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Short Communication

Secrets of Hearing

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Synopsis

A new signal pathway from the auricle, tympanic membrane and middle ear ossicles directly to the receptor has been described. Attention was drawn to the problems of information transmission to the cochlear fluid, caused by swaying movements of the stirrup. The resonance of the longitudinal wave in the cochlear fluid with the transverse waves of the basilemma has been subject to critique. Critical considerations in relation to the encoding of auditory information by the cochlear fluid and the tip-links mechanism have been also presented. Both the middle ear amplification and the amplification by OHC contractions are issues of the analysis. A new formula for the amplification of the auditory signal, received, but too small to reach the center, is set forth. This is an amplification at the molecular level in the auditory cell.

Analysis of the hearing mechanisms

A relevant stimulus for the auditory organ is the mechanical energy of sound waves. Part of the sound wave energy is received by the auricles. The main stream of energy comes through the external auditory canal to the eardrum. Sound waves incident on the human auricle are partly absorbed and partly reflected, in accordance with the law that the angle of reflection is equal to the angle of incidence. The surface of the auricle is uneven, which causes scattering of the reflected waves, with only a small share of the waves being directed into the external auditory canal.

A different situation is, instead, in mammals, where large dangling ears completely obstruct the external auditory canal. The wave energy received by the auricles is used to recognize the direction from which the wave is coming. Such breeds of dogs, like dachshunds, bassets, setters, pointers have long dangling ears, covering the auditory canal; yet, they can hear perfectly, recognize the directions quite well and are hunting dogs. Cats have 32 ear muscles used for adjusting the position of the ear so as to receive wave energy as well as possible. They can change the position of the ear by 180°, which excludes the transmission of waves to the ear canal. The auricles of these mammals are very hairy, which increases the absorption of wave energy.

Owls have dense, short stiff feathers arranged around their eyes and ears, forming a facial disk. They have excellent hearing, perceiving sound waves with an amplitude of 0.001 nm. They are excellent at recognizing the direction of waves and the distance from the sound source. A sound wave incident on the auricle as well as on the eardrum encounters a new environment with higher resistance. Part of the energy is reflected and part of the energy - according to the transmission coefficient - passes into the new environment. According to Huygens' principle (1629-1695), 'every point in the medium reached by a sound wave becomes the source of a new spherical wave'. Therefore, generated are partial waves, able to cause interference [1].

The reflection coefficient of a wave is the difference between the total energy of the wave and the transmission coefficient. For water, when a sound wave passes from air directly into water, the reflection coefficient is 0.999 and the transmission coefficient is 0.001. Bekesy assumed that these ratios play a role in the transmission of sound wave energy from air to the cochlear fluids of the inner ear. The acceptance of this thesis was the basis for proposing a mechanism for the middle ear amplification [2].

The inconsistency of the thesis with the facts consists in that the sound wave does not fall on the cochlear fluid, but on the elastic eardrum with its high transmission coefficient. On the basis of an incorrect thesis assumed was the occurrence of 3 mechanisms of sound wave amplification in the middle ear.

- The difference in surface area of the eardrum and the stirrup plate in a ratio of 17:1 amplifies the sound wave 17 times. According to the theory, the pressure exerted by the stirrup plate on the oval window membrane is 17 times greater than the air pressure exerted on the eardrum. The pressure increases, but does the amplitude of the wave increase, too? Vibrometry does not confirm this.
- The leverage mechanism resulting from the difference in length between the malleus handle and the long leg of the anvil in the ratio 1.3: 1 results in a 1.3 x wave amplification. Problem: Will a reduction in the amplitude increase the energy in the ratio 1.3: 1?
- A funnel-shaped structure of the tympanic membrane causes an additional double wave amplification: This means a wave amplification of 44 times = 33 dB, (1.3 x 17 x 2) (Audiology 2005). It is not stated what wave is amplified 44 times? According to the theory, this amplification ensures that approximately 50% of the original acoustic wave energy is transferred from the external environment to the inner ear.

Should one assume that the energy of the wave is proportional either to the square of the amplitude, or to the square of the sound pressure - which is consistent with physics, then, the lever mechanism increases the force but decreases the amplitude of the wave excursion. The hydraulic mechanism resulting from the difference in the surface area of the membrane of the eardrum and the stirrup plate is not confirmed by the stapedotomy operation, where the difference in the surface area of the eardrum and the active surface area of a 0.4 mm diameter piston is 100, and for a 0.6 mm piston amounts to 50. The described amplification of the sound wave is not observed in the case of stapedotomy.

The funnel-shaped structure of the eardrum, with the retraction of the central part thereof towards the eardrum cavity, reduces the absorption of sound wave energy by making the eardrum (tympanic membrane) more oblique to the incident waves, which increases the reflection coefficient of the waves. Greater reflection means less energy resorption.

The eardrum consists of a taut part and a flaccid part. The taut part is attached to the tympanic groove in the eardrum ring of the temporal bone. The flaccid part is attached, instead, to the periosteum of the temporal bone shell. Part of the energy absorbed by the eardrum is conducted to the temporal bone and undergoes constructive interference with the wave energy transmitted from the auricle. The main part of the energy is transmitted to the ossicles of the eardrum having ligamentous and articular connections with the bony squama of the tympanic cavity. Through these connections, and especially through the vibrating stirrup plate in the oval window, part of the sound energy is transferred to the temporal bone squama. This energy, which has the same frequency as the energy transmitted from the auricle and eardrum, undergoes constructive interference with the summed energy of the auricle and eardrum. The energy of this wave is equal to the square of the amplitudes of the summed waves, travelling directly to the receptor through the bone at a speed of approximately 4,000 m/s [3].

It is difficult to accept the thesis of the travelling wave theory that the sound wave energy transmitted in bone conduction, through the bone, does not go directly to the receptor but is transmitted to the cochlear fluids so as to cause a travelling wave on the basilemma, which sets the cochlear fluids in motion to tilt the auditory cell hairs in a tip-links mechanism.

The main part of the sound energy is transferred from the eardrum membrane via the malleus and anvil to the stirrup. The junction between the articular process of the anvil and the stirrup forms a ball-and-socket joint that allows the stirrup plate to move in different directions - these are the rocking (swaying) movements of the stirrup. At low frequencies, these are piston-like movements. Medium frequencies cause movements of the stirrup plate in the transverse axis of the stirrup. High frequencies cause rocking movements in the longitudinal axis of the stirrup. A serious problem arises with the transmission of the information contained in the sound wave. When one part of the stirrup plate generates a forward movement of fluid, at the same time the other part of the plate generates a backward movement of fluid. Thus, there will occur not only two streams of fluid with opposite directions acting on each other, but also friction, energy is lost, and the transmission of information is disrupted. One wave stream increases the acoustic pressure in the fluid whereas the other stream decreases this pressure at the same time.

How is a travelling wave formed at the basilemma? How is the longitudinal wave in the cochlear fluid resonated with the transverse wave of the basilemma? How is the information conducted through this pathway to the receptor encoded? Swaying movements have already been described by Bekesy in his works, but without any conclusions. There is still no knowledge of how the full set of auditory information is transmitted to the basilemma at high frequency. If the wave amplitude and frequency are straightforward to transmit, how are harmonics, phase shifts and sound length components transmitted through the cochlear fluid and the basilemma?

Wave resonance arises when the frequency of the forcing wave matches the forced wave. It has been assumed that in humans proper vibration of the basilemma loaded with the massive organ of Corti with fluid spaces, vessels and nerves, embedded in the cochlear fluid, with no ability to regulate tension, is between 16 Hz and 20 kHz. This result is inconsistent with studies on proper vibrations of human tissues, where the natural frequencies of various tissues range from 5 - 100 Hz [4].

If the intensity of the forcing wave is less than the attenuation of the forced wave, no resonance will be produced. This situation exists when listening to near-threshold tones, which are otherwise audible, indicating a different signal path to the receptor.

The fact that tones up to 100 kHz can be heard by other mammals with the same hearing mechanism is not taken into account. There is no possibility of correspondence between the frequency of the sound wave in the fluid and the proper frequencies of the basilemma.

Another problem concerns the speed of the waves involved in the transmission of auditory information and the encoding thereof. The speed of the sound wave in the fluid = 1,450 m/s and is constant. The travelling wave's speed at the basilemma is 50 m/s near the base of the cochlea and decreases to 2.9 m/s near the ossicle (Bekesy). This speed is variable for each wave frequency. Consequently, each wave frequency is transmitted to the cochlear fluid separately after resonance, and transmitted to the receptor in a different time.

It is rather hard to imagine the transmission of information contained in multitones, especially low frequencies. Assuming an average wave speed at the basilemma of 10 m/s - for low frequencies, per 1 mm of traveling wave must be recorded 145 mm of longitudinal wave recording in the cochlear fluid. Within 1 ms, the wave in the fluid travels 1450 mm, whereas the wave on the basilemma travels 10 mm. Such a compression of encoded information is impossible. The compressed waves at the basilemma are supposed to set the cochlear fluid in motion and to encode both harmonics and phase shifts.

The problems will intensify if one should analyse the hearing of threshold tones, which a young, healthy person can perceives - by a different route. Threshold wave energy reaches the receptor. The threshold wave has a vibrational amplitude of 8 picometres in the external auditory canal [5].

Vibrometric studies show that a 500 nm wave at the entrance will decrease to about 12 nm on the stirrup plate – viz. about 40 times. No one has investigated how many times will the amplitude of the threshold wave decrease on the stirrup plate, having 8 pm at the entrance. Assuming a wave fading symmetry, the wave forcing wave resonance is several hundred times smaller than the diameter of the atoms entering the basilemma structure. It is hard to imagine a wave arising at the basilemma to move the fluid masses that move auditory cell hairs. The suggested fluid flow in the cochlear ducts is not laminar only one way from the oval window to the round window. The fluid flow takes place within the amplitude range of the sound wave with the assurance of full auditory information encoding, consistent with the information contained in the sound wave. The thesis that cochlear fluid encodes and transmits information to the receptor is unlikely. Fluid flow is influenced by the varying diameter of the ducts with some obstacles along the way, viz. the cupula, varying fluid pressure, fluid density and viscosity, and the condition of the duct walls - elasticity and roughness. Of importance is the frequency of directional change, which is associated with the occurrence of acceleration, and therefore, the fluid mass, velocity and acceleration will generate an inertia problem. It is difficult to understand how the fluid flow can provide quantization of the information transmitted. In a sound wave, information is transmitted in packages separated from each other by a full multiple of a quantum of energy. The transfer of energy is stepwise, according to quantum physics, in the same way like computer printing has letters, words and sentences separated from each other [6].

The receptor receives sounds with a duration of tenths of a millisecond, whereas only 1 or 2 wave periods are active in the resonance mechanism. In such a short time it is impossible for the waves to resonate and for information to be transmitted. Resonance needs time, even more so the resonance of the longitudinal wave with the transverse wave of the basilemma.

Vibrometric studies provide evidence demonstrating an error in the travelling wave theory concerning the representation of wave amplification in the middle ear. Waveform amplitude was studied at the entrance 90 dB = 500 nm, on the stirrup plate and at the beginning of the vestibular canal.

Frequency	Entrance	Plate	Atrium
1000 Hz	500 nm	5.09 nm	0.275 nm
4000 Hz	500 nm	1.37 nm	0.00886 nm
8000 Hz	500 nm	0.0905 nm	0.00153 nm

Table 1

Such a large decrease in the energy of the wave transmitted to the cochlear fluids may be due, among other things, to the structure of the oval window. Vibrations of the stirrup plate are transmitted to the cochlear housing bone through the annular ligament. Rocking movements of the stirrup reinforce the transmission of vibrations to the bone. During rocking movements, a part of the plate generates a forward motion of the wave, while at the same time the remaining part of the stirrup plate generates a backward motion. Sound waves running in opposite directions in the same plane, will undergo destructive interference. The energy of the wave decreases. The formation of a wave traveling on the basilemma is questionable or impossible. Transmission of accurate information by this route is impossible.

At high frequencies, a signal takes a different path to the receptor, as evidenced by our hearing and excellent hearing of animals perceiving sound waves up to 100 kHz. A decrease in the amplitude of the wave transmitted to the cochlear fluids proportional to the increase in frequency may be related to the increase in inertia of the vibrating elements in the middle ear. Inertia is proportional to the square of the frequency in wave motion, and proportional to the amplitude of the wave and to the mass of the vibrating element. Vibrometric tests can provide evidence of the disappearance of sound wave energy in the ear proportional to the increase in wave frequency at the entrance for the same wave intensity.

Laser Doppler vibrometry studies have confirmed the disappearance of sound wave energy on its way through the basilemma and cochlear fluids [7,8]. An 800 Hz, 90 dB = 500 nm tone has at the entrance an 0.5 nm amplitude at the round window. The pathway to the round window is the pathway of wave degradation, not the pathway directly to the receptor. The section of this pathway subjected to the greatest attenuation of wave energy is the section to the cochlear cupula, especially for low tones. Here will occur, respectively, reflective attenuation caused by wave reflections from concave duct walls, absorptive attenuation by the absorption of energy on the walls and interference attenuation due to reflected waves acting on each other. In this section, the decay of the wave amplitude can be 100-300 times that of the wave amplitude at the entrance. If the rounded amplitude threshold tone is 0.01 nm and the amplitude decreases only 100 times, it will be 0.0001 nm. Such a wave is supposed to tilt, or bend the hairs of the auditory cells with a stiffness and a hair diameter of 100 nm = one million times the amplitude of the sound wave. Viz. such a proportion if someone should want to tilt or bend a tree with a diameter of 10 metres with a twig having a 1 cm dimeter. Should the tilt of a hair by a millionth of a nanometre (that's a trillionth of a millimeter!) lengthen and shorten the peak position of the hairs in the tip-links mechanism [9]. Cadherin link pulling is supposed to open the potassium-dependent mechanosensitive channel of the auditory cell wall. Myosins are unable to close the potassium channel precisely.

The timing of the channel opening and the degree of opening is consistent with the information contained in the sound wave. How can the hair tilting and peak connections encode this information about the amplitude, frequency, aliquot, vowel length, accent and melody? Without this, hearing does not exist. All this information is transmitted by a sound wave directly to the receptor, without any interference, distortion or time delay the wave has no mass and is not subject to the law of inertia. The sound wave travels directly to the receptor, without altering the position of the environmental elements through which it travels; there occurs only a change in pressure consistent with the frequency and intensity of the sound wave.

The mechanism for converting the mechanical energy of the sound wave transmitting the encoded wave energy into electrical energy of the receptor, and further, into the chemical binding energy of the intracellular information transmitters takes place at the submolecular and electron level [10].

The stimulus relevant to the auditory organ is the energy of the sound wave; in the case of speech - a sound wave specifically formed in the larynx and upper respiratory tract resonators, and transmitted by vibrating environmental particles as a sound wave to the receptor.

Signal amplification

In all senses there is an intracellular, controlled molecular amplification. Most chemical reactions and energy transfer between small molecules take place in 10^{-14} s. These are reactions at the atomic and electron level. 'Difficult' reactions are 1000 times slower, but it is still 10^{-11} s.

Intracellular amplification means a whole complex of factors such as: phosphorylation and dephosphorylating of ion channels responsible for cell membrane conductance, ATP concentration, cAMP levels, cGMP, cell pH, osmotic pressure, presence of ligands, operation of Ca++ATPases pumps. These cellular membrane-associated pumps play a major role in maintaining the fluctuating calcium levels in the cell. Intracellular intensification is also related to the work of calcium-binding proteins, where calmodulin, which influences the production and breakdown of cAMP and cGMP, plays an important role. It activates protein kinases and phosphatases and controls the calcium pump. It influences the contraction of muscle and non-muscle cells through activation of cAMP-independent myosin light chain kinase. Calmodulin also affects transmitter's exocytosis. The binding of 4 calcium atoms by calmodulin will increases its action by 1000 times. Enzyme production or the rate of enzyme degradation is subject to regulation.

Calcium is the second messenger of information in the cell, acting faster than the other second messengers: cAMP, cGMP, DAG, IP3 which are produced either in association with an increase in calcium levels or activated by G protein. The stage of second messenger production is one of several mechanisms of the intracellular amplification. One enzyme molecule can produce several hundred second messengers. Amplified are tones received whose energy is too low to reach the centre. Intracellular signal amplification is one of the main pillars of the 'Submolecular Theory of Hearing' [11].

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