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Macromechanics of Hearing: The Unknown Known

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Abstract

The following summarizes the key points addressed during a tutorial session on the Macromechanics of Hearing that took place at the 12th International Workshop on the Mechanics of Hearing held at Cape Sounio, Greece, in June 2014. The tutorial was intended to present an overview of basic ideas and to address topics of current interest relevant to the Workshop. The session was recorded, and the audio file and accompanying visual content of the presentation can be found in the Mechanics of Hearing Digital Library (www.mechanicsofhearing.org).

INTRODUCTION

In this tutorial presentation, I discuss a handful of issues, sometimes controversial, related to the macromechanics of the mammalian cochlea. By macromechanics, I mean processes on the scale of the wavelength of the traveling wave. Topics are drawn from the vast well of the “unknown known”—things that we don’t know but should, once knew but have forgotten, or know but sometimes refuse to acknowledge. Although I aim for a diversity of topics, the coverage is far from comprehensive, and certain simplifications (but hopefully not gross distortions) are necessary. The topics are framed as series of questions, including: Is the middle ear an acoustic transformer? What are fast waves and slow waves? How do otoacoustic emissions get out of the cochlea? Are traveling waves amplified as they propagate? What is scaling? And, finally, how many cochleas are there?

KEY DISCUSSION POINTS

What Does the Middle Ear Match?

By many textbook definitions, the middle ear is an acoustic transformer that evolved to match the high impedance of the cochlear fluid to the low impedance of the air. I argue that the middle ear is better understood as a wave converter that matches the low impedance of sound waves in air to the higher impedance of a completely different type of wave that propagates inside the cochlea. By assuming that the middle ear matches these two wave types, one can calculate that the speed of the functionally important intracochlear waves is about a hundred times slower than the speed of sound in water. Because the speed of these waves is so slow, we call them slow waves.

What Are the Slow and Fast Pressure Waves Inside the Cochlea?

The slow pressure wave is the difference between the scalae pressures whereas the fast wave is their average. These two waves have very different properties. For example, the slow wave creates a force that can move the cochlear partition; as a result, it both affects and can be affected by the mechanics of the partition. The fast pressure wave does not move the partition and is not affected by its mechanics. The slow wave travels slowly because its speed is determined, in part, by the properties of the cochlear partition (e.g., its stiffness). By contrast, the fast wave is essentially a sound wave in the fluid, and its speed therefore depends upon the fluid compressibility.

How do Otoacoustic Emissions Travel Out of the Cochlea?

My answer addresses the question as it applies to acoustically evoked distortion products (DPOAEs). Do they travel out by slow waves or by fast? Much experimental evidence suggests that DPOAEs are generated over a distributed region along the cochlea—perhaps the entire basal region—and not from a single point. As a result, it can be challenging to interpret delays measured between the putative “site” of OAE generation and the arrival of the OAE in the ear canal. I argue that a better way to infer the propagation mechanism of these emissions employs the so-called constant. Experimental results obtained using the Allen-Fahey paradigm indicate that acoustically evoked distortion products emerge from the cochlea primarily via slow waves.

Are Traveling Waves Amplified as They Propagate?

To address this question from a macromechanical point of view, I rephrase it as follows: Does the power carried by the slow traveling pressure wave increase as the wave propagates along the cochlear partition? I review what we know about the traveling wave and use the inverse method approach to argue that the cochlear partition does work on the fluid, amplifying the slow traveling wave pressure near the peak of the BM response. I conclude that traveling waves are (almost certainly) amplified as they propagate. The hedge stems from the issue of where the power that amplifies the slow wave comes from. Does the power come from a locally “active” source (e.g., the outer hair cells acting as force generators)? Or was the power initially extracted from the stimulus near the base of the cochlea and then transferred into the slow wave after it propagated to the peak region via some alternate route (e.g., via waves traveling within the tunnel of Corti or along the tectorial membrane)? The first scenario involves true active amplification; the second is a form of mode conversion.

What is Scaling?

Scaling is an approximate local symmetry. A symmetry can be thought of as something that stays the same when something else changes. In the case of scaling, the thing that varies is the measurement location along the cochlear partition, and the thing that stays the same is the shape of the mechanical transfer function. In particular, transfer function magnitudes and phases nearly overlap when expressed versus normalized frequency (i.e., frequency divided by the local characteristic frequency). What do we mean by a symmetry that is approximate and local? First, the overlap of transfer functions is imperfect and shows systematic deviations, hence the symmetry is approximate. Second, local means that the match is

generally good for CFs within an octave or so of one another. I discuss how the concept of approximate local scaling facilitates the study of cochlear mechanics (e.g., it reduces the number of independent variables; it enables one to find the frequency response from the spatial response; and so on). Finally, but I think most importantly, deviations from scaling can alert one to potentially significant phenomena.

How Many Cochleas Are There?

I argue that there are at least two cochleas, an apical one and a basal one. To support this contention, I review apical/basal differences in a variety of macromechanical response features.