



# **Basic Concepts of CLINICAL ELECTROPHYSIOLOGY in Audiology**

**John D. Durrant, PhD  
Cynthia G. Fowler, PhD  
John A. Ferraro, PhD  
Suzanne C. Purdy, PhD**





5521 Ruffin Road  
San Diego, CA 92123

e-mail: [information@pluralpublishing.com](mailto:information@pluralpublishing.com)  
Web site: <https://www.pluralpublishing.com>

Copyright © 2023 by Plural Publishing, Inc.

Typeset in 10.5/13 ITC Garamond Book by Achorn International  
Printed in the United States of America by Integrated Books International

All rights, including that of translation, reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, recording, or otherwise, including photocopying, recording, taping, Web distribution, or information storage and retrieval systems without the prior written consent of the publisher.

For permission to use material from this text, contact us by  
Telephone: (866) 758-7251  
Fax: (888) 758-7255  
e-mail: [permissions@pluralpublishing.com](mailto:permissions@pluralpublishing.com)

*Every attempt has been made to contact the copyright holders for material originally printed in another source. If any have been inadvertently overlooked, the publisher will gladly make the necessary arrangements at the first opportunity.*

Library of Congress Cataloging-in-Publication Data:

Names: Durrant, John D., editor. | Fowler, Cynthia G., editor. |  
Ferraro, John A., editor. | Purdy, Suzanne C. (Suzanne Carolyn), editor.  
Title: Basic concepts of clinical electrophysiology in audiology /  
[edited by] John D. Durrant, Cynthia G. Fowler, John A. Ferraro, Suzanne C. Purdy.  
Description: San Diego, CA : Plural, [2023] | Includes bibliographical  
references and index.  
Identifiers: LCCN 2021017656 (print) | LCCN 2021017657 (ebook) |  
ISBN 9781635501759 (hardcover) | ISBN 163550175X (hardcover) |  
ISBN 9781635501797 (ebook)  
Subjects: MESH: Audiometry, Evoked Response | Hearing Disorders—diagnosis |  
Electrophysiological Phenomena  
Classification: LCC RF294 (print) | LCC RF294 (ebook) | NLM WV 272 |  
DDC 617.8/075—dc23  
LC record available at <https://lcn.loc.gov/2021017656>  
LC ebook record available at <https://lcn.loc.gov/2021017657>

# Contents

<i>Foreword by José Juan Barajas de Prat</i>	<i>ix</i>
<i>Preface</i>	<i>xiii</i>
<i>Special Message to Student Readers and Others Aspiring Toward Competent Use of Clinical Neurophysiology in Audiology</i>	<i>xiii</i>
<i>Special Message to Instructors Adopting This Textbook</i>	<i>xv</i>
<i>Acknowledgments</i>	<i>xxi</i>
<i>Contributors</i>	<i>xxiii</i>
<i>Dedication</i>	<i>xxvii</i>
<b>1 Basic Concepts of Clinical Electrophysiology in Audiology</b>	<b>1</b>
Prequel—A Peek at the Auditory Evoked Potentials and Areas of Application	1
<i>John D. Durrant</i>	
<b><i>Heads Up:</i></b> Like in Space, It Takes Time to Travel Along the Auditory Pathway—So What?	2
<b>2 Signals and Systems Essentials</b>	<b>7</b>
Signal Generation, Analysis, and Conditioning—Analog Versus Digital Perspectives	7
<i>J. Robert Boston and John D. Durrant</i>	
Temporal Versus Spectral Views: The Saga Continues—Impulsive Versus Steady State	20
<i>W. Wiktor Jędrzejczak</i>	
<b><i>Heads Up:</i></b> Prequel 2: Why Are Computers So Important in This Area of Audiology and Are They Everywhere?	29
<i>Rafael E. Delgado</i>	
Signal-Issues Particular to Stimulating the Auditory System and the Importance of Being Calibrated	34
<i>Robert F. Burkard</i>	
<b><i>Heads Up:</i></b> Wideband Transmission and the Middle Ear Bottleneck	43
<i>M. Patrick Feeney</i>	
<b>3 Electrically Connecting to Humans To Access Their Auditory Neurosensory Systems</b>	<b>49</b>
Bioelectric Basics, Interface Dilemmas, and Electrode Montages/Caps— One Size Fits All?	49
<i>John D. Durrant, Krzysztof M. Kochanek, and Lech K. Śliwa</i>	
Functional Neuroanatomy of “AEP Space” and Underlying Neurophysiological Bases	62
<i>Frank E. Musiek</i>	
<b><i>Heads Up:</i></b> Need That Like a Hole in the Head? What About a Nail? A Case in Point!	77
<i>Christopher D. Bauch and Wayne O. Olsen</i>	

<b>4</b>	<b>Stimulating the Auditory System and the How and Why of an “Evoked” Response</b>	<b>83</b>
	Extracting the Response’s Signal From Noise Background	83
	<i>Steven L. Bell</i>	
	The Good, Bad, and Ugly—Optimizing Response Extraction From Background Noise and How Signal Processing May Become Too Much	101
	<i>Ozcan Ozdamar and John D. Durrant</i>	
	<b>Heads Up:</b> Interlude—And You Don’t Even Have To Raise Your Hand When You Hear the Beep	115
	<i>John D. Durrant, Cynthia G. Fowler, and Suzanne C. Purdy</i>	
<b>5</b>	<b>Evoking Responses of the Peripheral Auditory System</b>	<b>121</b>
	First Sign Something’s Going On in There: An Acoustic Response of the Inner Ear	121
	<i>Jacek Smurzynski</i>	
	<b>Heads Up:</b> Otoacoustic Emission Without Turning On Sound? Who Knew?	134
	<i>W. Wiktor Jedrzejczak</i>	
	CM, SP, and AP: Not Alphabet Soup and First Signs AEPs Are Afoot!	138
	<i>John D. Durrant and John A. Ferraro</i>	
	Electrocochleography: How Do Electrical Signals Get From Hearing Organs to the “Outside” and What Good Are They?	147
	<i>John A. Ferraro and John D. Durrant</i>	
	<b>Heads Up:</b> Intriguing ECoChG App: Sensing Weakened Wall of Semicircular Canal	159
	<i>John D. Durrant, John A. Ferraro, and José Juan Barajas de Prat</i>	
	What More Can Electrocochleography Teach, Including About What to Expect Later?	163
	<i>Martin Walger</i>	
<b>6</b>	<b>Evoking Responses of the Central Auditory System: Testing the Brainstem</b>	<b>177</b>
	Brainstem Auditory Evoked Potential: General Interpretation—Its Nature and Peripheral Versus Central Systems Aspects	177
	<i>George A. Tavartkiladze</i>	
	<b>Heads Up:</b> Binaural Interaction in Auditory Brainstem Potentials	193
	<i>Cynthia G. Fowler</i>	
	Brainstem Responses to Complex Stimuli—Frequency and Envelope Following Responses	195
	<i>David Purcell and Viji Easwar</i>	
	<b>Heads Up:</b> Speech-Evoked EFR and FFR	205
	<i>Ananthanarayan Krishnan</i>	
	Auditory Steady-State Response—80-Hz Response	209
	<i>Maria C. Perez-Abalo</i>	
	Evoked Potential Audiometry Using Auditory Brainstem Response/Auditory Steady-State Response Measurements	219
	<i>Susan A. Small</i>	
	Differential Diagnostic Applications	231
	<i>Cynthia G. Fowler and Jun Ho Lee</i>	

**DOUBLE-HEADERS UP**

**Heads Up:** Differential Diagnostic Case Studies and the Challenge of Auditory Neuropathy 247

*Jun Ho Lee and José Juan Barajas de Prat*

**Heads Up:** Postauricular Muscle Response—Friend/Foe/Why Care? 254

*Suzanne C. Purdy*

**7 Testing Midbrain and Cortical Projection Pathways 271**

Auditory Middle Latency Response and 40-Hz Auditory Steady-State Response—Signals En Route to the Cortex 271

*Joaquín T. Valderamma-Valenzuela*

Why Evoked Response Audiometry (ERA) Using AMLR or 40-Hz ASSR Measures 284

*Cynthia G. Fowler and So E. Park*

Differential Diagnostic Applications of AMLR 292

*Thierry Morlet and So E. Park*

**Heads Up:** BIC Update—Whither Beyond Pontine CANS 302

*Cynthia G. Fowler and So E. Park*

**8 Cortical Level Testing 313**

Call Them Late, But They Were the First AEPs for Practical ERA—LLRs 313

*Barbara K. Cone*

Why ERA Using Cortical Response Measurement 322

*Linda J. Hood, Rafael E. Delgado, and Abreena I. Tlumak*

**Heads Up:** A Case Spared Operative Treatment Thanks to Testing of Both Brainstem and Cortical AEPs 332

*John D. Durrant and Martin Walger*

Late-Late Shows in AEPdom—Beyond Obligatory Potentials: When Just Turning On the Same Stimulus Is Not Enough 336

*Mridula Sharma*

**DOUBLE-HEADERS UP**

**Heads Up:** Peek at EEG Analyses Via Advanced Signal Processing 349

*Ronny K. Ibrahim and Mridula Sharma*

**Heads Up:** The Change Potential—Sometimes What's Later Tells More 352

*Fabrice Bardy*

**9 Difficult-to-Test Patients—General Methods and Newborn Screening 365**

Screening Hearing Responses Versus Threshold Estimation and Estimating Audiometric Configuration 365

*Monica J. Chapchap and Patricia C. Mancini*

Bone Conduction Testing—A Special Challenge, Yet Efficacious With Understanding 377

*Susan A. Small*

Testing Patients Under Natural Sleep or Medically Induced Sedation/Unconsciousness 388

*Diane L. Sabo*

**Heads Up:** Testing Patients Who “Exaggerate” Their Hearing Thresholds 395

*John D. Durrant and Cynthia G. Fowler*

Testing Patients With Cochlear or Brainstem Implants 400

*Andy J. Beynon*



<b>10</b>	<b>Testing Potentially Beyond Hearing-Related Yet of Interest in Audiology the Profession</b>	<b>421</b>
	<i><b>Heads Up:</b> Not Only Electric Fields, Magnetic Fields Too—Confirming Origins</i> <i>John D. Durrant, David L. McPherson, and Lionel Collet</i>	421
	Quick Look at Intraoperative Neuromonitoring and Other Evoked Potentials <i>Abreena I. Tlumak and John D. Durrant</i>	428
	<i><b>Heads Up:</b> A Case of Elective Surgery That Could Have Gone Badly Were It     Not for IONM</i> <i>John D. Durrant and Abreena I. Tlumak</i>	441
	Whose Land Is This? <i>Suzanne C. Purdy</i>	444
	 <i>Index</i>	 455



## ■ Foreword

This book is meant to be a basic introduction for students interested in auditory electrophysiology of the peripheral and central auditory systems, particularly those intending to enter the professional practice of audiology, although certainly not exclusively. This volume provides a guideline and a comprehensive overview of measurement of auditory evoked potentials and other responses of possible interest in this field. It reflects the work of a group of clinicians and scientists who have been working in auditory electrophysiology for years and sharing their research and clinical findings at biennial symposia of the International Evoked Response Audiometry Study Group (IERASG). The group was seeded over a half century ago by its iconic founder, the late Hallowell Davis, easily recognized as the “father” of evoked response audiometry.

The two most key terms of this book are *brain* and *auditory evoked potential (AEP)*. Let's start with *brain*. The only way the brain can grasp reality is through the processing of signals sent up pathways from specialized sensory organs. Evolution has been selecting neurons by trial-error principles. Many of these neurons, gifted with properties that provide them with special physiological characteristics, procure information on sensorial states and that has become a part of our genetic predetermination. From the very moment of our birth, these neuronal circuits are exposed to sensorial experiences that will be stored in our personal memory. Every sensation, being in its own nature secret and abstract, should be regarded as an interpretation and classification of events based on past individual or species-specific experiences. Thus, experience operates on physiological events giving them mental significance. These sensorial experiences become our mental possessions.

Unlike other species that are exoskeleton (crabs), humans are mainly endoskeleton. The bad news is that it is precisely the area where the brain lies that is exoskeleton. In fact, the brain is surrounded by an implacable bony frame and, to make matters

worse, the auditory sensorial organ is hidden inside the hardest bone in the human body, the temporal bone, in such a way that our knowledge of brain function cannot be obtained by direct means.

However, the good news is that many years ago we learned that if we attach a pair of electrodes to the surface of the human scalp and connect them to suitable instrumentation, the minute electrical signal recorded could be used to discern brain activity locked in time to a sensory experience. Such signals can even be recorded and processed in a manner that suggests the resulting response reflects cognition—a higher level of the brain's job than mere sound detection. Never before have we had a *toolbox* with such a powerful instrumentation to extract audiological electrophysiological information of the nervous system. Still, it remains the user's responsibility to have the appropriate knowledge base and skill set to properly make use of this important armamentarium and to be mindful in their use in research and clinical strategies alike.

In this text, the reader is led along the temporal sequential process that gives rise to AEPs, a sort of *journey* from the receptor (ear) to the cortex. As expected from conventional audiometry, the stimuli will play a key role in pursuit of the ascending activation of the auditory pathway. The AEPs elicited will take on characteristics in different ways along the way. Tools then will be needed to analyze both stimulus and response. Therefore, before setting off on this journey, our luggage will have to include a substantial *toolbox* by which to reveal important parameters of measurements of their stimulus-response relationships. Another important preliminary concept to bear in mind is that, at all times, we are looking for physiological events that provide only indirect evidence of the phenomenal sense of audition. At the same time, the tools in the box presented will have gotten there only from extensive vetting, which in the clinical sciences is best expressed as *evidence based*. The box contains



plenty of technology that has greatly empowered modern advances, including advanced digital-signal processing, but without a truckload of equipment for general-purpose computing.

The tools often will draw on concepts outside of routine audiometry conducted in the course of the basic audiological evaluation. Occasionally something like masking—to help ensure the results have come by way of processing of sound by the ear intended—will be equally of concern in assessing AEPs. Often, and naturally, assessment of these electrophysiological signals will be scrutinized in relation to results of behavioral audiometry. Prior knowledge of that area will help the reader to best understand the intent and information within this book. Such foundation of knowledge then is built on the side of electrophysiological methods, not in isolation nor to its exclusion. Another parallel and important concern from the “culture” of behavioral audiometry is calibration—not only of stimuli and acoustic test environments but also of the AEP test parameters. There will be a goodly number of methodological procedures presented as a part of molding the tools in the box, some of which will be in the vein of audiometry and others will be unique to electrophysiological methodology.

A particular challenge will be to extract signals of interest in less than ideal circumstances. The reader will be challenged to wonder what’s real—whether or not the recording of a given AEP and time of measurement actually corresponds to the subject’s real biological response. Here too, this concept is not unique to electrophysiology. Again, in behavior, the patient is asked to signal when hearing the stimulus presented. Can the response always be trusted to reliably reflect the patient’s true hearing sensitivity? Furthermore, what if during the examination workers next door were preparing a room for, let’s say, another/new test booth? If sudden banging on the wall occurred during audiometric assessment, are any responses observed still credible? These or like issues pervade clinical electrophysiology. Some tools will be dedicated to addressing the challenge. Fortunately, the toolbox will prove to be robust in this regard. Some of the “tricks of the trade” in electrophysiology will not be alien but addressable by common approaches (in concept) in behavioral science. For example, in

the assessment of a test’s reliability, there are similarities between the previous example in judging an individual’s response and evaluating success of hearing screening of industrial workers. Were the tests reliable/repeatable or even valid in the first place? Such matters are often approached in good part using statistics. It will be seen that signals can be recorded and treated as sets of data; as such, they too are often treatable statistically (such as with measures of central tendency and tests of correlation).

A clear understanding of the neuroanatomy and neurophysiology of the auditory system will help the clinician to understand the AEP attributes at each level of the auditory system and their interpretation. The editors and writers rightfully do not accept full responsibility to cover such background. Nevertheless, they do endeavor to catalog and present in appropriate depth (for the scope and aims of the book) nuances that most help to account for origins and nature of the AEPs commonly employed in clinical electrophysiology in audiology. Here, it is important to establish at the outset that there is not always a direct relationship between structure and function or that the electrophysiological response does not always reveal the precise locus of a particular dysfunction. Nevertheless, principles will be expressed by which to interpret AEP “findings” for a useful functional level of assessment. Predictably, one of the common final paths between conventional audiological (behavioral) tests and findings of AEP measurement(s) will be the derivation of an estimate of just how sensitive is the patient’s auditory system and perhaps other correlations between test modalities. Here the reader is ensured of some interesting “twists” (in effect) along the auditory pathway.

This book gives the opportunity both to beginners and even more advanced students/readers to review the intriguing area of clinical auditory electrophysiology as well as various overviews of areas beyond and/or not necessarily broadly used clinically, yet promising and truly fun facts beyond the primary scope of the text. Within the scope, the text is written in a very practical way and provides comprehensive information of direct application in both clinical settings and for research purposes. The main aim of the book, I submit, has been





achieved by trying to answer the questions of what technology to use and when and what is well supported fundamentally—salient principles that are supported substantially by an evidence base. The coverage demonstrates, indeed, that the *toolbox* is bountiful. Now, it soon will be your turn to decide

what tools to use for your clinical objectives or perhaps even a research plan. We hope this book can help you make the right choice. Good Luck!

—José Juan Barajas de Prat, MD, PhD





# ■ Preface

## The Producers

John D. Durrant  
Cynthia G. Fowler  
John A. Ferraro  
Suzanne C. Purdy

## ■ i. Special Message to Student Readers and Others Aspiring Toward Competent Use of Clinical Neurophysiology in Audiology

If this page is the first one to which you have jumped, dear reader, please return to the *Foreword*. It will help your mindset for reading this textbook throughout, namely to do so with a sense of curiosity and adventure. Thereafter, let us address the perennial question up front about the content to follow in this preface; it should not “be on the exam”, if the *Producers* have any say in this. However, that does not relieve you of the responsibility to read the following, for the best experience and learning with this textbook. The next questions should be, “Who are ‘the producers?’” and, “Why are you talking that way?” They (well, we) are the editors of this volume—a document of substantial proportion (OK, it’s long) to serve purposes of instruction in a technically demanding, yet clinically important, part of assessment of function of the auditory system. In general, there are numerous academic books produced among the professions intended particularly for students in postgraduate education, often toward a clinical or research accreditation and/or for credentialed workers in the professions trying to keep abreast of the incredibly voluminous literature in the clinical sciences

alone. Any authors of such books are expected to speak with authority about what is important to know, where a field is heading, or perhaps about the current or the lack of standards of practice, and so forth. This is a tall order for any singular author to pull off. Here, the production has been envisioned in the context of how the editors hope readers will embrace this book. The production concept of this book is in reference to the likes of projects that give us today’s television or cinematic “productions,” often in some variant of a series of *episodes* that, with good luck, may be sponsored for multiple seasons of a given show.

The producers of this volume have recruited a considerable number of writers to join them in their production of series that truly are intended to be followed from the first chapter—*season*—and therein sequentially through each series of stories—again, *episodes*. The sequence comprises the logical building blocks of a foundation of knowledge. Each episode helps to present the topics of the next within a season, and each season leads to the next. While the concept of building a broad foundation of knowledge is the desired outcome, the “build” is not, say, a pyramid or, if a pyramid, then it is being built upside down. This depiction is simply how the auditory nervous system looks. The inner ear is a marvelous and cleverly designed part of this system, but it cannot think. Hence, we need the brain, which physically expands dramatically going up the pathway that is to be followed in our quest to fill the toolbox pondered in the *Foreword*. Special feature stories along the way, entitled *Heads Up* (HU), will entertain you further with still more facts, more advanced concepts, and/or more tools even beyond the scope of the last episode and/or the book. They will not be comprehensive presentations; they are intended more as, well, a heads-up about what else is going on. While perhaps not in routine practice today, they will concern promising methods worthy of at least some awareness. After all, this is a dynamic field.

The producers are from the rank and file of the profession of audiology, as it has come to be today. They are highly seasoned clinicians and educators as well as having individually contributed to the evidence base of the targeted subspecialty—clinical electrophysiology as applied to enrich audiology. The writers are similarly endowed contributors, the producers have been compelled to contribute as well, and the entire production team has been charged to ensure presentation of practices in this area that are consistent with the ever-evolving stories to be told. The subspecialty presented herein has been more than a half century in the making, through research and technological advances that have led to reasonably stable tools of the trade based on sound principles of understanding of auditory electrophysiology of clinical interest, or at least (again) of considerable promise.

The initial episodes embrace stories that the producers hope are more familiar in subject than not. These topics are not to be belabored in this book; if some readers find any topics beyond their comprehension after thorough reading, they certainly should take a pause to get some tutoring in that area. This textbook is intended for readers with undergraduate or like level of preparation, thus with the expectation that they will have studied hearing science and have some foundation of knowledge in general neuroanatomy and neurophysiology. For readers with such background, perhaps even more, the episodes are intended to serve as overviews. This approach permits the writers to zero in on bits of broader areas that specifically are relevant to readers' understanding and (ultimately) proper interpretation of results of tests of the auditory evoked potentials. As such, it will be advisable to avoid approaching the reading of this book somewhat in parallel to a no-no in reliable research—"cherry-picking" data that best suits the researcher's hypothesis. In that vein and in the present context, you thus are urged not to cherry-pick episodes, namely to read only the one(s) that you perceive as uniquely relevant to your clinical/other interest(s). First, this approach is likely to cause you to miss important lessons about principles; again, these episodes build the foundation for various clinically routine interests. Second, just selectively reading likely will not allow you to become empowered by

the knowledge base as intended. The technology is not confined to one part of the brain and/or one clinical application. Therefore, why should users confine the competence of their knowledge? Topics herein are presented to minimize "reinventing wheels," rather starting with some "good wheels" and refining some parameters for the next application and/or level of the auditory system to be evaluated.

The end of each chapter provides a summary of key issues from the episodes and HUs in a brief segment called *Take-Home Messages* (THMs). The previous admonition for avoiding cherry-picking parts of the book to read is naturally followed by the "sin" of only reading abstracts of chapter summaries, journal articles, and so forth. Each THM is intended to be (borrowing jargon from comedic entertainment) somewhat like "one-liners," although often compound sentences taking more than one line of print to make the point. What they are not are "tell-alls," not even collectively. If the main points of the content provided were understood, these quasi-one-liners should be understood immediately. They also can contain some of the many abbreviations introduced in the episodes—an inherent part of vocabulary building—but not being redefined. The THMs thus are designed to trigger recall, not reteach. They are presented with the conviction that there is no better way to renew memories than to review the relevant part of the chapter when the meaning of the THM is not clearly understood.

Lastly, much effort in production has been invested in producing the figures in a manner to fit the episodes. There are lots of them, but the objectives of this textbook and what all you really need to know (ultimately) to competently practice the methods presented cannot be learned from just looking at the figures and reading the captions. The flip side of that "coin" is not to judge importance of content based on density of figures or tables or, conversely, discounting portions of the text with relatively low numbers of figures. A picture well may be worth 1,000 words, but the narrative is still what frames the picture and expresses the intended relevance to the story in which it is presented. In any event, and by all means, please enjoy.

## ■ ii. Special Message to Instructors Adopting This Textbook

To anticipate perhaps a question, dear instructor, neither what the *Producers* have expressed directly to your students in *Preface i* nor what is expressed in the *Foreword* by our distinguished colleague should appear on an exam. However, they do reflect a bit of our motivation and approach to this textbook. The objective here is to address more specifically and thoroughly the authority that this group of editors has endeavored to impart to the book, both regarding the editors' backgrounds and commitments to minimize a couple of problems that sometimes can compromise a multiauthored volume intended primarily to serve as a textbook.

Even single or coauthored books can present difficulties achieving evenness of depth and style of writing throughout, especially given substantial diversity of content across chapters. The senior editor (to discount any self-impression of infallibility on this point) once suffered the sting of a prepublication review of a textbook wherein the reviewer pondered whether the same person had written both halves of the book. Even in books of one to a few authors, illustration materials typically derive from many sources and at times seem somewhat disjointed. Despite these challenges, edited texts often serve well the objective of producing a compendium of works on such topics as state of the science of methods, trends of research in a given area, and so forth. They still make great reference books and intellectual food for more advanced graduate students and postgraduate/professionals who are fully at ease going to the research/comparable literature. Indeed, the authority of such books, by way of skillfully recruited writers, is hard to match by one to few authors, given the relatively high level of technology and voluminous literatures of clinical sciences of today. We contend that for a textbook at the more foundational level, however numerous the contributors, it needs to be inviting and its contents flowing well across the book—the goals to which this volume is dedicated.

The production of this text was developed on the notion of having a group of very knowledgeable writers contribute to a volume wherein each draft

would evolve from more detailed organization, interactive editing between editors and writers, and central management of illustration production. These steps in the current textbook were designed to ensure their fit to the main points presented, in synchrony with the table of contents, using novel figures as much as possible, and throughout more or less customizing them to the text's narrative. The picture being worth 1,000 words was not wisdom lost on our producers and writers. When details are expected to be recalled, images supported by adequate/well-correlated narratives can be particularly helpful come exam time. While at the graduate level the students certainly should be prepared to deal with the literature, articles containing voluminous data, and diverse ways of presentation of the data, this process need not be the initial goal all textbooks.

Here then is the product of collective efforts to build a solid foundation of reasonably well-established principles and practices in clinical electrophysiology of audiological interest. Coming full circle back to the written text, writers have been charged to address significant units of foundational knowledge as the editors see them, and therein were "assigned" as highly seasoned and trusted reporters to address various principles to build a substantively essential foundation for clinical work in this area.

The approach taken in this project also reflects the bias of the editors that objective measures today deserve more than a single term of coverage in academic programs, whether in the context of a master's or professional-doctoral curriculum. The mantra here is a priority of building the foundation of knowledge that hopefully will serve well in the growth and development of users of clinical electrophysiology for audiological applications as well as into the next course and beyond during their professional life. In general, the conviction guiding the production of this book is that competency in practice demands competent knowledge bases. For the student/novice reader, it is equally important to present material that will spur on their interests in further foundational building and with a hint that continued education (beyond degrees or certification) will be expected and is indeed essential for anyone intending to continue to practice in the field. We also have aimed to provide exposure and develop in the reader a recognition of various areas

that are deemed, at this writing, as not yet ready for “prime-time,” routine clinical practice. To this end, instructors also are encouraged to not include content of the *Heads Up* (HU) features (in effect, “short stories”) for exam purposes. There is more than ample material for tests of comprehension in the episodes of each chapter to which any given HU is associated. Discuss them in class, nevertheless? Surely. If a term paper is required, they are also fair game for topics (and thus grading). Otherwise, please just let your students read the HUs and “get” what they can from these short stories, perhaps together with your own tutelage to address some of the issues therein and/or enhancing from your own experience. The topics of the HUs often are higher end, yet included to kindle interests for what else is “out there.” In some cases, the HUs are used to plant seeds of upcoming episodes, but at that juncture, just a blush. This hopefully will tweak curiosity without “overcharging” their brains with issues not yet essential to the teaching points of the respective current episodes.

The notion of production of a volume dedicated to defining an essential foundation of knowledge for ultimate competency is not novel. In the latter 1980s, the Committee on Audiometric Evaluation, a standing committee of the American Speech-Language-Hearing Association, formed the Working Group on Auditory Evoked Potential Measurement. Academic audiologists recruited were charged to develop a guideline on “Competencies in Auditory Evoked Potential Measurement and Clinical Applications” (1990; *Asha* [Suppl. 2]). In the course of their deliberation, the group decided, in effect, that developing a monograph summarizing information gathered could be useful, subsequently published as “The Short Latency Auditory Evoked Potentials” (1988; *Asha*). This area, after all, was a subspecialty that had led to one of the most pervasive transformations of audiological practices, bringing clinical electrophysiology into routine practice in the hands of clinically certified audiologists. The working group members included editors Fowler and Ferraro. As chair of the working group, the senior editor, with additional help of Dr. Kenneth E. Wolf, subsequently rounded out the coverage to include longer latency potentials, published as a chapter in *Hearing Assessment* (W. F. Rintelmann [Ed.], 1991 [2nd ed.]; Pro-Ed). In the same vein, writers

and editor-writers alike were challenged in the current project to present the most salient bases of a given method, application, and so forth but now appraised after over a half century of research and development comprising extensive clinical practice, well-developed evidence bases, and continuing research and development. Thereafter, they were asked to overview promising further advances. To get the writers “creative juices” both flowing and calibrated to the design and intended level of treatment in this textbook, the contributors were advised first to think of the assignment much as that of writing an editorial. From their expertise and scrutiny of the state of the science in their assigned areas respectively, they were asked to express what in their judgment are the most well-established principles and concepts that are truly foundational.

Our editors and several associate reviewers were recruited to help vet the manuscripts—highly seasoned academics in communication science and disorders or allied field who have dedicated substantial portions of their careers to clinical electrophysiology and other objective methods used in audiology today. All have substantially contributed to the evidence base of this book (thus active in research); they also have contributed broadly to higher education, instructional presentations at national/international society meetings, and/or educational publications. Senior editor Durrant was educated in a traditional American program in communication science and disorders (CSD), namely speech-and-hearing therapy in the day. He had a substantial formation in psychology and physiology, leading to a postgraduate education in audiology and physiological acoustics, earning the degree of doctor of philosophy and a postdoctoral fellowship (Northwestern University). He later became clinically certified and ultimately came to direct audiology clinics in the medical schools of Temple University and (more recently) the University of Pittsburgh, with primary and secondary appointments (or vice-versa) in otolaryngology and CSD. He lastly served as the vice-chair of the CSD department and is now a professor emeritus. He also had a 3-year stint of Atlantic-hopping bimonthly to the Université Lyon I (France) as an associated professor of medical physiology. These various posts and sites collectively allowed him over his career to work in nearly all areas covered in this book. A career-long mem-



ber of the American Speech-Language-Hearing Association (ASHA), ultimately fellow and honoree of the Association, he also contributed to activities of the American Academy of Audiology (AAA). He and his colleague J. H. Lovrinic (professor, Temple University, retired) authored the first foundational book on hearing science for CSD programs by clinical audiologists—*Bases of Hearing Science* (1977, 1984, and 1995 [editions 1–3]; Williams and Wilkins). He continues to be active in the profession nationally and internationally and currently serves as a research scientist for Intelligent Hearing Systems (Miami) in projects supported by the National Institutes of Health. He remains actively involved in the International Society of Audiology, including as a founding associate editor of the *International Journal of Audiology*, and as the former chair of the Council of the International Evoked Response Audiometry Group (IERASG). In addition to his primary responsibility to this project, he managed the final production/reproduction of all figures as they appear herein.

Editor Fowler entered CSD with an undergraduate background in psychology. She soon became interested in auditory electrophysiology, which developed into a career. Upon consummating her clinical and research education (doctor of philosophy, Northwestern University), she served as a clinical and research audiologist at the Long Beach Veterans Hospital and University of California-Irvine, where she taught medical students and residents. At the VA, the audiology group attracted students from around the country and abroad in their clinical fellowship year, including having mentored many who became leaders in the field. She taught auditory electrophysiology at California State University-Los Angeles. She subsequently moved to the University of Wisconsin-Madison, where she continued to mentor students and pursue research in auditory electrophysiology. She subsequently developed and served as the founding director of the doctor-of-audiology program, a joint venture with the University of Wisconsin-Stevens Point. Her research program has been primarily concerned with clinical applications of auditory brainstem responses, yet not exclusively, and overall in pursuit of electrophysiological manifestations of perceptual events and effects of aging. She has been a career-long member of ASHA and elected Fellow of both

ASHA and AAA. She has been active in still other professional associations, not the least of which is the IERASG (Council Member). In this project, she bore responsibility to review all contributions with the senior editor and particularly with the charge of copyediting to smooth out writing across the substantial number of contributors, including the other editors with their contributor hats on.

Editor Ferraro came to CSD as a card-carrying biologist (bachelor's and master's degrees with minors in chemistry and psychology). However, he became interested in the auditory system and earned his doctor of philosophy in speech and hearing sciences (University of Denver), followed by postdoctoral work in physiological acoustics (Northwestern University). He started his career at The Ohio State University, but in due course became more broadly recognized for his leadership in the Intercampus Program in Communicative Disorders, between Kansas City (medical center) and Lawrence (main campus), University of Kansas. His decades of chairing of the KU Medical Center Hearing and Speech Department included service as associate dean, associate dean of research, and acting dean of the School of Health Professions. He was particularly active in the Council of Academic Programs in Communication Sciences and Disorders and thereby kept a thumb on the pulse of CSD-education programs, especially through the formative years of the professional doctorate in audiology. He also authored *Laboratory Exercises in Auditory Evoked Potentials* (1997; Plural Publishing, under its former name, Singular Publishing Group)—a step-by-step manual to lead students to successful recordings. A career-long member of ASHA, ultimately fellow and honoree of the Association, and active as well in the AAA, ensured him broad and deep involvement in both didactic teaching and mentoring of students, medical residents, and fellows throughout his career. At the same time he was a dedicated and continuously productive researcher that literally helped to keep electrocochleography “alive” in the profession. He continues to probe evident issues of this technique and to endeavor to keep the method still ripe for current clinical interests.

Editor Purdy is a career audiologist and hearing researcher in New Zealand who has enjoyed extensive collaborations over the years with international



colleagues in a number of countries, including Australia, the United Kingdom, China (Hong Kong), and South America. She earned her doctor of philosophy in the United States (University of Iowa) and has been a frequent participant/contributor to professional conventions/scientific meetings there as well as globally abroad. These contributions were recognized by the AAA's 2021 International Hearing Award. She has contributed to the establishment of postgraduate programs in audiology and speech pathology and is currently the head of the School of Psychology, University of Auckland. She succeeded the senior editor as the present Council Chair of the IERASG. Through research, mentoring, and clinical work, she has embraced broadly the measurement of auditory evoked responses and their bases and potential clinical applications. Her work has taken on a range of electrophysiological challenges beyond the conventional, including those aspects that sometimes suffer the waxing and waning of popular interests and/or understanding (as demonstrated in one of her contributed stories).

The three invited reviewers who contributed to the project are also distinguished workers in auditory electrophysiology and related areas. While thus not members of the team contracted by the publisher and indeed purposely valued for their relative independence, they were recruited to help vet the book's content. Reviewer Guy Lightfoot has been a clinically based scientist specializing in auditory electrophysiology and vestibular assessment throughout his career with the English National Health Service, based in Liverpool. He obtained his doctor of philosophy degree working on brainstem-auditory evoked responses and came to run a specialist training course in evoked response audiometry, attracting an international audience for 30 years. He has published results of a number of studies on ERA-related topics and recently contributed the chapter on brainstem-response-based ERA in *Pediatric Audiology—Diagnosis, Technology, and Management* (J. R. Madell et al. [Eds.], 2019 [3rd ed.]; Thieme Publishers). He has coauthored many of the British national guidance documents relating to ERA. Dr. Lightfoot is a long-standing member of the IERASG's Council and a regular contributor to its biennial meetings.

Reviewer Paul Avan is both a physicist and doctor of medicine who has dedicated his career to biophysics, wherein falls the theoretical bases and methods of eliciting and measuring sensory evoked responses. He has developed complementary skills to study objective methods of exploration of the cochlea and auditory pathways, such as otoacoustic emissions (cochlear "echoes"). He validated them on models of mutant mice with precisely defined molecular deficits. These models bridge the gap between two domains that shared very few bits of common knowledge merely a few decades ago, namely audiology and molecular physiology. He today heads the Center for Research and Innovation in Human Audiology at the Institut de l'Audition in Paris, France. He works on the design and validation of electrophysiological equipment with the aim of detecting formerly inaccessible functional parameters. He also has served as an editor of *Les Cahiers de l'Audition*—a professional magazine dedicated to disseminating clinical/research findings, even those of his countrymen who are compelled to publish in English academically and namely to help ensure that the science is also reaching frontline French-speaking workers. This includes physicians and therapists alike, especially in the area of audio-prostheses.

Reviewer David McPherson is a professor of communication disorders and neuroscience at Brigham Young University. He is also a principal investigator in the BYU MRI Research Facility. His current research focuses on the simultaneous recordings of fMRI and evoked potentials. He has also served on the editorial board of several professional organizations and as a consultant to NIH grant reviews. He continues to mentor graduate students and maintain research grants and thus is active in research. He was the first hearing scientist to publish a book dedicated to auditory cortical responses—*Long Latency Auditory Evoked Potentials* (1996; Singular Publishing). He is an elected member of the Society for Sigma Xi at the California Institute of Technology and recipient of the Honors of the Association (ASHA) for his research and contribution to the field of CSD. He is an officer of the IERASG Council. He earned his degree of doctor of philosophy at the University of Washington, followed by postdoctoral studies at the Brain



Research Institute, University of California-Los Angeles, in cochlear physiology. He then served on the faculty at the University of California-Irvine and worked extensively with Arnold Starr, currently professor emeritus, University of California and Brigham Young University. Professor Starr was not only his mentor, but a mentor to many others and he is an iconic worker in auditory neurophysiology and pathology and has been a long-time contributor to the IERASG Biennial Symposia.

Finally, frequent mention of the IERASG has been made in these introductory pages reflecting its considerable inspiration and motivation for the production of this textbook, but perhaps eyebrow-raising at the same time. What sort of academic society would persist in calling themselves a “study group.” Introspection by the Council and at times in the general assembly of the biennial meetings has been given to the issue of continued use of “Study Group” in the society’s name. However, Davis ar-

gued at its inception (in effect) as being appropriate apropos its first purpose—practically at the dawn of clinical electrophysiology in audiology as we know it today—to explore what we do not know. Thereto, the content of this book is intended to provide points of departure, neither bottom lines to suggest it as a consummate study of clinical electrophysiology in audiology, nor its reading as a consummate education in this specialty. The producers sincerely hope that this textbook will help instructors to teach their students the fundamentals herein, providing a rich source of illustrations but readily harmonious with other materials and/or manners of presentation per nuances of their respective course/curricular structure. At the same time, these writings hopefully will help to instill in their students the importance of a lifetime commitment to continuing education, as ultimately mandated by the profession and essential in such a dynamic area





## Acknowledgments

This textbook was produced ostensibly under the auspices of the International Evoked Response Audiometry Study Group. It is not a formal society in the sense (these days) of a “nonprofit” or an academy. However, the IERAG’s Biennial Symposia have been a recognized mainstay in evoked response audiometry and related areas of clinical electrophysiology and hearing science for more than a half-century, founded principally by Hallowell Davis. More recently, the IERASG has become formally affiliated with the International Society of Audiology and has conducted minisymposia within their biennial World Congresses of Audiology. Royalties from the sales of this book are to be donated to help sustain the Biennial Symposia and/or initiatives as these have served to produce high-quality scientific meetings for airing out new approaches and/or continued vetting of even well-established evidence bases, as the scientific method demands. The biennials also have been a forum of complete openness to newer workers/students with and among seasoned workers in the field. These meetings have left the participants with deep and abiding memories for some of the best of times in their careers, have introduced or sustained their participation in the international community, and/or seeded many a new collaboration.

The views expressed herein also should not be taken as opinions or edicts of the IERASG’s past or present members, nor of the Council members. The latter are long-time colleagues and career-long workers in the field. For this project, Council members were straightforwardly approached during the development of the proposal to the publisher, namely to hear it out in concept and to thereafter (pending overall support in concept) be invited to join in the actual production of the book. The sitting Council members at the inception and throughout this project and to whom the editors are grateful for their encouragement and confidence were as follows:

Council Chair, Suzanne C. Purdy; Vice-Chair, Andy Beynon; Treasurer, Susan Small; Secretary, Martin Walger; Membership Chairman, David McPherson; Webpage Manager, W. Wiktor Jedrzejczak

Council Members: José Barajas, Steven Bell, Robert Burkard, Monica Chapchap, Barbara Cone, Robert Cowan, Cynthia Fowler, Andrew Dimitrijevic, Ferdinando Grandori, Kimitaka Kaga, Krzysztof Kochanek, Jun Ho Lee, Guy Lightfoot, Ozcan Ozdamar, Maria Perez-Abalo, David Purcell, Mridula Sharma, and George Tavartkiladze.

There are still others too numerous to list who served on the Council and/or were frequent contributors to the Biennial Symposia over the years—scholars for whose exceptional knowledge, contributions to the field, and collegiality the production team and writers readily attribute substantial influence on their own knowledge bases, as often reflected in the reference lists of this textbook.

A special recognition is due to a Council Chair Emeritus for his ever-inspiring influence and leadership—Terence (Terry) W. Picton. A career-long researcher and innovator from the formative years on, he also organized the second Biennial Symposium in the New World—held in Ottawa, Ontario—and authored *Human Auditory Evoked Potentials* (2011, Plural Publishing) which continues to stand as an outstanding reference in this field.

More detailed information about the IERASG and past biennials may be found online at <http://www.ierasg.ifps.org.pl>.

The editors would be remiss if not advising that this textbook’s contents are not intended to be used as standards (de facto) or reference values in the use of any of the methods described herein, although the writers endeavored to represent characteristic data throughout. Such information is



**xxii** *Basic Concepts of Clinical Electrophysiology in Audiology*

---

provided uniquely to support stated principles and to make them tangible for the reader.

The final proposal of this textbook was developed by the editors and in cooperation with Plural's Executive Editor Val Johns. We are indebted to her

for her devoted commitment from its inception and thereafter the fine work of the Plural team for final production of this textbook, the encouragement of Editor-in-Chief of Audiology Brad Stach, and tireless efforts of our Project Editor, Christina Gunning.



# Contributors

**José Juan Barajas de Prat, MD, PhD**

Medical Director  
Clínica Barajas  
Santa Cruz de Tenerife, Spain  
*Foreword, Chapters 5 and 6*

**Fabrice Bardy, PhD**

Honorary Academic  
School of Psychology  
Faculty of Science  
University of Auckland  
Auckland, New Zealand  
*Chapter 8*

**Christopher D. Bauch, PhD**

Emeritus Associate Professor of Audiology  
Mayo Clinic College of Medicine and Science  
Rochester, Minnesota  
*Chapter 3*

**Steven L. Bell, PhD**

Associate Professor of Audiology  
Institute of Sound and Vibration Research  
University of Southampton  
Southampton, United Kingdom  
*Chapter 4*

**Andy J. Beynon, PhD**

Head, Vestibular and Auditory Evoked Potential  
Lab–E.N.T. Department  
Assistant Professor  
Radboud University & Radboud University  
Medical Center  
Faculty Medicine and BioMedical Sciences,  
Faculty Linguistics  
Donders Center for Brain, Cognition and  
Behaviour  
Medical Neuroscience–Hearing & Implants  
Nijmegen, The Netherlands  
*Chapter 9*

**J. Robert Boston, PhD**

Professor of Electrical Engineering and  
Biomedical Engineering (Retired)  
School of Engineering  
University of Pittsburgh  
Pittsburgh, Pennsylvania  
*Chapter 2*

**Robert F. Burkard, PhD, CCC-A**

Professor  
Department of Rehabilitation Science  
University at Buffalo  
Buffalo, New York  
*Chapter 2*

**Monica J. Chapchap, MS**

Electrophysiological Hearing Evaluation  
Hospital Sirio-Libanes  
Sao Paulo, Brazil  
*Chapter 9*

**Lionel Collet, MD, PhD**

Conseiller d'Etat  
Former Professor of Physiology  
Conseil d'Etat  
Paris, France  
*Chapter 10*

**Barbara K. Cone, PhD, CCC-A**

Professor  
Speech, Language, and Hearing Sciences  
The University of Arizona  
Tucson, Arizona  
*Chapter 8*

**Rafael E. Delgado, PhD**

Director of Research and Software Development  
Intelligent Hearing Systems Corporation  
Miami, Florida  
*Chapters 2 and 8*

**Vijayalakshmi (Viji) Easwar, PhD, MSc  
Audiology**

Assistant Professor  
Department of Communication Sciences and  
Disorders and Waisman Center  
University of Wisconsin-Madison  
Madison, Wisconsin  
*Chapter 6*

**M. Patrick Feeney, PhD**

VA Portland Health Care System  
Director, VA R&D National Center for  
Rehabilitative Auditory Research  
Professor, Oregon Health and Science University  
Departments of Otolaryngology, Head and Neck  
Surgery and Neurology  
Portland, Oregon  
*Chapter 2*

**Linda J. Hood, PhD**

Professor, Department of Hearing and Speech  
Sciences  
Director, Human Auditory Physiology Laboratory  
Vanderbilt University Medical Center  
Nashville, Tennessee  
*Chapter 8*

**Ronny K. Ibrahim, PhD, M.EngSc**

Postdoctoral Research Fellow  
Faculty of Medicine, Health and Human Sciences  
Macquarie University  
Sydney, Australia  
*Chapter 8*

**W. Wiktor Jędrzejczak, PhD**

Professor and Head of the Department  
Department of Experimental Audiology  
Institute of Physiology and Pathology of Hearing  
Warsaw/Kajetany, Poland  
*Chapters 2 and 5*

**Krzysztof M. Kochanek, DSc, Eng**

Professor and Scientific Director  
The Institute of Physiology and Pathology of  
Hearing  
Warsaw, Poland  
Professor at Marie-Curie University  
Lublin, Poland  
*Chapter 3*

**Ananthanarayan (Ravi) Krishnan, PhD, CCC-A  
Professor**

Department of Speech, Language, and Hearing  
Sciences  
Purdue University  
West Lafayette, Indiana  
*Chapter 6*

**Jun Ho Lee, MD, PhD**

Professor  
Department of Otorhinolaryngology-Head and  
Neck Surgery  
Seoul National University College of Medicine  
Seoul, Korea  
*Chapter 6*

**Patricia C. Mancini, PhD**

Associate Professor  
Department of Speech-Language Pathology  
and Audiology  
School of Medicine  
Federal University of Minas Gerais  
Belo Horizonte, Minas Gerais  
Brazil  
*Chapter 9*

**David L. McPherson, PhD**

Professor Emeritus  
Department of Communication Disorders  
Center for Neuroscience  
Research Faculty, MRI Research Facility  
Brigham Young University  
Provo, Utah  
*Chapter 10*

**Thierry Morlet, PhD**

Senior Research Scientist  
Auditory Physiology and Psychoacoustics  
Laboratory  
Nemours/Alfred I. duPont Hospital for Children  
Wilmington, Delaware  
Adjunct Professor Communication Sciences and  
Disorders  
University of Delaware  
Newark, Delaware  
*Chapter 7*



**Frank E. Musiek, PhD, CCC-A**

Professor & Director, NeuroAudiology Lab  
Department of Speech, Language and Hearing  
Sciences  
University of Arizona  
Tucson, Arizona  
*Chapter 3*

**Wayne O. Olsen, PhD**

Emeritus Professor of Audiology  
Mayo Clinic College of Medicine and Science  
Rochester, Minnesota  
*Chapter 3*

**Ozcan Ozdamar, PhD**

Professor of Biomedical Engineering  
College of Engineering  
Professor of Otolaryngology  
Pediatrics and Neuroscience (Grad Prog)  
Miller School of Medicine  
University of Miami  
Coral Gables, Florida  
*Chapter 4*

**So E. Park, PhD**

Doctoral Student of Audiology  
Auditory Electrophysiology and Aging Lab  
Department of Communication Sciences and  
Disorders  
University of Wisconsin-Madison  
Madison, Wisconsin  
*Chapter 7*

**Maria C. Perez-Abalo, MD, PhD**

Assistant Professor  
Albizu University, Miami Campus  
Miami, Florida  
*Chapter 6*

**David W. Purcell, PhD**

Associate Professor  
School of Communication Sciences and  
Disorders  
National Centre for Audiology  
Faculty of Health Sciences  
Western University  
London, Ontario  
Canada  
*Chapter 6*

**Diane L. Sabo, PhD**

Senior Global Product Manager-Hearing  
Screening and Assessment  
Natus Medical Inc.  
Beaver, Pennsylvania  
*Chapter 9*

**Mridula Sharma, PhD**

Associate Professor  
Course Director of Clinical Audiology  
Department of Linguistics  
Faculty of Medicine, Health and Human Sciences  
Macquarie University  
Sydney, Australia  
*Chapter 8*

**Lech K. Śliwa, PhD, Eng**

Assistant Professor  
Department of Experimental Audiology  
Institute of Physiology and Pathology of Hearing  
Warsaw, Poland  
*Chapter 3*

**Susan A. Small, PhD, RAUD**

Associate Professor  
Hamber Professor in Clinical Audiology  
School of Audiology and Speech Sciences  
The University of British Columbia  
Vancouver, British Columbia  
Canada  
*Chapters 6 and 9*

**Jacek Smurzynski, PhD**

Professor and AuD Program Coordinator  
Department of Audiology and Speech-Language  
Pathology  
East Tennessee State University  
Johnson City, Tennessee  
*Chapter 5*

**George A. Tavartkiladze, MD, PhD**

President  
National Research Center for Audiology and  
Hearing Rehabilitation  
Head of the Department for Clinical Audiology  
Russian Medical Academy for Continuous  
Professional Education  
Moscow, Russian Federation  
*Chapter 6*

**Abreena I. Tlumak, PhD, CCC-A, R. EEG T, CNIM**

Formerly, University of Pittsburgh  
Department of Communication Sciences and  
Disorders  
Pittsburgh, Pennsylvania  
*Chapters 8 and 10*

**Joaquín Tomás Valderrama-Valenzuela, PhD**

Senior Research Scientist  
National Acoustic Laboratories  
Sydney, Australia  
*Chapter 7*

**Martin Walger, PhD**

Professor of Audiology  
Audiology and Pedaudiology, Cochlear Implant  
Center of Cologne  
Department of Otorhinolaryngology, Head and  
Neck Surgery  
University of Cologne, Germany  
*Chapters 5 and 8*



## ■ Dedication

*This textbook was produced in the spirit of the International Evoked Response Audiometry Study Group and dedicated to the memory of*

- *Hallowell Davis, Principal Founder and First Council Chair*
- *Gideon Gestring, Council Secretary*
- *Michael Portmann, Newsletter Editor*
- *Gerhard Salomon, Council Chair*
- *Manfried (Marc) Hoke, Council Treasurer and Newsletter Editor*
- *A. R. Antonelli, Council Chair and Principal Organizer of a Biennial Symposium, Bergamo, Italy*

- *Roger Ruth, past Council Secretary and Principal Organizer of a Biennial Symposium, Charlottesville, Virginia*
- *A. Roger D. Thornton, Council Chair*

*. . . and to others too numerous to mention, but not forgotten fellow “peak pickers,” who also gave years of service in the development of clinical electrophysiology in audiology and participated in the Biennial Symposia held around the globe.*





# Basic Concepts of Clinical Electrophysiology in Audiology

## The Writers

Episode 1: John D. Durrant  
Heads Up: The Producers

## ■ Episode 1: Prequel—A Peek at the Auditory Evoked Potentials and Areas of Application

The grand tradition of sensory psychology toward the end of the 19th century and the subsequent explosion in both experimental psychology and neurophysiology from early on in the last century was greatly devoted to the exploration of sensory stimulus-response relationships. From the classical psychophysics perspective, this intellectual “game” indeed starts with quantifying nuances of the stimuli employed and subsequently measuring responses to them accordingly.

This textbook is about metrics based on a variety of bodily signals that derive from bodily functions and how they can be intentionally elicited and measured systematically. The primary focus, as bespeaks the title, will be signals of the auditory sensory system (although not exclusively) as it endeavors to process a variety of stimuli, whether environmental or research-based, yet certainly of ultimate clinical use or potential application. However, it is important to address one issue up front, and this hardly will be the last word on this matter. Measurement of the signals surveyed never should

be construed literally as measurements of hearing. As this sense is classically defined, it is considered uniquely to be evaluated based upon a subject’s voluntary or conditioned behavioral responses. However, this does not preclude measuring these signals to estimate hearing sensitivity, to demonstrate correlation with some behavioral measures of discrimination among different sounds, to corroborate some capabilities of binaural processing, or even to define metrics that reflect some level of cognitive processing of sound.

In general, these signals are substantially accessible by methods of electrophysiology that have come to help researchers and clinicians to better understand certain effects of sound stimuli and/or underlying mechanisms of the brain’s response to sound. With understanding, it becomes possible to apply such measures to clinical problems, such as indeed characterizing an individual’s hearing capacity or differentiating among certain types of hearing impairments/disorders. The foundation of knowledge that has empowered the presently high level of understanding comes from well over a half-century of research and development, instigating one of the most voluminous literatures in hearing science. Consequently, it provides a broad evidence base in clinical applications that has been enticing for robust technological advances and commercialization necessary to put tools of electrophysiology in the hands of researchers and clinicians alike.

To explain, conducting clinical tests using methods described herein are best conceived and approached as N-of-1 experiments. The clinician has some idea that such-and-such may account for a given patient’s condition, some test is purported to offer some possible insights, another

may confirm a given diagnosis, or otherwise the results may be at least to inform further management of the case. With modern technology, the clinical-electrophysiology “toolbox” is stocked with advanced and powerful tools that are highly efficacious in the hands of competent users. Their particular evidence bases are broadly overviewed herein, demonstrating indeed that these can be useful for teasing apart sophisticated issues of clinical concern and are broadly applicable over the life span.

In fact, the auditory system can be investigated in-depth using current electrophysiological tools, many requiring little of the subject/patient, often even with the individual being inattentive to the stimulus, sleeping naturally or under sedation/anesthesia. Examples include screening infants for possible hearing loss shortly after birth, estimating hearing sensitivity when conventional audiometric results prove unreliable, monitoring auditory function during surgery, differentially diagnosing peripheral versus central auditory lesions, assessing cognitive processing ability, or monitoring clinical treatment. The toolbox, much like a mechanic’s tool kit, provides a variety of instruments. What mechanic worth their salt would have a toolbox filled only with box-end wrenches? Different “jobs” require different tools; some require several tools to really do the job.

The overall goal here is to address major types of clinical electrophysiological tools that

are prevalent in current audiological practice and overview each one surveyed for their most common applications. Still others will be mentioned at least, if not featured, along the way to hint of potential interests, even if presently the topic is somewhat beyond the primary scope of this foundational textbook and/or not quite ready for “prime-time” (routine) clinical use. Their coverage is to serve as encouragement of continued study beyond “the book.” This text is thus intended as a launch pad toward competency in this very intriguing area of clinical practice. Ultimate clinical, hands-on competency starts with a “competent” knowledge base—a comprehensive background upon which to develop and that—together with further study and clinical mentoring—can lead to clinical competency. This foundation must also be such as to support growth (and certainly not to compromise it) in the further pursuit of knowledge, into the future. Any field worth its salt is not stagnant; any competent and seasoned worker will attest to not doing things today entirely the same as when they first became clinically certified and started working in the profession.

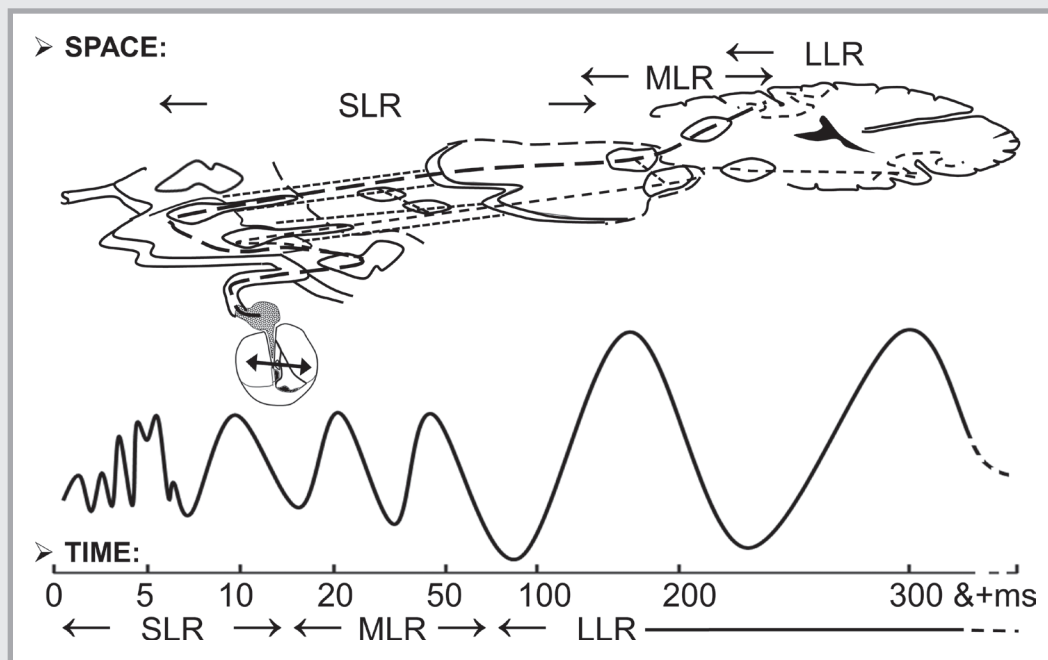
Therefore, the focus here is the systematic measurement and use of bioelectrical signals that are elicited (conventionally) at the beginning of the 8th cranial nerve, to elicit in turn activity along the ascending auditory pathway. Final destination—the cortex.

## HEADS UP

### Like in Space, It Takes Time to Travel Along the Auditory Pathway—So What?

It will be useful to look a bit ahead at the object of affection of the book’s writers and editors. Figure 1–1 presents schematically the “big picture of AEPdom”—what collectively are called *auditory evoked potentials (AEPs) or responses*. However, only with a specialized approach can such a panoramic view of these signals be approximated—a

singular continuum of *recorded* undulating waves of electrical activity, having been generated all along the auditory pathway from inner ear to cortex. Furthermore and particularly important technically, nor can such a pristine sample of the component AEPs be realized—ever. However, there will be plenty of opportunity to deal with reality reasonably effectively. It will suffice for the moment simply to note that a variety of technical



**Figure 1-1.** Temporal and spatial overviews of auditory evoked potentials and their underlying neuroanatomical origins. Perspective of the examiner is “eyeing” the initiation of the fascinating barrage of neural activity in the time domain (bottom of the figure) while it is traveling “away” toward the considerably larger, and even more elaborate, cortical projections and expansions therein. The three traditionally defined response latency classifications are demarked in time and (in effect) in space, although these divisions are more gray than black-and-white in either domain. Even for a sound like the snap of the fingers, the component waves of AEPs elicited along the way in space add up to hundreds of milliseconds in time, thanks to the multiple “weigh-stations” along the way. Not illustrated but also contributing to this complex wiring and adding time to signal propagation is the relative density of nerve-cell populations along the pathway. *Heavy dashed line:* primary, crossover path; *light dashed line:* secondary/uncrossed-path and/or additional levels of crossover in the brainstem system. (Inspired in part by illustrations of Netter [1962<sup>4</sup>] and Moore [1987<sup>3</sup>] and adaptations by the American Speech-Language-Hearing Association [1988<sup>1</sup>] and Durrant and Feth [2013<sup>2</sup>].)

“tricks” can and will be called upon to allow the examiner to measure reliably a variety of AEPs, as defined practically. This will include efforts to sort out specific influences of stimulus parameters as well as various other factors to which AEPs are sensitive (such as maturation and certain types of pathology). It will be shown that it is possible to target less or more specific levels of the ascending auditory pathway and interpret possible clinical significance of the resulting observations/measurements.

The citizen-wave components in AEPdom are extractions largely from *brainwaves*. It will not ruin the rest of the story to disclose that these waves are searched using fundamentally the tool of *electroencephalography (EEG)*, thus recording the signals of interest most often (but not exclusively) from the surface of the scalp. Furthermore, AEPdom is ultimately about time and space, with time–space coordinates effectively summarized in Figure 1-1. This virtual map reflects the substantial neuroanatomy involved and the



signals generated sequentially from events stimulating the *peripheral auditory system*, thus covering more than the *central auditory nervous system (CANS)*. Signals thus can be expected to arise and possibly be recorded whether from the hearing organ, 8th nerve, neural ganglia, and nerverlike tracts within the brainstem and midbrain and areas within the expansive cerebral cortex.

One of the major tactical decisions generally dictated by a given AEP test and its purpose is that of the time frame of recording of the particular AEP waves of interest. This is defined routinely by the period of time from the onset of the stimulus to a given peak of the targeted wave component. This measure is called *latency*, so the clock starts indeed in the periphery, upon initiation of the sound stimulus. AEPs are conventionally divided into three broadly defined intervals of latency—those of the *short, middle, and long latency responses (SLR, MLR, LLR)*. The whole issue arises from the simple fact that the neural pathways are not capable of instantaneous transmission of signals from the sensory organ, up the ascending pathway, and to (possibly throughout much of) the cortex. In the backdrop of complexity of the neuroanatomical pathways, the “time–space continuum” gets stretched in ways not entirely intuitive. Overall, the longer the pathway, the longer the total latency to the given wave of activity, at its presumed site of generation. However, the south-to-north trajectory is also not entirely the only possible way for electrophysiological signals to propagate (in effect), and the neuroanatomical architecture is truly three-dimensional. Nevertheless, by the methods considered herein, a number of simplifications will prove to be practical, thus, for instance, focusing only on potentials primarily from a specified level of the system. Making measurements from less or more locations around the head will be dictated by specific clinical inter-

ests. Speaking of which, this indeed is where the measurements are recorded routinely for most clinical interests in audiology, generally using methods that are strictly noninvasive and thus causing the patient minimal/no discomfort. The truly remarkable aspect of the AEPs (as illustrated in Figure 1–1) is their mutation, so to speak, along the time–space continuum—a sort of time–space warp occurs. Not only is transmission of signals along the pathway time consuming, the delay effect (again, latency) is progressive in time but in reverse. The signal does not speed up going to the cortex—rather, it slows down! Not only can this activity last for hundreds of milliseconds, this progression is such as to require the time base of the record to be scaled logarithmically (a nonlinear scale) to get essentially all major component waves plotted reasonably on the same page. This is in deference to the ensuing complexities of the ascending pathway wherein the underlying signals travel but also are mutated through space on the way to the cortex and even therein. Also noteworthy is that the peripheral system does not operate like a microphone, transducing sound into electricity nearly instantaneously and directly input to the brainstem, as if it were a public address system. Nevertheless, several component waves (SLR citizens) are witnessed well within an interval of merely 10 ms, and that includes a sequence of signals having traveled already a good bit up the brainstem. Mutation occurs because activation from one level of the system progressively spreads more and more in space, again taking more time, but while also building progressively larger waves, by an order of magnitude or so for some at the cortex—from one-millionth of a volt (1  $\mu\text{V}$ ) or less in magnitude (SLR-land) to upward of 10  $\mu\text{V}$  (LLR-land). There then will be quite a variety of approaches in both stimulus generation and response analysis as well as clinical interests that such approaches may serve.

## ■ Postquel

From this Heads Up overview, the recording of any of the waves of AEPs rightfully can be expected to reveal something about the status of different levels of the brain and/or permit extrapolation from findings of their measurement to predict the likelihood that the auditory system is, firstly, capable of responding to sounds in a given individual. Thereafter, issues of relative sensitivity (re: normal-hearing/neurologically intact patients), if not some aspect predictive of cognitive ability, can be addressed. Various details of underlying neuroanatomy and neurophysiology thus will need to be considered to provide fundamental understanding of what makes the AEPs “tick” and provide rationales for clinical use of their proper measurement. In order to correctly interpret results of AEP tests, it will be important to consider such bases even down to the microanatomical/cellular level at times. The rendering of a decision of abnormal function first relies upon foundational knowledge of normal function and basic aspects of what are or account for nuances of nonpathological findings. Only then can pathological variants be entertained knowingly to deduce what might have gone wrong along Patient X’s pathway.

More fundamental matters are essential knowledge before the would-be AEP examiner is ready to escort Patient X into the exam room. These are the various technical aspects involved, such as some of the computer science that is essential for “digging out” relatively small signals in less-than-pristine circumstances. The term “electro” (as in EEG) and “potential” (as in AEP) were used earlier without fanfare. Yet, some basic principles of electricity are essential to understanding both the audi-

tory system and electrophysiological tests thereof, although not too much more than understanding the basic battery-operated flashlight. The term “signals” was thrown around a good bit too, and that implies the need to know some methods of analyzing the bioelectrical activity to be recorded during the electrophysiological examination. There will be some fancy math underlying the signal-processing concepts essential to AEP measurement, yet only conceptually and studied with confidence that the methods themselves can be expected to be implemented broadly in commercially available test systems. These instruments incorporate high-speed computing and hardware both to generate suitable stimuli and to permit detection/other analyses to aid the examiner in rendering their judgment of what the findings mean. Operating today’s AEP test systems are much like operating a home computer/laptop and using common software for word processing, electronic-spreadsheet analyses, producing virtual photo albums, and so forth. So, let’s go!

## ■ References

1. American Speech-Language-Hearing Association. (1988). *The short latency auditory evoked potentials: A tutorial paper by the Audiologic Evaluation Working Group on Auditory Evoked Potential Measurements*. Author.
2. Durrant, J., & Feth, L. (2013). *Hearing sciences: A foundational approach*. Pearson Publishers.
3. Moore, J. K. (1987). The human auditory brain stem as a generator of auditory evoked potentials. *Hearing Research*, 29(1), 33–43.
4. Netter, F. H. (1962). *Nervous system* (Vol. 1). CIBA Pharmaceutical Company.