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Mechanisms of Hearing

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Synopsis

Through various mechanisms, a sound wave travels from the outside world to the receptor, and then continues to the central nervous system. It is a kind of mechanical energy that can be converted into another form of energy; it cannot either be created de novo or fade away without a trace. Associated with the sound wave is the transmission of auditory information to the receptor. The sound wave is a quantized wave. There is no continuity in the transmission of changes, as in classical mechanics. This is important in the accurate encoding of information. Through a transmission of information to the center, the mechanical energy of the sound wave is transformed into the electrochemical potential of the auditory cell membrane, into the energy of chemical bonds in the auditory cell itself, and finally - into the action potential.

The principle of those transformations is the fidelity of the information conveyed. The first mechanism is the reception and conversion of sound wave energy of the external world, mainly of air, into sound waves conducted through the tissues of the body to the receptor. In this complex mechanism of hearing, the problem of wave resonance, inertia in the middle and inner ear as well as signal amplification must also be considered.

***Keywords*: ** Sound Wave, Basilemma, free Vibration, Resonance

Conduction in the Air

The eardrum of the middle ear plays a very important role in air conduction [1]. But this is not the only route, followed by sound wave energy, to reach the receptor. Sound waves first fall on the auricles which, also in humans, are not shaped in such a way as to concentrate the waves into the auditory meatus. Due to their diversified shape, reflections of waves cause rather their scattering, not concentration. The angle of reflection of a wave is equal to the angle of incidence. In part the incident energy is absorbed by the tissues of the ear, and in part it is conducted further after passing through the tissues. Actually, that absorbed energy is important for hearing because it does not disappear, but is conducted to the bone and further on to the receptor. Sound waves enter the auditory meatus directly, in addition to scattered waves, reflected from the unevenness of the auricle. Humans cannot adjust their ears to the direction of an incident sound wave. The dog and the cat do not need to turn their heads towards the direction of the sound [2].

The dog has 18 ear muscles for adjusting an ear to the direction of sound. The cat has 32 ear muscles, and she can change the direction of an ear towards the sound by 1800. The auditory meatus remains is in the same position, so it is not about increasing the energy flux transmitted to the meatus, since the angle of reflection is adversely affected. It is about something more important here - so that the sound wave should fall perpendicularly on the auricle, because important is the energy of the wave received by the auricle, not that reflected into the air. This portion of sound wave energy absorbed by the auricle is conducted to the receptor and to the center, and it constitutes merely an addition to the energy conducted through the auditory meatus. In contrast, it plays a very important role in recognizing the direction from which a sound wave is acting.

The auricle is a kind of radar that catches wave energy. This is evidenced by the fact that dogs such as dachshunds, setters, spaniels and basset hounds have very large ears that descend and obstruct the auditory meatus. They can hear very well. Elephants have enormous dangling ears, used for more than just fanning in the heat. Elephants can hear low sounds from several miles away.

Little by little, they pick up vibrations transmitted through the ground with their feet. Elephants stomp their feet to talk to each other, to transmit information. Sound is transmitted to the receptor not through the eardrum, middle ear or basilemma. The energy of the sound wave is transmitted through soft tissues, bones to the osseous housing of the cochlea, and directly to the receptor [3]. The same principle applies in humans. This is how a baby hears even in its mother's womb before birth. We can hear a camertone applied to the knee, or an ankle on the leg; the energy of the wave does not act through the auditory canal.

Dolphins do not have an external ear; they perceive sounds through the lower jaw. A signal is conducted to the ear bone and to the receptor. This is not mediated by either the basilemma or the traveling wave. Bats, having the best hearing among mammals, have very large, asymmetrical ears. One is directed forwards, the other backwards. They are designed to pick up signals very quickly from all around, without time-consuming directional adjustment as in cats. There is no concentration of energy flux into the auditory meatus. Some bats can produce and receive between 20 and 250 signals in 1 second. Bats have their own signal frequencies. If, by chance, should 2 bats meet with each other and transmit on the same frequency, one of them will immediately change its frequency. There is no possibility of a time-consuming resonance, or a slow travelling wave on the basilemma. The signal reaches directly the receptor and the main centers for analysis.

The sound wave has no mass; while passing through the auditory meatus, it causes to vibrate both the eardrum and middle ear ossicles - which have mass. Those elements are connected to the osseous housing of the cochlea. Vibrations of those mass-bearing elements are transmitted to the osseous housing of the cochlea. The most important role is played by the vibrations of the stapes base, transmitted via the tendinous ring to the cochlear bone. There is an overlap of waves from the auricle and ossicles – viz. superposition of waves occurs. At a given frequency, interaural differences in wave energy, wave phase and wave time constitute the basis for the recognition of the direction of sound.

At low frequencies, there is a correspondence of vibration between the eardrum and ossicles, the piston mechanism transmits vibrations to the cochlear fluids and information reaches the receptor on this route [4]. Bekesy noted that above 2,400 Hz, the malleus cannot keep up with the vibrations of the eardrum. At high frequencies, instead, the vibrations of the malleus are invisible. A sound wave, having no mass, is conducted through the ossicles in the same way as through other environments. The stapes base, on the other hand, will no longer perform piston-like movements; it will make rocking (oscillating) movements. At medium frequencies, those are movements along the transverse axis of the base, whereas at high frequencies there will be movements along the longitudinal axis of the base. This movement of the stapes allows and confirms the existence of a spherical anvil-stapes articulation.

Those movements cause a problem in the transmission of information via the cochlear fluid pathway. When one half of the base generates a forward wave motion of the fluid, the other half of it will generate a retrograde motion. This wave motion of the fluid in the vestibular duct, equal in energy, opposite in direction, cannot produce a pressure difference on either side of the basilemma; nor can it produce a wave traveling on the basilemma itself. If, for high frequencies, there is such an obstacle to the formation of a traveling wave, and we can nonetheless hear perfectly well, then there must be another signal pathway to the receptor. This pathway is the transmission of sound wave energy to the cochlear osseous housing, where a wave travels at a speed of 3-4 thousand m/s directly to the receptor of auditory cells.

Resonance in the Ear

This is the foundation of Bekesy's traveling wave theory [5]. The analysis is concerned with the mechanism by which the longitudinal sound wave in the cochlear fluid resonates with the transverse wave of the basilemma.

There are 3 conditions for resonance formation:

- frequency compatibility - it may be incomplete.
- directional compatibility - it may also be incomplete.
- the energy of the forcing wave must be greater than the attenuation of the forced wave.

This condition is absolute. At low sound intensities, only the 1st condition is partially fulfilled and a threshold and an above-the-threshold sound is audible. The 1st condition is not fulfilled either, since the natural vibrations adopted by Bekesy as the basis for the calculations are incompatible with accurate studies of natural vibrations of human tissues [6]. The 2nd condition - the action of mechanical waves, incident perpendicularly to each other, does not increase the amplitude of vibrations.

Another important problem is perfect transmission of information over a very short period of time [7]. Resonance itself is a transfer of energy over successive wave periods - it is time-consuming. The speed of a sound wave in the cochlear fluid is 1450 - 1500 m/s. In contrast, according to Bekesy, the speed of traveling wave on the basilemma from the oval window to the cupola is 2.9 - 50 m/s. According to American studies, it amounts to 5 - 100 m/s depending on frequency and location on the basilemma. An approximately 50-fold disparity in the speed calls into question the possibility of encoding information when each small segment of the sound wave contains new information.

We do not hear simple harmonic tones. We hear multi-tones of different frequencies, whereby each tone may have several harmonic tones. Hence, a question: how are multi-tones with aliquots encoded in a transverse wave, and how are they passed on? In the fluid, no transverse wave will work. Multi-tones with harmonic tones must be passed on to a wave emerging in the cochlear fluid. There is no laminar flow of the cochlear fluid. There is movement of the particles of the medium - they vibrate around their equilibrium position, at an amplitude that depends on the sound intensity. With an amplitude 100 times smaller than the diameter of the atoms constituting the basilemma - tilting or bending the hairs of the auditory cells is impossible. The same values of the fluid wave - according to Bekesy's theory - have to be transmitted to the auditory cell hairs and the cadherin threads.

In line with the traveling wave theory - if a sound is quiet, it has to be separated from loud tones and sent back for amplification. According to Bekesy's theory, the OHCs are only an amplifier for the IHCs; a signal received by the OHCs is not transmitted to the centre. If it should be assumed that the OHCs send information received to the center, what is the purpose of amplifying mechanically quiet tones at this stage? Tones not received by this method cannot be amplified? And even if it were a mechanical amplification by pulling at the basilemma - what wave would it amplify? The wave slowly rolling over the basilemma at this time? This is a new, completely different wave. That wave that was supposed to be amplified is long gone from the basilemma. The transfer of quantized energy performed by pulling at the basilemma is questionable [8].

Mechanical amplification of quiet sounds at high frequencies, up to 20 kHz in humans, up to 50 kHz in dogs and up to 100 kHz in young cats, is questionable. There is no possibility of OHC contraction to such frequencies. There is an amplification by molecular mechanism, regulated in the auditory cell - viz. of received tones that have too little energy to reach the center [9].

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