Short Commentary

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Errors in The Assumptions of Bekesy's Traveling Wave Theory

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1. Introduction

Hearing theory should serve in learning and understanding the important factors contributing to the reception, processing and transmission of auditory information. Assumptions for theory that is developed should be consistent with the laws of Nature, up to date body of knowledge and logic. Analyzing in detail Bekesy's obsolete theory of hearing, it can be concluded that these rules were not followed [1]. The reception and transmission of auditory information, as described by the traveling wave theory in humans, must be consistent with hearing mechanisms in other mammals and birds. Billions of creatures on Earth do not have the basilar membrane and cochlear fluids and yet they perfectly receive auditory information at frequencies up to 300 kHz. This indicates that there is a different mechanism for the receptor to receive sound signal. It is possible to transmit the mechanical energy of sound wave directly to the receptor, without the intermediary of the basilar membrane [2]. The sound wave has no mass, and can be transmitted through the bone housing of the cochlea directly to the receptor. The information encoded in the sound wave about amplitude, frequency, harmonics, phase shifts, accent, length of sound and melody is accurately transmitted to the receptor [3]. It is impossible to transmit all this information via the basilar membrane, the resonance of the longitudinal wave with the transverse wave of the basilar membrane, the flow of cochlear fluids, the tilting of hairs of hair cells and the tip-link mechanism.

2. Justification

The basis of Bekesy's theory is the resonance of the wave traveling on the basilar membrane and the hydro-dynamics of cochlear fluids. Wave resonance occurs when the frequency of the waves is consistent, the direction of wave action is consistent, and when the energy of the forcing wave is greater than the damping of the forced wave. In the case of the ear, these conditions are not always met. The sound wave in the atrial fluid is a longitudinal wave, while the wave in the basilar membrane with which resonance is to occur is a transverse wave with a deflection direction at an angle of 90 degrees to the direction of the sound wave. Resonance and accurate transmission of information is impossible. There is also the problem of the resonance compatibility of the sound wave and the basilar membrane's own vibrations. Bekesy prepared a thin strip of the basilar membrane, cut it into 1 mm sections and tested its elasticity with a blunt needle 10-25 µm thick loaded with 1 ml of water. He calculated that the natural frequencies of the basilar membrane range from 16 Hz near the cap to 20 kHz near the base. Anatomically, the diameter of the cochlear ducts from the oval window to the cap decreases by approximately 3 times. At the base, it is 1.7 mm. Bekesy, on the other hand, assumed that the basilar membrane separating the cochlear duct from the tympanic duct at the base is 0.25 mm and widens to 0.75 mm near the cap. The width of the basilar membrane of 0.25 mm cannot separate the fluid spaces of the channels of 1.7 mm. The length of the basilar membrane in small mammals and birds ranges from 1 mm to several mm. Received frequencies are up to 100 kHz. The basilar membrane has no such resonance capability. If a pigeon receives sounds starting at 5 Hz, the length of this wave in the cochlear fluid is 290 m [4]. Half of this wave with a maximum deflection is at 145m of the wave. Resonance is impossible with basilar membrane length of 2-5 mm. String vibrations depend on the tension of the string. The basilar membrane has no afferent or efferent innervation, and there is no regulation of tension. It is a flaccid connective tissue. Studies of human tissues have shown that their natural frequencies range from 5 to 100 Hz [5].

Owl hears 0.001 nm waves at the input. In the cochlea, the amplitude of the wave fades several hundred times. A sound wave approximately 100 times smaller than the diameter of a hydrogen atom will not induce a wave traveling on the basilar membrane. Owl can hear perfectly. It has very good directional hearing [4]. This is an evidence of the existence of a different signal pathway to the receptor.

Hummingbird can hear 50 Hz waves of 29 m in the fluid of the inner ear when the length of the basilar membrane is 1 mm. Resonance is not possible when one wave period is 29,000 times longer than the length of the basilar membrane. Hummingbird can hear well and recognize frequencies. There is another signal pathway to the receptor without the involvement of the basilar membrane and cochlear fluids.

Bekesy erroneously assumed for his calculations that vibrations of the basilar membrane take place in the air. This is evidenced by the assumption that information is transmitted to the receptor this way. The basilar membrane is not an independent entity, it is burdened by a massive organ of Corti with fluid spaces, and is immersed in cochlear fluids that have great damping properties. With such damping, the resonance of threshold tones and low-intensity tones is impossible because the damping energy of the forced wave exceeds the energy of the forcing wave.

Bekesy observed the wave traveling through a hole in the cochlear wall and connected an electromechanical device to the vestibular window that imitated the vibrations of the stapes plate. The description lacks an indication of the location and size of the hole made. The test was performed underwater. The opening in the atrial duct does not provide insight into the basilar membrane. The opening in the cochlear duct gives a view of the tectorial membrane and the organ of Corti lying on the basilar membrane. The opening in the tympanic duct makes it possible to observe the negative of the traveling wave. The traveling wave to set the cochlear fluids in motion is invisible from the side of the tympanic canal.

In order to simplify his calculations, Bekesy assumed that the cochlea is a straight pipe with a narrowing in the middle, corresponding to the cap. The sound wave travels on both sides of the basilar membrane, inducing a pressure difference on both sides of the basilar membrane, which creates a traveling wave. This assumption of the sound wave course is contrary to physiology. The sound wave runs in the atrial duct. Bekesy eliminated Reissner's membrane, directed sound wave through the endolymph fluid to the tectorial membrane, the fluid of the subsegmental space, another layer of fluid, and the wave encounters the organ of Corti with receptors in the auditory cells. The wave passing through the receptor does not transmit information, because its purpose is to reach the basilar membrane to produce a wave traveling on the basilar membrane. There is a clear lack of logic here. Nature could not accept such solutions. Wave resonance is a gradual transfer of energy of the forcing wave to the forced wave which takes place over a certain period of time. One or two periods of a wave are not able to transmit full information to the forced wave. We do not hear simple harmonic tones. We hear polytones, where each period may contain new information difficult to convey in this way. One or two wave periods do not allow the transmission of harmonic components, phase shifts, length of sound, accent and melody. In tests, the receptor receives sound signals with a duration of tenths of ms when there are only one or two wave periods [6]. The path of such a signal cannot depend on resonance and the path through the basilar membrane. The signal travels to the receptor via a different route bypassing the basilar membrane and cochlear fluids.

There are elements in the middle and inner ear that undergo vibration during the transmission of information. There is motion of matter, positive and negative acceleration and mass of the vibrating element. According to the law, inertia increases in proportion to the square of the frequency and in direct proportion to the amplitude and the vibrating mass - according to the formula: Inertia = (2π x frequency)2 x amplitude x mass g/mm/s2. Bekesy's theory lacks consideration of the importance of inertia at high frequencies.

The incus-stapes joint is a ball-and-socket joint, which indicates that the stapes performs rocking (oscillating) movements at high frequencies. Low frequencies induce a piston motion. At medium frequencies, the movement of the stapes takes place in the transverse axis of the stapes. At the highest frequencies, the movement of the stapes plate takes place in the longitudinal axis of the stapes. In both cases, one half of the stapes plate produces forward fluid movement when, at the same time, the other half of the plate produces backward fluid movement. Two oppositely directed waves are formed, parallel and adjacent to each other. There is friction, attenuation and disturbances in the energy transfer of the wave encoding information. Oppositely directed, simultaneous waves of endolymph fluid cannot tilt the hairs of hair cells? There is no possibility of transmitting information, especially polytones with aliquots. Bekesy's theory does not see the problem here.

The speed of sound wave in cochlear fluids is 1450 m/s. The speed of movement of the wave traveling on the basilar membrane is on average 50 m/s. Each period of a sound wave can contain new information. Recording information on a 29 x slower wave cannot be accurate. It is not possible for the basilar membrane, cochlear fluids and auditory cell hairs to encode all the information. Bekesy's theory lacks a thorough discussion of the transformation of sound wave energy to receptor potential and the action of the hair cell, as well as a detailed description of the further signal path to the brain.

The submolecular theory correctly explains the mechanisms of reception, processing and transmission of auditory information, in line with the current body of knowledge [7]. It does not contain the numerous ambiguities and inconsistencies contained in Bekesy's traveling wave theory, published in 1928 and updated many times since then. The assumptions of the traveling wave theory remain unchanged.

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