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Review Article

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Hearing Theory Controversies

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Summary

Over the last 5 centuries, a number of theories have been developed trying to explain the mechanisms of hearing. Despite the widespread acceptance of Bekesy's traveling wave theory, there is still much controversy regarding hearing. The description of the signal path to the receptor is not sufficient. Cochlear fluid hydrodynamics and wave resonance adopted as the pillars of the traveling wave theory do not fulfill their purpose. In the ear, there is a "flow" of the sound wave through the fluid environment.

The new hypothesis presented in this work indicates the possibility of transmitting auditory information via the route leading from the middle ear through the bony casing of the cochlea to the receptors of hair cells. The paper highlights the importance of the rocking movements of the stapes plate in high-frequency transmission. The possibility of resonance of the longitudinal wave in the cochlear fluids with the transverse wave of the basilar membrane was critically analyzed. Some details of the conversion of sound wave energy into molecules responsible for gating mechano-dependent potassium ion channels are presented. The work of the hair cell at the molecular level is briefly discussed. Controversies Related to Bekesy's traveling wave theory are presented.

Keywords: Eardrum, Hearing theory, Inertia in the ear

Abbreviations: Pa: Pressure Unit= Pascal pm; Picometer: 10^{-12}m; CNS: Central Nervous System; ABR: Auditory Evoked Potentials; ATP: Adenosine Triphosphate; cAMP: Cyclic Adenosine Monophosphate; cGMP: Cyclic Guanosine Monophosphate, Ca++ATPase: Protein Transporting Calcium in the Cell Membrane; DAG: Diacylglycerol; IP3: Inositol Triphosphate

The Path of the Auditory Signal to the Receptor

The receptor potential is generated within tenths of a millisecond after the signal is applied [1,2]. The speed of travel of a traveling wave on the basilar membrane is 2-50m/s. At the speed of the wave in the cochlear fluid of 1450m/s, there is a need to compress the transmitted auditory information [3,4]. When a sound wave transmits a wave of 145mm in 1/10ms, the traveling wave travels an average of 3 mm in this time. Accurate transmission of information is impossible with 48:1 compression. The time of receiving and processing information in a hair cell is approximately 1.5ms. OHC depolarization and contraction causes the basilar membrane to pull up 1.5ms after the silent wave was received. In 1.5ms, a new sound wave with auditory information recorded traveled approximately 215mm. Pulling up the basilar membrane after 1.5ms disrupts the extraneous wave. The sound wave in the cochlea's fluids decays [5]. A wave of 90dB and 800Hz has an amplitude of 500nm in the external ear canal and has an amplitude of 0.5 nm on the round window. The amplitude of the wave decreases 1000 times. The energy of the wave is proportional to the square of the amplitude. It should be assumed that a threshold tone of approximately 0dB, with an amplitude of 8 pm in the external ear canal, decays similarly. The energy of this wave cannot reach the receptor and create a receptor potential. It is also unable to create a pressure difference on either side of the basement membrane. Such a quiet sound cannot produce a traveling wave and cannot be amplified by OHC contraction because it has too little energy to cause depolar-

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ization and OHC contraction. A threshold tone is heard, indicating that there is another signal pathway to the receptor.

The Mechanism of Receiving Information Encoded in A Sound Wave

The adequate stimulus for the hearing organ is the sound wave energy transmitted by environmental molecules. Every molecule as well as every atom in the molecule is in constant motion [6]. It is a progressive movement-oscillatory, pulsating and rotational, or a mixture of these movements. The kinetic energy of the molecule is associated with motion. In addition to kinetic energy, the molecule has potential energy, which consists of chemical bonds and the forces of electrostatic attraction and electromagnetic interactions. The sum of these energies creates the energy of the sound wave.

The particles vibrating in the wave (donors) have an electric charge. Each atom has electrons that form an electron cloud around the nucleus of the atom. The size of this cloud depends on the number of orbits in which electrons are distributed. Electrons in the outer orbit-the valence orbit-easily enter into compounds with other atoms, forming atomic and covalent bonds. The electron can change its orbit, but to move to an orbit closer to the nucleus, it must receive additional energy. Changing 1 orbit from 2 to 1 requires 3.4 eV. Such transitions are quantized, which means that there is or is not a jump-there is no middle ground. If an atom in a molecule receives a quantum of energy from a sound wave particle, the electron jumps to an orbit closer to the nucleus - its internal energy increases-in a quantized step [6]. The so-called the excited state of an atom, which, unlike the ground state, is unstable. This state is unstable and immediately tries to return to the ground state by emitting 1 photon of energy-when the problem concerns the transition of 1 atom by 1 orbit. If in the connection between a wave + a sound-sensitive receptor molecule there are countless such transitions, or transitions of 2 orbits or more, there are 1020 possibilities of transmitting different types of quantized energy. This provides an endless amount and variety of transmitted auditory information. The wave transfers only energy and not chemical composition to the acceptor. The energy received by the acceptor is passed on, but cannot be changed. The energy connection with the acceptor is unstable. The attempt of an excited atom or molecule to return to the ground state with the lowest energy, in accordance with the principle of entropy, causes the transfer of energy further and at the same time the molecule is able to accept another portion of energy. In the case of very small molecules, such a reaction takes place in 10-14 s. large portions of energy are transferred even 1000 times slower, but it still takes 10-11s. This energy transmitted by the sound wave is responsible for the gating of mechano-dependent potassium channels. The sound wave energy acts on ionic and covalent bonds, changes bond angles, and changes the vibrations of molecules and atoms.

Conformational changes in proteins perform work for the gating mechanism. Proteins stretch and fold, causing the particles to move. The information carried by the sound wave is precisely transmitted to the hair cell. This regulation is called "gating" the ion channel. The diameter of the narrowest part of the channel is 0.3nm, the speed of opening and closing the channel and the frequency of changes, which depend on the frequency of the sound wave, are regulated. The received sound wave energy generates the so-called gate currents, responsible for the rate of passage of potassium ions through the channel. These currents also influence the regulation of the specificity of ions passing through a given channel. The difference in the potential of the endolymph and the interior of the hair cell and the generated electrostatic field is the driving force for potassium ions in the ion channel. The smallest portion of energy that causes changes in the receptor is the pressure of the sound wave in the external auditory canal of 2.0x10-5Pa, at a frequency of 1000Hz. After converting to the wave amplitude, it is 8x10-12m, i.e.0.008nm [7]. Opening the potassium channel causes an inflow of positively charged potassium ions into the negatively charged interior of the cell. 6,000 ions can enter the cell through the open potassium channel in 1ms. The membrane potential changes and the cell depolarizes [8].

Calcium and sodium ion channels, sensitive to changes in potential, respond to depolarization. Sodium and calcium flow into the cell, depolarization increases. The influx of calcium causes the release of calcium from the endoplasmic reticulum, nucleus and mitochondria. Calcium binds to calcium-dependent proteins and enzymes. Calmodulin plays an important role; its activity increases 100 times after the addition of 4 calcium ions. This is one of the mechanisms of intracellular reinforcement. Calcium plays an important role in the production, transport and secretion of the transmitter into the synapse. After approximately 1-2ms. depolarization, sodium channels are inactivated, potassium begins to flow out of the cell and ion pumps throw sodium out of the cell. There is a repolarization phase. Calcium pumps and calcium ion transporters move calcium out of the cell and within the cell, calcium is transferred to the endoplasmic reticulum, nucleus and mitochondria. After each sound wave, the situation repeats itself. The hearing receptor responds to a very short signal time, despite the impossibility of resonance of the sound wave with the basilar membrane. Without resonance, this signal cannot travel to the receptor through the cochlear fluids and basement membrane. Stapedotomy surgery indicates that high-frequency sounds, regardless of sound intensity, do not reach the receptor through the cochlear fluids and basement membrane. It should be assumed that the reason for the lack of high-frequency conduction in this way is the lack of use of the physiological mechanism of the stapes rocking movements. Only a simple piston mechanism transmits vibrations of the middle ear ossicles to the fluids of the cochlea.

The Importance of Inertia in the Middle and Inner Ear

The sound wave causes the ossicles of the middle ear to vibrate through the eardrum, and the vibrations are transmitted through the oval window to the cochlear fluids and the basilar membrane. The weight of the ossicles together with the mucous membrane and ligaments is approximately 70mg. In wave motion there is speed, acceleration and mass. Therefore, there is inertia, which is calcu-

lated according to formula: (2πx frequency)2x amplitude x mass g/mm xs2. For high frequencies, the inertia values increase rapidly in proportion to the square of the frequency and in direct proportion to the amplitude. A sound wave, having no mass, is not subject to the law of inertia and can be transmitted, regardless of frequency, directly to the receptor.

Basement Membrane

Bekesy determined the natural vibrations of the basilar membrane. He prepared a thin strip of basement membrane, cut it into 1-millimeter sections and tested its elasticity with a blunt needle 10-25μm thick loaded with 1 ml of water. He calculated that the natural frequencies of the basilar membrane range from 16 Hz near the cerclage to 20kHz near the base. Anatomically, the diameter of the cochlear ducts from the oval window to the capus decreases by approximately 3 times. At the base it is 1.7mm. Bekesy, however, assumed that the basement membrane separating the cochlear duct from the tympanic duct is 0.25mm at the base and widens to 0.75 mm in the area of the cones. A basement membrane width of 0.25 mm cannot separate the 1.7 mm fluid spaces of the channels. The load on the basement membrane by the organ of Corti and the fact of vibration of the basement membrane in the highly damping cochlear fluid were omitted. This calculation of the natural vibrations of the basilar membrane is still one of the foundations of the traveling wave theory. Frequency reception depends on the distribution of hair cells along the basilar membrane with receptors sensitive to decreasing sound wave frequencies. The phenomenon of tonotopy is responsible for the transmission of these frequencies to the CNS. The ability of receptor cells to receive given frequencies and their location on the basement membrane is genetically determined [9].

Amplification of Quiet Tones, Hearing Cell Work

According to the traveling wave theory, quiet tones are amplified by 40dB [10]. After amplifying 10,000 times, sounds are still heard as soft tones. The theory is that OHCs are only amplifiers for IHCs, but these cells have afferent innervation, transmitting information to the center. In complex sounds, loud and quiet sounds occur simultaneously. Loud calls are received and the signal is sent directly to the center. Quiet sounds undergo time-consuming amplification, which is superimposed on new waves heading to the ear at that time. The original multitone signal is split and the new wave is mixed with the amplified wave. Quiet information is transmitted with a delay separately from loud tones. There is intracellular, regulated, molecular enhancement in all senses. Strengthening is a whole complex of factors such as: phosphorylation and dephosphorylation of ion channels, ATP concentration, cAMP level, cGMP, cell pH, osmotic pressure, presence of ligands, work of Ca++ATPase pumps. This strengthening is also related to the work of proteins binding to calcium, where calmodulin plays an important role, influencing the production and breakdown of cAMP and cGMP. It activates protein kinases and phosphatases and regulates the functioning of the calcium pump. Calmodulin also affects transmitter exocytosis. Calcium is the second transmitter of information in the cell, acting faster than the other second transmitters: cAMP, cGMP, DAG, IP3, which are produced in connection with an increase in calcium levels or activated by protein G. The stage of production of second transmitters is one of several mechanisms of intracellular strengthening. One enzyme molecule can produce several hundred-second messengers. The size and location of the receptor fields from which impulses in the form of excitatory potential reach the nerve cell of the spiral ganglion play an important role. Sounds that are above the excitability threshold are perceived. Quiet sounds received with too little energy are amplified intracellularly at the molecular level. The energy of the signal transmitted by the auditory nerve is amplified by depolarization at each node of Ranvier.

Justification of the Hypothesis

There are hearing mechanisms that cannot be explained using Bekesy's current traveling wave theory [11,12]. Experimental studies indicate large losses of sound wave energy in the cochlea ducts. According to this theory, hearing threshold tones is impossible. They are audible, so the mechanism of this hearing is different than current theory suggests. The lack of improvement in high frequencies after stapedotomy indicates the importance of inertia in the ear and the role of stapes rocking movements [13].

To justify the traveling wave theory, incorrect assumptions were made that the worm is a straight pipe and not a spirally wound wire. It was wrongly assumed that there is no Reissner's membrane in the ear, which means that the vestibular canal is connected to the cochlear canal, and as a result, the sound wave runs on both sides of the basilar membrane. It was also incorrectly assumed that the basement membrane was an independent entity and could vibrate on its own, without connective tissue on its lower surface and without the mass of the organ of Corti. The law of physics that states that resonance is impossible when the damping of the forced wave is greater than the energy of the forcing wave has been ignored.

Conclusions

Belief in the truths about hearing is widespread at the elementary level as well as at the university level, despite so much controversy. Rejecting an established theory as dogma seems unlikely, but it will happen over time. Countless works continue to be published to advance the theory that was created 96 years ago. New analyses, new evidence pointing to the gaps in this theory are omitted. Current knowledge allows for a better understanding of the processes that constitute the reception, processing and transmission of auditory information at the sub molecular level. There is a basisto create a new theory of hearing called "Sub molecular theory of hearing" [14].

Controversies of the Traveling Wave Theory

a) No explanation of the hearing of threshold tones

b) No analysis of the effects of the difference in the speed of the sound wave in the cochlear fluid and the transverse wave of the basilar membrane

c) Incorrect determination of the natural vibrations of the basilar membrane

d) Failure to take into account the natural frequency of vibrations of the basilar membrane of mammals hearing up to 100 kHz.

e) Assuming incorrect dimensions of the basement membrane

f) Ignoring the fact that vibrations are damped by cochlear fluids

g) Straightening the cochlea into a straight tube to simplify calculations-Amplification of quiet sounds by 40dB =100,000 times-we still hear them as quiet.

h) Mechanical amplification of soft tones by OHC contractions pulling up the basement membrane when the OHCs are not in contact with the basement membrane.

i) No explanation of the amplification mechanism for quiet multitone

j) No explanation of the formation of a traveling wave for multitone with harmonic frequencies, phase shifts and times.

k) The existence of cochlear fluid flows was incorrectly assumed.

l) No explanation for the resonance of the longitudinal wave in the fluid with the transverse wave of the basement membrane.

m) How is quantized, encoded energy transferred?

n) Inability to encode the quantized sound wave energy by a traveling wave, a transverse wave, by tilted or bent hair cells of hair cells, or by tightening cadherin fibers.

o) There is no molecular description of the mechanism for converting the mechanical energy of a sound wave into the energy of molecules regulating the gating of mechano-dependent potassium ion channels.

p) There is no detailed description of the formation of the postsynaptic excitatory potential and the action potential of the auditory nerve.

q) Failure to acknowledge the existence of intracellular enhancement at the molecular level.

r) No explanation for hearing after basilar membrane immobilization in cochlear implant surgery

s) The lack of conduction and improvement of high tones after stapedotomy has not been explained

t) The loss of sound wave energy in the cochlea excludes the hearing of quiet sounds by up to 1000 times. The energy of this wave decays a million times.

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Disclosure of Conflict of Interest

None.

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