event with characteristic British understatement and humor, pointing out von Bekesy's less than enthusiastic response to the new ideas on cochlear function. Dr. Gold's observations on active and nonlinear processes in the cochlea prophesied the discovery 30 years later of otoacoustic emissions by another British auditory scientist, Dr. David Kemp.

Dr. Gold was born in Vienna in 1920. After schooling in Switzerland and his tenure at Cambridge University, he accepted a position at Harvard University. Then, in 1959, Gold accepted a faculty position at Cornell University where he had a distinguished career serving as chair of the astronomy department and director of the Center for Radiophysics and Space Research. As an aside, at Cornell, the popular astronomer Carl Sagan was a colleague and a friend of Dr. Gold. Gold repeatedly generated controversy with his innovative research and provocative publications. In 1955, for example, he made the then outrageous claim that the surface of the moon was covered with fine powder. Although he was criticized rigorously at the time, his theories were proven in 1969 when the Apollo 11 crew returned to earth with samples of the rock powder. A fascinating obituary of Gold, published in Physics World by deputy editor Martin Durrani, documents numerous other controversies that characterized Gold's illustrious career.

As noted by Louis Friedman, Executive Director of The Planetary Society and a former student of Gold's, "Whether he was ultimately proved right or wrong, his (Gold's) ideas always challenged his colleagues to think deeply about any subject he pursued. His approach exemplified the scientific method at it's best, posing hypotheses and testing them to advance our basic understanding of the universe." Clearly, this statement appropriately describes Dr. Gold's contributions to our understanding of the workings of the inner ear. His innovative approaches to research questions and his willingness to face criticism for ideas that challenged accepted thinking and wisdom of the day offer a valuable model for auditory scientists of our day.

*Obituary by James W. Hall III, University of Florida, Gainesville, FL. Reprinted with permission from: *Audiology Today, 16*(September/October), 2004, p. 42.

Consequently, OAE screening outcome (e.g., Pass versus Fail) quickly, objectively, and rather effectively differentiated children who were likely to have reasonably normal peripheral auditory function and hearing sensitivity within normal limits versus those with peripheral auditory dysfunction and perhaps some degree of hearing loss.

In the early years of OAE screening, from about 1985 to 1995, some authors inevitably compared OAEs very favorably to the, then-established, auditory brainstem response (ABR) screening technique. OAEs were praised for both the relative brevity and simplicity of the technique: "no electrodes are required!" These specific advantages, however, were not always supported by evidence from formal investigations with head-to-head comparisons of the OAE and ABR techniques. Limitations of OAEs as a hearing screening tool also became quite apparent with accumulated clinical experience, particularly problems with unacceptably high failure rates associated with noise in the test environment and with vernix caseous in the external ear canal of newborn infants within the first day or two after birth. We can now also add the insensitivity of OAEs to auditory neuropathy spectrum disorder (ANSD) to the list of limitations of the technique in selected patient populations. Still, on balance, the many clinical advantages of OAEs as a screening technique outweigh the drawbacks. OAEs unquestionably remain an attractive option for hearing screening in varied pediatric populations, ranging from newborn infants to school-age children.

The introduction of commercially available OAE devices, and especially instrumentation for recording distortion product OAEs (DPOAEs) and transient evoked OAEs (TEOAEs) from an international list of manufacturers, led naturally to multiple nonscreening applications of the new technique. Beginning in the mid-1990s, clinical researchers enthusiastically explored the potential diagnostic value of OAEs in virtually every imaginable etiology for hearing loss. We can attest personally to the excitement produced by evaluating, for the first time in a specific patient population, auditory function with a new procedure. As soon as the newly purchased OAE device was unpacked, it was given a test run on the clinician's ears and maybe the ears of one or two handy coworkers (or offspring!). Then, almost certainly before the manual was reviewed, OAEs were somewhat shakily recorded from the first unsuspecting patient to arrive in the clinic. Typically, the new "service" initially was provided as a professional courtesy at no charge.

Arbitrary and somewhat random application of OAEs by individual clinicians within a short time gave way to systematic clinical investigations and to the development of evidence-based rationale for OAE measurement. By the year 2000, the diagnostic value of OAEs as a component within an audiologic test battery was reported for a wide spectrum of etiologies in pediatric and adult patient populations. Presentations at scientific meetings and peer-reviewed publications soon appeared describing patterns of OAE findings in disorders from malingering to Ménière's disease. The unique sensitivity and specificity of OAEs to cochlear, and specifically outer hair cell, dysfunction logically led to the measurement of OAEs in at-risk persons, such as patients exposed to hazardous levels of sound and those with tinnitus.

The etiology now typically known as ANSD is perhaps the best example of the dramatic impact of OAEs on diagnosis of auditory dysfunction. The term *auditory neuropathy* was actually coined in 1996 just as the application of DPOAEs was rapidly expanding around the world as a clinical procedure. The different types and sites of auditory dysfunction included within the preferred term ANSD were relatively unexplored and inadequately appreciated prior to the widespread clinical use of OAEs. It is not an exaggeration to claim that the advent of OAEs as a clinical procedure contributed directly to the recognition of the clinical entities we now know as ANSD.

Just as in ANSD, the presence or normalcy rather than absence of OAEs made news more recently in the discovery and diagnosis of a condition now known as hidden hearing loss (Kujawa & Liberman, 2009). Shown first in various rodent species, hidden hearing loss describes the condition where synaptic connections between the inner hair cells and auditory nerve fibers initially and then the auditory nerve fibers themselves are compromised, while outer (and presumably) inner hair cells remain healthy (Liberman, 2015; Liberman et al., 2016; Liberman & Kujawa, 2017).

Initial demonstration of the condition followed the induction of noise-induced temporary thresholds shifts. However, more recent evidence in human subjects seems to suggest chronic exposure to high levels or impulse noise could lead to the same outcome (Bramhall, Konrad-Martin, McMillan, & Griest, 2017). The clinical signature of hidden hearing loss appears to be normal OAE amplitudes accompanied by a reduction in the ABR wave I amplitude at suprathreshold levels. Yet again, OAEs prove to be an excellent tool in a test battery that allows accurate differential diagnosis between various auditory pathologies.

OAEs continue to evolve as a clinical tool, as does our understanding of the physiology associated with OAEs. Much of this book is devoted to a review of the current understanding of the physiology and biophysics related to OAEs as well as the numerous applications of OAEs in children and adults. There is still plenty of room for development and implementation of more sophisticated and rigorous strategies for OAE measurement and analysis. Without doubt, new clinical applications for OAEs will be discovered and developed in the years to come. Also, technological advances in instrumentation will considerably enhance the clinical value of OAEs and their role in the hearing test battery. An as example, newly introduced devices combining OAE and ABR or OAE and tympanometry or wideband acoustic absorbance technology (reviewed in Chapter 10) likely will contribute to more efficient and effective identification and diagnosis of auditory dysfunction.

INTRODUCTION TO AUDITORY SYSTEM ANATOMY AND PHYSIOLOGY IN OAE MEASUREMENT

Introduction

A good understanding of the anatomic and physiologic underpinnings of OAE generation and measurement is essential for recording, analyzing, and interpreting findings in the clinical setting. This topic, particularly current knowledge and theories regarding cochlear anatomy, physiology, and mechanisms that play a role in the generation of OAEs, is reviewed in far more detail in Chapter 2. As illustrated schematically in Figure 1–3, four general regions of auditory system anatomy are involved in the generation and measurement of

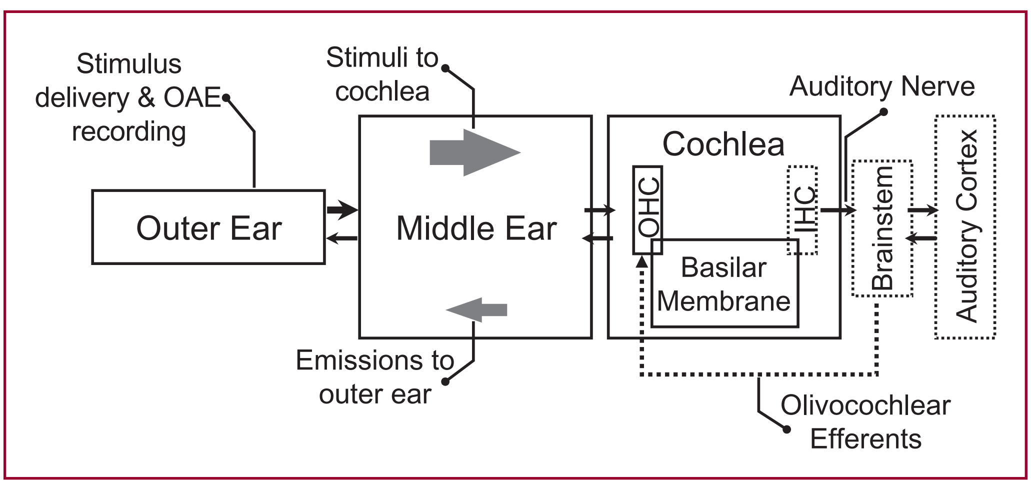

FIGURE 1–3. A simple block schematic of the major regions of the auditory system that influence the measurement of otoacoustic emissions. Note the directional arrows in the middle ear depicting the bidirectional energy transfer through this space. The size of the arrows is representative of the relative magnitudes of the energy traveling into and out of the cochlea. Structures outlined in dashed lines play a secondary role in modulating OAEs.