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Short communication

# Remarks on the theory of hearing-a traveling wave part two

**Jan Myjkowski***

Mielec, Polska, Poland

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***Corresponding author:** Jan Myjkowski, Mielec, Polska, Poland, E-mail: janmyjkowski@poczta.onet.pl

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## Abstract

In the paper, attention was paid to the procedure of reception and transforming auditory information, which does not comply with Bekesy's traveling wave theory. This concerns the sound reception below the hearing threshold in some animals and birds. Discussed are some issues related to the traveling wave theory with an explanation of directional hearing. Indicated was a possibility of reception, especially, of high frequencies, directly on the receptor, without the basilar membrane, due to the conduction of sound waves through soft tissues and a bone.

## Abbreviations

Hz: Hertz; kHz: 1000Hz- kiloHz; Pa; Pascal; pm: picometre= $10^{-12}$m; OHC: Outer Cell Hair; nm: nanometer= $10^{-9}$m; ms: millisecond= $10^{-3}$ second; BM: Basilemma= Basilar Membrane;

The sensitivity of the human ear at a frequency of 1000Hz is 0 dB, the reference level being $10^{-12}$W/m$^2$ or $10^{-16}$ W/cm$^2$, which corresponds to an acoustic pressure of 20µPa [1]. The pressure amplitude of the threshold wave is equal to $2.0\times10^{-5}$ Pa, which, after conversion to the sound wave deflection in the external auditory meatus amounts to $8\times10^{-12}$m = 8 pm. The reference level is abbreviated to SPL (sound pressure level). In the air, the level of the threshold sound intensity in various mammals - having the same organ of hearing - is very different. The sound intensity and acoustic pressure are expressed with the formula: $I= pa^2/p\times V$ (I- sound intensity, pa- acoustic pressure, p-medium density, V- sound speed in the medium). In the air, p=1.2kg/m$^2$, V= 340m/s. In water - p= 1000kg/m$^2$, V= 1500m/s. At the same acoustic pressure, the sound in water has an intensity level 35.5dB lower than in the air, which is caused by the speed of the sound wave in the medium. Based upon the traveling wave theory, the reception and transformation of sounds of wave amplitudes of 8 pm on the boundary of the hearing threshold in humans are barely explicable or even inexplicable [2,5]. A pigeon can hear from 2Hz to 8kHz, the hearing threshold being minus 20dB. A bottlenose dolphin can hear from 1200Hz to 100 kHz, the hearing threshold being minus 20dB. A cat can hear from 70Hz to 70kHz, the hearing threshold being minus 45dB. The record-holder is, instead, the barn owl which can hear from 80Hz to 12kHz, the hearing threshold being minus. 50dB [1]. In the decibel scale, as the reference point is taken the value of $10^{-12}$W/m$^2$, viz. 8pm, after rounding 0.01nm; and so, for minus 20dB, the amplitude of a sound wave reaching the ear is 0.001nm and at minus 40dB, this is a 0.0001nm wave. Mammals and humans have identical ear structures. A bird's ear has an identical cochlear structure, but instead of 3 middle ear ossicles, there is only one ossicle called columella which connects the eardrum with the stapedial base. Be also mentioned that the aforesaid values concern merely the wave amplitude in the external auditory meatus which disappears in the cochlear fluids and on the basilar membrane on the path to the receptor [3]. According to the traveling wave theory, quiet tones are amplified, which is time- and energy-consuming and entails numerous changes in the energy encoded in a sound wave. So small sound wave amplitudes, several hundred times smaller than the hydrogen atom diameter, are unlikely to bring about a pressure difference on both the sides of the basilaris membrane; they are unable,



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either, to generate either a traveling wave on the basilaris membrane or flows of cochlear fluids in the subsegmental space, which is indispensable for bending the auditory cell hairs [4]. And thus, auditory information cannot reach the receptor [5] according to Bekesy's traveling wave theory. A sound wave of an amplitude of 0.001 nm or even 0.0001 nm on the entrance to the system, disappearing on the way to the receptor, does not have sufficient energy to bend the auditory cell hairs which have diameters of 100 nm and are 20,000 – 100,000nm long, at a speed of up to 100,000/s (Dallos). Yet, those creatures can hear such sounds, which conditions the survivability of the species. This is significant proof that the traveling wave theory is imperfect. Hence, a question: so how can information of so low amplitude reach the receptor and how is it received and transformed? There are many indications that this issue is better elucidated by the 'Submolecular theory of hearing' [5] which assumes that there must be a path through the cochlear fluids and the basilaris membrane, and regards mainly low frequencies as well as higher sound intensities. Proof of such a thesis is also stapedotomy which improves hearing but only up to a limited frequency range. The lack of conduction of high frequencies may be limited by the inertia of sound conducting parts having a mass. The sound wave itself has no mass and is not subject to the law of inertia. The energy of a sound wave is conveyed through fluids, soft tissues, and the bone of the cochlear housing directly to the receptor. There is no time delay and superfluous energy transformations, which ensures the reception of small sound intensities, fast reactions as well as precision - so important for the correct encoding of information contained in a sound wave. It can be corroborated by hearing through bone conduction, hearing of a fetus in the mother's womb from the 2$^{nd}$ half of gestation, transfer of information from the ear conchas to the receptor, not only based upon the reflection of waves into the auditory meatus, as well as hearing sounds of very low amplitude. The traveling wave theory does not explain in a clear way the sound localization in the horizontal and vertical planes; nor does it elucidate echolocation [6].

Sound localization is ascertained by each creature which compares the intensity and time of sounds that reach its ears through an analysis of complex sounds. A sound will reach faster the ear which is situated closer to the source of the sound. If a sound arrives on one side of the head, the other ear remains in the head's caustic shadow. This causes a stronger suppression of high-frequency sounds and changes the spectrum of the sound under analysis. There is no possibility of amplifying very quiet, high-frequency sounds through OHC contractions [6]. What is information encoding in cochlear fluids, basilaris membrane, and acoustic cell hairs like, at an amplitude of entering a wave of 0.001nm, assuming that the path to the receptor passes through the cochlear fluids? Information encoding occurring on the way to the receptor is very important. Be noted that sound localization constitutes also a very important ability in the life of creatures bereft of the cochlea, basilaris membrane and of the option of mechanical amplification caused by OHC contractions. Sound localization is used by fish, reptiles, amphibians, and even insects.

Another issue, barely explicable by means of the traveling wave theory, is echolocation used not only by bats but also by dolphins, a shrew - a small insectivorous mammal, oilbirds, and swifts (birds). A lesser horseshoe bat weighs under 10g, its length can reach up to 4cm. The length of its basilaris membrane is 1mm shorter. It produces and receives sounds of frequencies 1200Hz-100kHz. Are tones in the proximity of 0dB amplified in line with the traveling wave theory? If the average speed of a traveling wave – a transverse wave on the human basilaris membrane – is about 50 m/s, then what is the dependence of the wave speed in the cochlear fluid and transverse wave on the bat's basilaris membrane-like? Is there any significant incompatibility in the case of a bat at such frequencies of up to 100kHz? According to the 'Submolecular theory of hearing [5] a signal is immediately received by a receptor through soft tissues and osseous housing of the cochlea. Information is analyzed immediately, which allows sending a new signal into the space. If another bat works at the same frequency, one of them will quickly change its working frequency. There is no time for a wave- basilaris membrane resonance or time delay of the transverse wave on the basilaris membrane or amplification of quiet spends through OHC contractions.

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