

Our Hearing

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Abstract

The theory of hearing, announced by Bekesy in 1928, referred to as 'the travelling wave theory' has been updated and supplemented many times. Recently, there have been conducted some new investigations which indicate the need of analyzing the theory which is nowadays in force. Investigations and analyses shed some different light on the processes of reception, processing and transfer of auditory information. A new vision of hearing is influenced by such issues, like the disappearance of the sound wave energy in cochlear fluids, the time of generation of receptor potential, reception of tones whose duration time is shorter than tenth parts of millisecond, when the wave resonance lasts for 1-2 periods, a difference in the sound wave speed in cochlear fluids vs. the speed of the traveling wave on the basal membrane, Today's theory does not explain the mechanism of reception of a sound wave whose amplitude in the external auditory meatus is 1 pm. Neither determined is the value of inertia nor its importance in the middle and internal ear. Little attention is dedicated to the molecular transformations responsible for the transformation of the mechanical energy of a sound wave into the energy of intracellular information transmitters. The molecular transformations in an acoustic cell are responsible for the production and release of a transmitter into a synapsis and the signal amplification on the way to the center. The amplitude of a sound wave on the way from the external auditory meatus to the round window decreases a few hundred times. Such energy encodes information in cochlear fluids. The energy of the threshold wave does not reach the receptor, and it cannot be thus amplified by an OHC contraction. The problems related to the transfer of acoustic information to the receptor imply another path, without a share of a traveling wave on the basal

membrane as well as another amplification mechanism – viz. molecular.

Keywords: Amplification, Basilar membrane, ionic canal, transforming and transmitting auditory information

Abbreviations: PM: Picometer; NM: Nanometer; OHC: Outer Cell Hair; MS: Millisecond; MG: Milligram; S: Second; G: Gram; KHZ: KiloHertz; cAMP: Cyclic Adenosine Monophosphate; cGMP: Cyclic Guanosine Monophosphate; ATP: Adenosine triphosphate; BM: Basal Membrane

A New Vision of Hearing

The amplitude of a threshold wave, heard by a young man is 8×10^{-12} m, viz. 8 pm. A cat can hear sounds whose amplitude is 4 pm. An excellent sense of hearing has a barn owl receiving sounds of an amplitude of 1 pm. This magnitude of a sound wave is 40 times smaller than the hydrogen atom diameter and around 100 times smaller than the diameter of many other atoms constituting the basal membrane structure [1]. Despite such a low amplitude, it will reach the receptor and generate receptor potential. It has hardly acceptable that such a low wave amplitude at the entrance, fading in the internal ear might generate a traveling wave, cause cochlear fluids to flow and eventually bend the acoustic cell hairs whose diameter is 10,000 times larger than the wave amplitude in humans [2].

The investigations have proved that for opening a mechano-sensitive potassium ion channel a hair whose diameter is 100 nm must be bent [3, 4, 5]. The mechanical energy of a fluid wave of an amplitude of 0.01 nm is unable to perform such a work. A sound wave of so low an amplitude cannot be amplified for not reaching the receptor. If it should be received, it will reach the receptor through the cochlear osseous housing.

According to the traveling wave theory, quiet tones are amplified by 40 dB [6,7]. So that a quiet sound may be amplified by an OHC contraction, it must be first received to generate OHC depolarization and to stimulate prestin to contract. OHC depolarization depends upon tension-dependent channels of the lateral and inferior wall of the acoustic cell. Those channels remain open only for a certain time, and then a channel become inactive. Even an open channel will not allow ions to pass. Only a closed channel is sensitive to a change in the membrane potential [8,11]. This occurs in time, and OHC is unlikely to contract in line with the frequency of a sound wave of up to 100,000 times/s. Therefore, it is impossible to amplify high tones with this method.

Sound waves are conducted through soft tissues and the cochlear osseous housing directly to the receptor at a speed of 4,000 m/s. A signal in the cell is amplified on a molecular path [11].

The time of generation of receptor potential is very short, it amounts to hundredth parts of ms. Instead, the time for generating the action potential of the auditory nerve is 1.5-1.9 ms. In the case of quiet tones, mechanically amplified, those times ought to be considerably extended. No investigations have corroborated it yet.

We can hear complex sounds of different intensity and frequency [7]. If loud sounds are analyzed and received immediately, whereas quiet sounds are subject to a time-consuming amplification, the information is split. Information on quiet sounds reaches the center in delay, together with other information on a new wave, which disturbs the reception. It is impossible to encode that information. In multitones the respective tones have several harmonics each, and each harmonic has a different frequency, which creates a problem with the resonance on the BM. In addition, onto those vibrations superimposed is completely a new quiet, amplified tone of the preceding wave. Resonance is generated simultaneously in many spots on the BM for two independent waves: for quiet, twice amplified tones causing the BM resonance and the new fundamental wave. How is performed the encoding and reading of that information? In our life we do not receive simple harmonic tones, unless in a lab, only.

It was assumed that a vibration concerns only a very thin BM band (8), cut out for calculations. Vibration was excluded from the entire organ of Corti with fluid spaces, supported by the BM and a layer of connective tissue on the inferior area of the BM. Proper vibrations depend on the elasticity and vibrating mass as a whole. It changes the result of proper vibrations of the BM, especially in small mammals or birds which have a 1 mm long BM, receiving sounds from a few Hz to 100 kHz [1]. In addition, vibrations occur in a fluid having attenuating properties. It is hard to find resonance compatibility in a pigeon which can hear sounds from 2 Hz to 10,000 Hz, the BM length being approx. 1 mm. The sound wave length for 2 Hz in cochlear fluids in a pigeon is 720 m. We can hear well tones of frequencies of 50 Hz when the sound wave length is 290 mm, and the BM length is 35 mm. If the 10 kHz wave length is 145 mm, why then resonance occurs on a 4 mm BM? What is like the sound wave deflection on 4 mm to convey energy? Perhaps along the BM provided are some receptors to receive specific frequencies.

A man can hear short tones whose duration time is under tenth parts of ms when there are only 1 or 2 periods of a wave for resonance, which excludes any energy transfer through resonance. Then, there is also the problem of speed difference in the cochlear fluids – 1,450 m/s and the traveling wave speed on the BM – od 2,9 m/s – 100 m/s – according to various sources [10]. The speed of the traveling wave depends on the frequency and elasticity of the medium, so in multitones this speed is different in various spots on the BM. A sound wave in fluids is longitudinal, whereas the traveling wave on the BM is transverse, moving along the BM approx. 30 times slower than the sound wave in cochlear fluids. The resonance between the longitudinal and transverse waves needs elucidating. The difference in the speeds of the longitudinal and transverse waves hinders the encoding of information and causes a considerable delay in transmitting a signal to the receptor.

A bat sends waved of very high frequencies, it receives in flight reflected waves and reacts to them. If another bat also works at the same frequency, one of them will immediately change its frequency to a different value. There is no time to amplify quiet tones.

All senses are endowed with a perfect, controlled molecular mechanism of signal amplification. Intracellular amplification is an entire set of factors, like *phosphorylation and dephosphorylation of ion channels responsible for the conduction of the cell membranes, control of ATP concentration, levels of cAMP, cGMP, cell pH, osmotic pressure, presence of ligands, operation of Ca++ATPaz pumps*. Those pumps, related to the cell membrane, play an important role in maintaining a variable calcium level in a cell. An intracellular amplification is also related to the activity of proteins attached to calcium, in which case an important role is played by calmodulin influencing the production and decomposition of cAMP and cGMP. Calmodulin activates kinases and protein phosphatases, controls the operation of the calcium pump. It affects the contractions of muscular and non-muscular cells through activation of light myosin chains, independent of cAMP kinase. Calmodulin influences exocytosis. Saturation of 4 calmodulin domains will intensify its action up to 100,000 times. Controlled is the process of enzyme production or the rate of enzyme decomposition [8].

Calcium is the second information transmitter in a cell, and works faster than the other second transmitters - cAMP, cGMP, DAG, IP3 - produced in relation to an increased level of calcium, or activated with G protein. The stage of producing second transmitters constitutes one of several mechanisms of intracellular

amplification. One enzyme particle may produce several hundred second transmitters. For a correct operation of an acoustic cell there must be maintained the equilibrium between the calcium flowing into a cell through ion channels in compliance with electrochemical potential and a rapid release of calcium outside the cell through ion channels, ion pumps and pore exchangers (12).

In the middle and external ear there is speed, acceleration and mass; hence, there is also inertia. Inertia in the wave motion is calculated from the formula: $(2\pi \times \text{frequency})^2 \times \text{amplitude} \times \text{mass g/mm} \times \text{s}^2$. Middle ear: Malleus 25 mg, incus 30 mg, stapes 3 mg, as well as eardrum, mucous membrane, part of ligaments which together with the ossicles totals 70 mg.

For an amplitude of 0.1 nm (20 dB) and frequency 1,000 Hz - the inertia of the middle ear is $276 \text{ g/mm} \times \text{s}^2$.

For an amplitude of 100 nm (80 dB) and frequency 1,000 Hz - the inertia of the middle ear is $276,068 \text{ g/mm} \times \text{s}^2$.

Amplitude 100 nm (80 dB) – frequency 10 000 Hz – the inertia of the middle ear is - $27606880 \text{ g/mm} \times \text{s}^2$.

Basing thereupon it should be deemed that the inertia of the elements of the middle ear will increase yet more because of a considerably bigger vibrating mass. Each increase in the vibrating mass will increase inertia and lowers the limits to which the wave energy may be conducted through the vibrations of the elements of the middle and internal ear. There is a question: what is the inertia limit so that energy may be freely conducted? And what happens when this limit is exceeded? A sound wave has no mass and may be conveyed to the receptor freely and rapidly through the bone of the cochlear housing. That is why it should be deemed that the sound wave from the stapedial base is transmitted to the bone of the cochlear housing and without energy fading, at a speed of 4,000 m/s. It will reach the crista spinalis and then directly the receptor of acoustic cells. An important role is played by rocking movements of the stapes, especially in the transmission of high frequencies and intensities of sounds. Under 4 kHz there are movements in the transverse axis of the stapedial lamina. Above 6 kHz movements occur in the longitudinal axis of the lamina said.

A sound is located by each creature which compares the intensity and time od sounds reaching its ears, and through analyzing complex sounds. A sound will faster reach the ear closer to the source of sound. If a sound arrives from one side of the head, the other ear remains in the head's acoustic shadow. This causes

a higher attenuation of high frequency sounds, which changes the spectrum of the sound under analysis. There is no possibility of amplifying very quiet, high frequency sounds by an OHC contraction.

What is like the encoding of information through cochlear fluids, BM and acoustic cell hairs at an entrance wave amplitude of 0.01 nm, assuming that the path to the receptor passes through cochlear fluids? The encoding of information on the way to the receptor is very important. It should be noticed that sound location is also a very important ability in the life of creatures which do not have a cochlea, BM or the option of mechanical amplification due to OHC contractions. Sound location is used by fish, reptilians, amphibians or even insects.

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 10 g, its length can reach up to 4 cm. The length of its BM is under 1 mm [1]. It produces and receives sounds of frequencies 1,200 Hz - 100 kHz. Are tones in the proximity of 0 dB amplified in line with the traveling wave theory? If the average speed of a traveling wave – a transverse wave on the human BM – 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 BM like? There is a significant incompatibility in the case of a bat at such frequencies of up to 100 kHz. According to the 'Submolecular theory of hearing' [13], 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. There is no time for a wave - BM resonance, frequency discrimination through the BM and resonance or time delay of the transverse wave on the BM or amplification of quiet sounds through OHC contractions.

Also, the speed of auditory reaction implies that this path is short and fast [11]. Conducted are sounds of very high frequency, which is impossible according to the traveling wave theory due to inertia of the vibrating elements on the way to the receptor covered by a signal. A bone conducts sounds at a speed of up to 4,000 m/s. Soft tissues also conduct sounds, but at a lower speed. Such a streamlined reception of information by the receptor can be ensured only on the signal path from the middle ear through the cochlear osseous housing directly to the receptor. A proof can be also bone hearing [14] when the stapedial base is immobilized, and a wave traveling from the oval window to the cupula is unlikely to occur. Since the round window's elasticity is 20 times higher than of a healthy, mobile oval window, so there

may be generated a wave traveling in the retrograde direction from the round window towards the cupula [10]. All the more so because the oval window in otosclerosis is immobile. In the absence of a traveling wave, resonance on the BM is unlikely to occur; nor possible is the frequency resolution dependent upon the BM.

Conclusion

A large number of investigations and analyses, which were not known in the time of the elaboration of the traveling wave theory, imply another signal path to the receptor. This concerns in particular high frequencies in which case an important role is played by the law of inertia. Very short signals, shorter than tenth parts of ms, give no possibility of obtaining resonance on the BM; hence, there is no further transfer of information. Quiet sounds, fading in cochlear fluids, are not received by the receptor and cannot be amplified. Because of a disproportion of the sound wave speed in cochlear fluids to the wave speed on the BM, OHC contractions and possible encoding of information on multitones through cochlear fluids, bending of acoustic cell hairs pulling cadherin threads in order to control the gating mechanism of ion channels, a precise and fast transfer on this way is impossible. If information is received accurately and very fast, there must be another type of transfer, since this is the prerequisite for the survival of many species on Earth.

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