How Hair Cells in Cochlea Analyze Sound Waves

New Hypothesis Based on Extraordinary Transmission in Acoustic Metamaterials

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***Abstract*— This paper discusses hearing system of human from engineering point of view, and reports four questions we have now; 1) why eardrum is so sensitive and broadband, 2) how middle ear compensates significant impedance mismatching, 3) how sounds are detected by such a small cochlea, and 4) how the sounds are absorbed perfectly without ringing. Discussion is focused on question 3), and new hypothesis based on extraordinary transmission in acoustic metamaterials is proposed.**

Keywords—acoustic metamaterials; extraordinary transmission; hearing system; organ of Corti; cochlea; hair cells

I. INTRODUCTION

Since 19th century, mechanism of human hearing system has been studied intensively in fields of medicine, pharmacy, and biology. Medical researchers have studied various kinds of diseases and troubles on ears, and developed state-of-art treatment and surgical operation techniques. While, the researches on biology have clarified the process of evolution, that is, how creatures got highly advanced biological systems.

However, looking at hearing systems of human from engineering point of view, we cannot help but think that some of common sense believed in these fields have not been clarified yet, and cannot be explained in physics. For example, V. Békésy won the Nobel Prize in Physiology or Medicine 1961 for his discoveries of the physical mechanism of stimulation within the cochlea. In his comprehension, incoming sound vibrations from pinna are guided into cochlea and generate traveling waves on basilar membrane, leading to stimulating a large number of sensory hair cells in Organ of Corti[1]. Our question is how the traveling waves are generated on the membrane whose total length is only 30 mm. While, the wavelength of the audible frequency processed on the basilar membrane is 75 m for 20 Hz and 75 mm for 20,000 Hz in liquid (lymph). By using such a small organ, we human hear the sounds clearly with huge dynamic range of 120dB and notice 0.5% frequency change sensitively[2].

In this paper, we summarize our questions for the hearing system, and try to understand how the sensory hair cells pick up sounds in related to *extraordinary transmission* in acoustic metamaterials.

II. OUR QUESTIONS FOR HEARING SYSTEM

A. *Configuration of Hearing System of Human*

As shown in Fig. 1, hearing system of human is structured by outer ear, middle ear and inner ear. Outer ear including pinna and ear canal works as an antenna to catch incoming sounds as vibration of air. Middle ear, configured by eardrum and ossicular (joint of three bones of malleus, incus and stapes), provides broad impedance matching between outer ear (filled with air) and inner ear (filled with liquid) beyond the huge impedance gap between $430\ \Omega$ for air and $1.5e^6\ \Omega$ for liquid. In inner ear, semicircular canals help our sense of balance, and cochlea analyzes incoming sounds sensitively and accurately.

In cochlea, three pairs of ducts called scala vestibuli (SV), scala media (SM), and scala tympani (ST) are set up together to make a spiral architecture. Organ of Corti in SM includes 3500 inner hair cells (IHC) and 15000 outer hair cells (OHC) on basilar membrane. Stimuli of incoming sounds make the auditory hairs on the top of the hair cells, stereocilia, touch to the tectorial membrane above, and impulse currents are generated in the hair cell and connected auditory nerves.

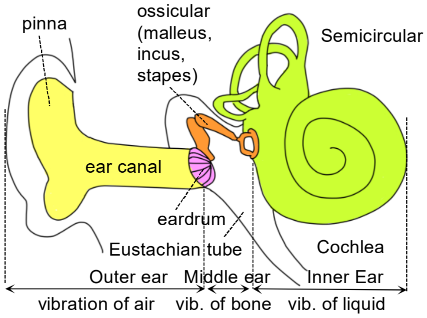

Fig. 1. Configuration of hearing system of human.

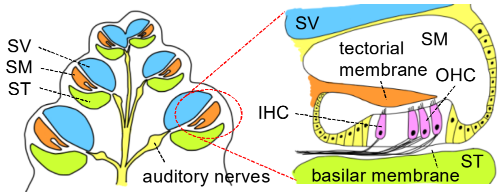

Fig. 2. Cross section of Cochlea and Organ of Corti in scala media (SM).

B. *Our Questions on Ear from Engineering Point of View*[3]

- (Q.1) Eardrum with Super-Sensitive and Broadband Performance

The received sounds by pinna travel in ear canal in the form of plane wave. However, the eardrum whose edge is fixed tightly to the canal wall will convert the fundamental mode (plane wave) into the higher order one. Especially, the sound

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pressure at the lower frequencies would be reduced largely if the eardrum worked simply a membrane. However, the eardrum converts the vibration of air into mechanical one with negligible loss, and guides it to ossicular (joint of three bones) smoothly. Considering the size of the eardrum, such broadband and low-loss conversion provided by the eardrum is quite amazing for authors.

- (Q.2) Middle Ear as a Broadband Impedance Converter or Loss Compensator

The middle ear compensates the significant impedance mismatch between outer ear (air-filled, $430\ \Omega$) and inner ear (liquid-filled, $1.5e^6\ \Omega$). If we did not have middle ear like a fish and outer ear was directly connected to inner ear, the sound level would be reduced to -30dB evenly at all frequencies. To compensate such huge insertion loss, it is explained that the eardrum amplifies the sound by 25dB by changing relative area of eardrum and oval window. Ossicular also amplifies the sound by 2.5dB utilizing principle of leverage and rotation force. However, authors think that the story is not so simple. We need to discuss more in accordance with transmission line theory, focusing not only on transmission but also on reflection.

- (Q.3) Organ of Corti as a Super Compact Sound Analyzer

The place theory based on traveling waves on basilar membrane, which was proposed by V. Békésy, is widely accepted as a mechanism to pick up sounds in Organ of Corti[1]. However, as we pointed out in Introduction, it is hard to explain the excellent performance of our hearing system in terms of high frequency resolution and large dynamic range. It is true that the hair cells with the length of about 30μm ~ 90μm are extremely shorter than the wavelength of the audible sounds. However, we believe that the hair cell has its own resonant frequency and catches the sound based on resonance. Details of this new approach are introduced in Sec. III.

- (Q.4) Cochlea as a Broadband Sound Absorber

Incidental sounds from pinna are guided and analyzed in Organ of Corti in cochlea. However, after the analysis, where the remaining sounds go? General answer is like this. The incoming sound is reflected at the end of cochlea and comes back to the outer ear through ossicular and eardrum again, and finally emitted from pinna. This is called *otoacoustic emission*. However, the sound level of otoacoustic emission is quite small. We believe that the sound waves coming into cochlea are mostly absorbed in the bones surrounding cochlea. In other words, the cochlea is a perfect broadband absorber for incoming sounds.

III. PLACE THEORY BASED ON EXTRAORDINARY TRANSMISSION IN HAIR CELLS

Each OHC looks like a round-bottom test tube of chemical instruments as shown in Fig. 3, and only the bottom of the OHC is supported by other cell. The height of the OHC is approximately 30 ~ 90 μm and a diameter is about 10 μm. The top of the OHC is covered with a tight cuticular plate, and sensory hairs, stereocilia, are standing at the surface of the plate so as to form V-shape. The side wall of the OHC is layered by plasma membrane, cortical lattice, and subsurface cisternae. We believe that such layered architecture is quite important to detect sound waves.

Our idea is as follows. Generally, a membrane tensioned in a tube works as a series capacitor for the incidental waves (fundamental mode). While, when a board with a small pin hole is given in the tube, instead of the membrane, it works as a series inductor[4]. If such ideas are applied to the surface structure of the OHC, the plasma membrane provides a series capacitance C, and small openings in the lattice provide a series inductance L. Therefore, when the series connection of L and C resonates, the sound wave can come inside of the cell and inner pressure level will be increased. On the other hand, when the LC circuit does not resonate, since the sound waves can not come in and the inside pressure level of the cell will be kept in normal state. We are going to confirm this new idea theoretically soon and report the results in the presentation.

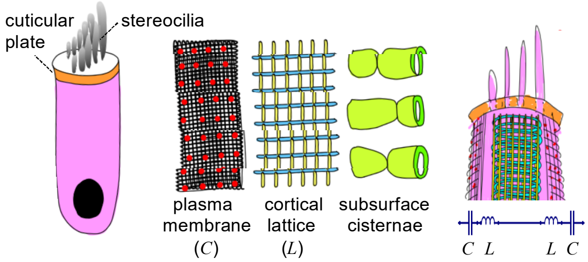

Fig. 3. Overall view of a hair cell, layered architecture on the sidewall, and an equivalent circuit for extraordinary transmission through the wall.

IV. CONCLUSION

In cochlea, ion concentrations of K^+ and Ca^{2+} in SM are larger than those in ST and SV. Such difference of ion concentration helps to generate impulse currents on auditory nerves when stereocilia receives stimuli of sounds. Ref.[5] introduces that hair cells are contracted under appropriate ion concentration of K^+, and external Ca^{2+} is required for relaxation of contracted hair cells. However, trigger signal is also required to tension the cell. That is, the auditory pressure inside the cell plays an important role to tension the cell, and we believe that extraordinary acoustic transmission is deeply related to the sound detection mechanism.

ACKNOWLEDGMENT

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