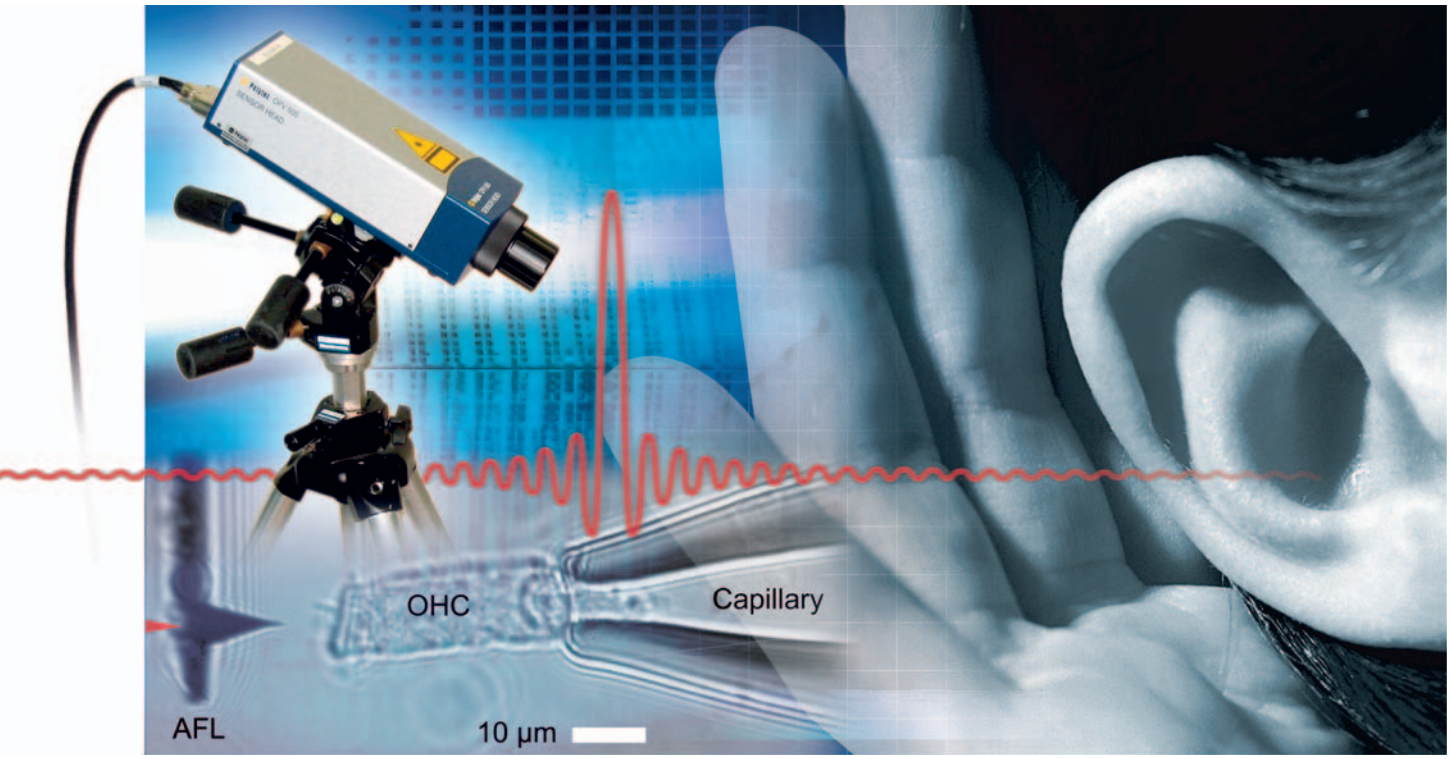
Tiny Sensors – *Accurate Ear*



Laser-Doppler Vibrometers Probe the Basic Mechanism of Hearing

Intensive medical, molecular and biomechanical research activities have provided much insight into the function of signal processing inside the ear. However, we are still far from a comprehensive understanding of the hearing mechanism. Current research work deals with the details of electro-mechanical signal transduction occurring in the cochlea of the inner ear. For the investigation of the inner ear biomechanics, Laser-Doppler Vibrometers have proven to be highly sensitive vibration sensors that don't affect the specimen.

Ears and Hearing – Biological Miracles of Signal Processing

Our ears are the most critical sensory organs with regard to interaction with the environment and to communication. They process various spatially resolved signals in real time featuring a remarkable spectral resolution and a tremendous dynamic range. From a biomechanical point of view, the ear is a highly sophisticated acoustic sensor converting sound pressure waves into electrical signals.

There are three sections to the human ear (Figure 1):

- The outer ear (A) includes the auricle, the earlobe and the ear canal.
- The middle ear includes the tympanic membrane or eardrum (B) and the ossicles (C), the three tiny bones of the middle ear known as the malleus, incus, and stapes.

  These bones transfer the tympanic membrane motion to the inner ear through the oval window.
- The inner ear (D) comprises both the cochlea (the organ of hearing) and the labyrinth or vestibular apparatus (the organ of balance). Inside the cochlea and labyrinth is a fluid medium and hair cells with their cilia either free-standing in the fluid or in contact with a covering membrane. Moving the fluid or membrane, the cilia are deflected generating nerve impulses.

The perception of acoustic signals depends essentially on how acoustic vibrations are transmitted and converted on their way from the outer ear via the middle ear to the hair cells in the inner ear.

The details of biomechanical signal processing in the cochlea are a current topic of medical research.

Structure of the Cochlea

The cochlea is a spiraled, hollow, conical chamber of bone (for a cross-section see Figure 2, left) and consists of three fluid-filled chambers (Figure 2, right). Its core component is the Organ of Corti, the sensory organ which supports the receptors of hearing.

Vibrations transmitted from the stapes to the cochlea generate a wave traveling along the basilar membrane. The basilar membrane separates the scala media and the adjacent scala tympani. A certain sound frequency generates a displacement maximum at a corresponding location on the basilar membrane. The stiffness of the basilar membrane decreases from bottom to top of the cochlea. Thus high frequencies cause a maximal displacement at the base of the basilar membrane while lower frequencies maximally affect more distant positions.
The wave propagation inside the cochlea is influenced by active mechanical amplification processes that are responsible for the extraordinary dynamic range and the frequency selectivity of hearing.

Transduction in the Cochlea

The hair cells are arranged in four rows across the Organ of Corti and along the entire length of the cochlear coil.

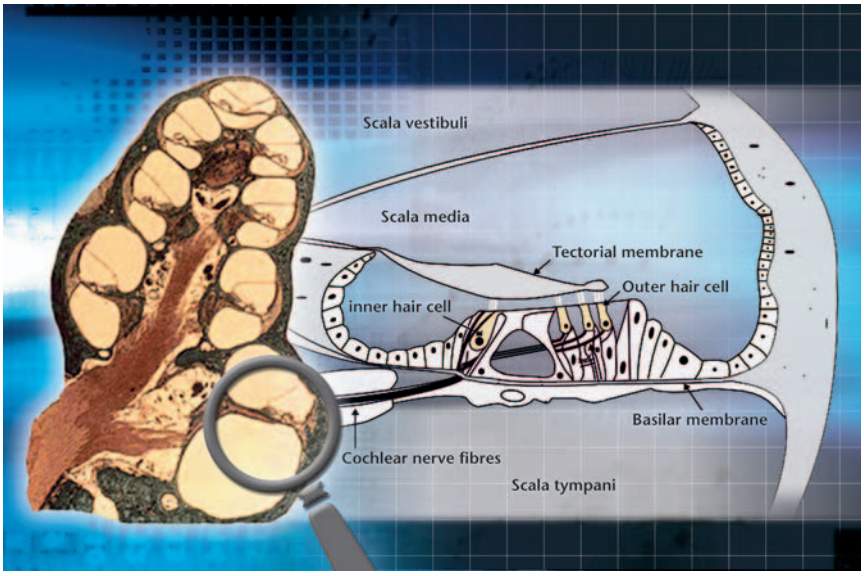


Figure 2: Cross-section of the cochlea (left) and enlarged view of the Organ of Corti with hair cells (right)

Three rows consist of outer hair cells (OHCs) and one row consists of inner hair cells (IHCs).

- The inner hair cells (IHCs) provide the main neural output of the cochlea and generate nerve impulses from the mechanical vibrations induced by the sound wave.
- The outer hair cells (OHCs), however, are responsible for mechanical amplification within the cochlea. These are the object of current research.

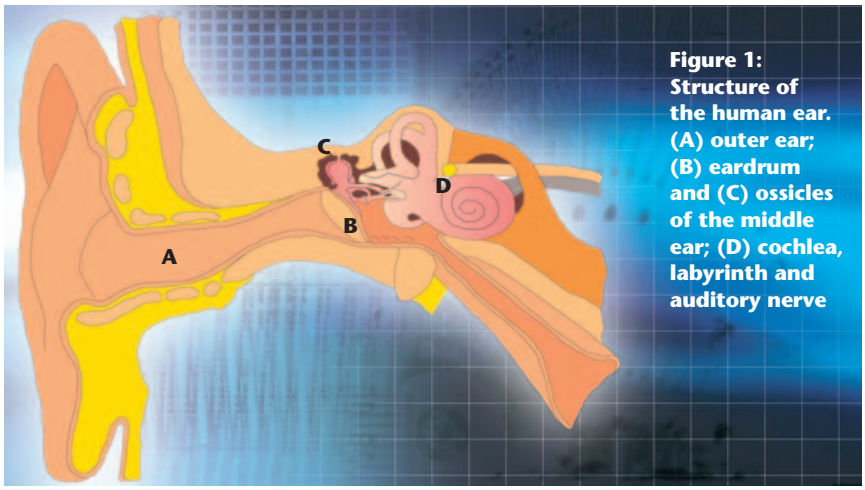


Figure 1: Structure of the human ear. (A) outer ear; (B) eardrum and (C) ossicles of the middle ear; (D) cochlea, labyrinth and auditory nerve

Electromechanical Transduction in Outer Hair Cells

How can the outer hair cells influence the traveling wave?

A change of membrane potential of the outer hair cell (OHC) causes the cell body to contract and elongate. This electrically induced motion, called somatic electromotility, is believed by many researchers to be the basis of the exquisite frequency selectivity, sensitivity and dynamic range of the cochlea.
The electromechanical force produced by the cell is thought to counteract damping forces in the cochlea, such as those inherent to the motion of fluids and cells, to produce the extraordinary mechanical tuning of the cochlea.
The motor molecule responsible for somatic electromotility is called prestin. There are at least 6,000 of these molecules per square micrometer of cell surface. It is not known how the motion of all these molecules is coupled to the cytoskeleton, to generate the somatic electromotility. The process is exceedingly fast and works up to ultrasonic frequencies. Destruction of this transducer leads to deafness.

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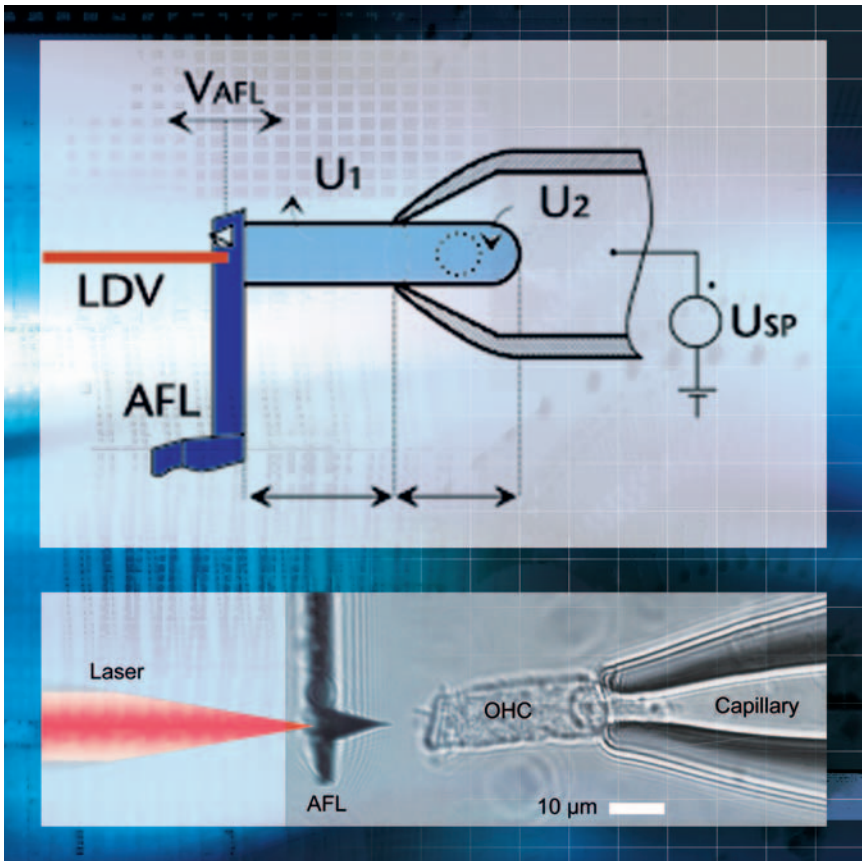

Figure 3: Layout and micro image of the experimental setups for electromechanical force (upper) and impedance (lower) measurements of an outer hair cell (OHC)

The electromechanical transduction process was investigated employing laser Doppler vibrometry together with atomic-force spectroscopy. Using the vibrometer the somatic electromotility was found to follow changes of the membrane potential cycle-for-cycle up to at least 100 kHz. The soma of the OHC turned out to have the necessary molecular machinery to generate electromechanical responses – with little attenuation and time delay – well above the frequency limit of hearing. Since these measurements were completed, an innovative method to measure the mechanical properties of biological structures up to at least 40 kHz has been developed. This technique employs an atomic force cantilever and has general applications outside the area of hearing research; it is particularly attractive for investigation of biological structures in a fluid. It was also applied to investigate mechanical and cell biological properties of cellular and membranous structures in the cochlea.

Dynamical Measurements of an Outer Hair Cell

To investigate the dynamics of the OHC, a portion of the cell is sucked into a glass capillary (Figure 3). For determining electromechanical force, the transmembrane potential of the cell is modified by applying a voltage (U_{SP}) to the pipette solution inducing voltage drops, U_1 and U_2, across those sections of the cell membrane excluded from and contained in the pipette, respectively (Figure 3, upper). The somatic electromechanical force was determined by placing a high-impedance mechanical load, the reverse side of a lever used in atomic force microscopy (AFL), against the apical end of the cell. The velocity of the AFL, V_{AFL}, in response to electrical induced force by the excluded section of the cell was measured with the Laser Doppler Vibrometer (LDV) focused on the AFL. The force is then calculated from V_{AFL} and the known mechanical impedance of the AFL.

To measure the axial impedance of the cell, the tip of an AFL was placed against the apical end of the cell (Figure 3, lower) and a known force applied to the AFL using a magnetic field. The impedance is then computed from the resulting velocity V_{AFL} measured by the LDV and the known mechanical impedance of the AFL.

Velocity measurements were performed using a contemporary OFV-505 Sensor Head and an OFV-5000 Vibrometer Controller.

Results

The experiments show that isolated OHCs can compensate for fluid forces with nearly constant displacement amplitude and phase up to frequencies exceeding their local frequency on the basilar membrane. From this it follows that electromechanical transduction in the OHCs provides the high frequency capabilities that are necessary to amplify the traveling wave within the whole acoustic range.

CONTACT

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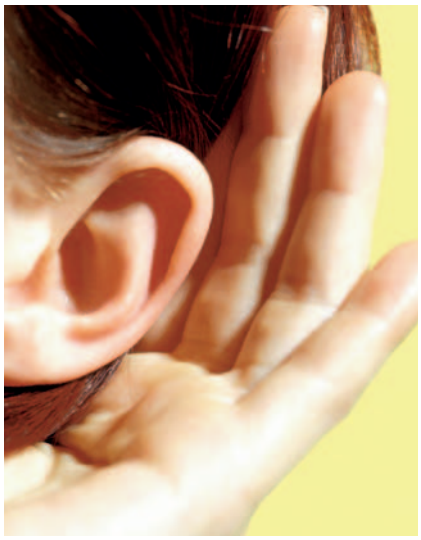
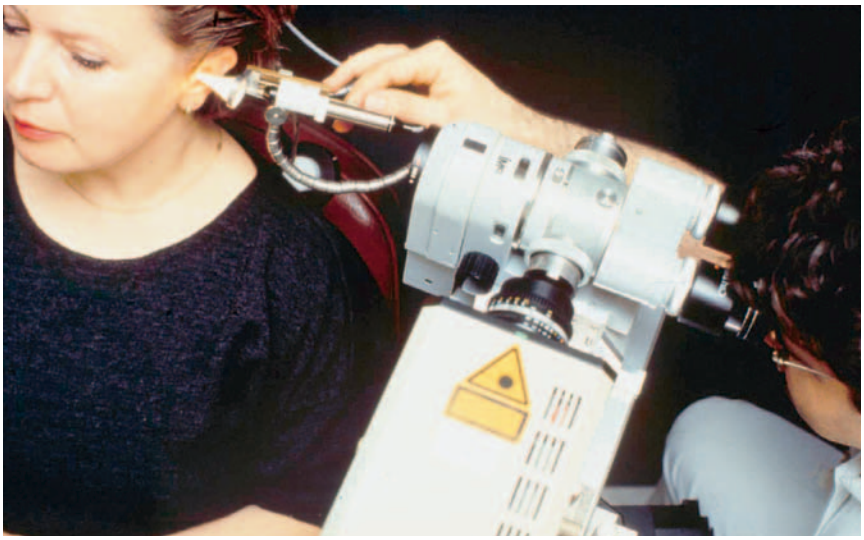
www.uni-tuebingen.de/cochlea
Visiting this address you will also find a comprehensive glossary about the structure and function of the inner ear.

We Can "See" *How the Patient Hears*





Interview with Professor Anthony W. Gummer about the Use of Laser Vibrometers for Hearing Research and Clinical Diagnostics

Anthony W. Gummer is director of the Physiological Acoustics & Communication section of the Dept. of Otolaryngology, University of Tübingen. www.uni-tuebingen.de/cochlea

Professor Gummer, how has Laser-Doppler-Vibrometry (LDV) found its way in to hearing research and diagnostics?

The first experimental vibration measurements on the eardrum were in the seventies and eighties. Some years later, the LDV started to provide insight into the micromechanics of the inner ear with an article by Nuttall et al in 1991. Since the nineties, the application of LDV in clinical diagnostics has been continuously reviewed. At that time, the experimental setup was cumbersome and the measurement time prohibitively long. In 1995, our research group succeeded in combining a highly sensitive Polytec vibrometer with all other components to produce a so-called Laser Audiometer that provides full diagnostics within a couple of seconds.

Which pathologies can be diagnosed by LDV measurements, and which are the regions of the ear that can be accessed via eardrum measurements?

Measurements on the eardrum can be used to diagnose pathologies of the middle ear, such as luxations of the ossicles, otosclerosis or dysfunctions of middle-ear implants and prostheses. It also allows us to investigate the micromechanical function of the inner ear. The active amplification process inside the cochlea, which generates an otoacoustic emission, can be assessed non-invasively by the highly sensitive single-point vibrometer as a vibration of the ear drum. We can "see" how well or poorly the patient hears. This could have important applications in screening infants for dysfunctional hearing.

Can you outline the advantages of LDV compared to other methods?

I just mentioned the benefits to clinical diagnostics. Regarding our fundamental research on biophysical processes in the cochlea, there is no other measurement technology providing appropriate sensitivity and a resolution below 1 pm.

What are the clinical practice requirements for a LDV-based diagnostic device?

The system must be simple to operate by a technical assistant, the measurement time short so as not to unnecessarily inconvenience the patient, and the laser power must be below 1 mW, as in the case of Polytec vibrometers.

How would you rate the performance of the current Polytec product line?

We are extremely satisfied with the capability of Polytec's single-point vibrometers. The depth-of-field is in the µm range, enabling well-focused high-resolution measurements. Our current experimental setup for the investigation of hair cells involves an OFV-505 Sensor Head and our newly developed AFM cantilever and has a 100-fold better sensitivity than the previous combination (see article).