Visualization of ear impairment using optical coherence tomography (OCT)

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The ear senses, amplifies, analyzes and transduces sounds to relay auditory information to the brain.

Central Auditory Nervous System

- Central nervous system can only encode incoming information over a limited range (*compression*)
- Ideally want to maintain sensitivity at low levels (*amplification*)

Peripheral Auditory System

- Compression and amplification and frequency selectivity are achieved in the mechanics of the cochlea
Clinical diagnoses of hearing loss

Our ears are physiologically vulnerable to noise/blast, chemical/ototoxicity exposures etc., and deteriorate with age...

Structure exams (not enough resolution)

Hearing (function) tests (summed responses along the pathway)

- **Lengthy and costly and with limited information** to pinpoint the damage of ear structure and dysfunction.
- Can we perform hearing tests in a more efficient way including both structural & functional information?
Observations of sound-induced vibrations (or potentials) along the auditory pathway form the foundation for our understanding of the mechanics of hearing, including middle ear function, cochlear mechanics, and the generation of otoacoustic emissions in normal and impaired ears.
What have we learnt from classical (single-point) vibrometry measurements?
Classical approaches of *vibrometry* and *micro-pressure sensor* to directly measure middle ear function

Invasive: Requires opening of middle ear cavity to access ossicles/cochlea

Human ME Pressure Gain: $\text{MEPG} = \left| \frac{P_{\text{stapes}}}{P_{\text{TM}}} \right|$
Classical approaches of **vibrometry** and **micro-pressure sensor** to directly measure intracochlear responses

**Invasive and challenging:** Requires opening of the cochlea to access the cochlear partition and preserves hearing.
Classical approaches of vibrometry and micro-pressure sensor to directly measure intracochlear responses

- **Compression**: 90 dB range stimulation → 40 dB range of responses
- **Amplification**: Sensitivity of soft sounds > higher sound intensities
- **Frequency selectivity**: peaks at characteristic frequency

There is a little documentation from the apical or middle turns
Limitations of classical approaches

- We have very little/limited direct information about middle ear function and cochlear mechanics (site measurement).

- Invasive measurements are difficult to do (in vivo + middle ear and cochlear healthy).

- We only have measurements from a few species, along certain direction, and from the base and apex of the cochlea.

- We cannot get measurements from humans.

- We need noninvasive measurements.

The reality in the field for many decades...
Optical Coherence Tomography (OCT)

Imaging ear structure

(resolution: 2-10 µm)
Novel real-time imaging: optical coherence tomography (OCT)

**OCT:** imaging technique that uses low-coherence light to capture micrometer-resolution, two- and three-dimensional images from within optical scattering media (e.g., biological tissue).

Penetrate into samples with enough resolution to detail the ear structure.

Confocal image of the cochlea  Medical Imaging resolution / size  MRI image of the cochlea
The intensity (I) of the signal recorded by the line camera is a function of wavenumber (k).
Optical coherence tomography (OCT) – Hearing

- 2D image, i.e., cross-section of the intact cochlea
- 3D image, i.e., the middle ear (non-invasive)
- Vibrometry to measure motions
3D image of middle ear

Gerbil

malleus ➔ eardrum ➔ incus ➔ stapes ➔ stapes footplate

Human

Ossicles visual

Umbo: tip of the manubrium that attaches the eardrum
PLP: plate of the lenticular process of the incus
Measuring the thickness of the eardrum

(Figures in Cai et al., 2019)
Imaging cochlear partition *in vivo* from intact cochlea.
Gerbil cochlea: cross-section of three turns

Base = 1\textsuperscript{st} turn
High-frequency

2\textsuperscript{nd} turn
mid-frequency

Apex = 3\textsuperscript{rd} turn
Low-frequency
Gerbil cochlea: the 2\textsuperscript{nd} turn
Gerbil cochlea
Organ of Corti in 2\textsuperscript{nd} turn

Lay, 1972
Gerbil cochlea
Organ of Corti in 2\textsuperscript{nd} turn

Lateral compartment

BM
IHC
OHC
ToC

Lay, 1972

100 \text{\mu m}
Optical Coherence Tomography (OCT)

Vibrometry – function of the ear

(resolution: < 1nm)
OCT vibrometry – middle ear sound transmission

Vibrometry performance
- Linear
- Large dynamic range
- Sensitivity < 1nm

OCT image of the umbo

Sound induced umbo motion
(many of these motions < 1 nm)

![Graph showing motion measured with OCT](image)

- Pezo driving voltage (mV) vs. motion measured with OCT (nm)
- Linear fit

![Image of the umbo](image)

- Noise floor @ 100 pm

![Graph showing motion at different frequencies](image)

- Frequency (kHz) vs. motion (nm)
- 80 dB SPL
- 70 dB SPL
- 60 dB SPL
- Noise floor @ 100 pm
OCT vibrometry – Conductive Hearing Loss

- What is the ideal material for eardrum repair and reconstruction?
The 1st intracochlear measurements

---- Light microscopy

- Directly observe the traveling wave along the basilar membrane
- ‘Slow’ displacement waves that propagate on the BM from base to the apex.
- Travels much slower than that of the sound wave (~ 1550 m/s)
- Peaks at a specific place (tonotopic) – best frequency (BF).

Our Focus in Cochlear Micromechanics

How does the cochlear partition move with the traveling wave to achieve frequency selectivity, sensitivity, and amplification/compression?

Urgent need for the understanding of low-frequency mechanics that is poorly understood but important for human sound perception & speech!
Evidence of tonotopic organization in living animal

Tonotopic arrangement (frequency selectivity)

A: BM displacement

C: BF along the cochlea

Intact cochlea

Mechanical BF = ANF CF

Physical location of decoding different sounds
Evidence of traveling wave in living animal

Phase accumulates with fs

→ Traveling time

Wavelength became shorter while approaching the BF
Deformation of the cochlear partition

• The different structure moves differently
• Different in frequency selectivity
• We think the complex pattern is important for frequency selectivity, sensitivity, amplification and compression.
The complex pattern is important for hearing because it disappeared after damage/animal died.

- The different structure moves almost in unison
- Linear responses – no amplification/compression
- Sensitivity decreased (much less)
- Lost frequency selectivity
Where does the frequency selectivity arise?

- Different regions are tuned differently with different sensitivities.
- The sensory OHC region exhibits the greatest sensitivity BUT is not well tuned.
- The basilar membrane (BM) is more tuned with high sensitivity at the best frequency (BF).
Comparison of mechanical tunings with auditory nerve fiber (ANF) tunings

- Cochlear frequency coding comparing to ANF → The BM tuning was similar to ANF.

- **Open question: why?** The ANF connects to hair cells not to the BM
OCT application in hearing research and the clinic

OCT provides

- Real-time imaging with resolution ~ 2-10 micrometers, sufficient for the middle and inner ear.

- Vibrometry measuring sub-nanometer displacements of sound-induced vibration within the middle and inner ear.

- All of these can be obtained from intact middle- and inner-ear from living animals
OCT application in hearing research and the clinic

_Potential applications:_

- Hearing loss related to functional/anatomical variations
  - Stria vascularis
  - Noise/blast overexposure
  - Ototoxicity and drugs
  - Age-related
    - Cochlear synaptopathy (‘hidden hearing loss’) by addressing the pre-synaptic status of auditory neurons
- Cochlear implantation with residual hearing
- The function of semicircular canals
- Providing noninvasive functional/pathological and recovery evaluation of brain injuries (TBI).

And the most important

- Application in otology for humans – to improve precision diagnosis for personalized medicine.

_These are unique projects that require extensive and specialized programming of the system to be able to design and implement these studies._
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