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Mechanisms of Hearing - Part Two

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SUMMARY

On the signal pathway to the hearing receptor, the first mechanism is the eardrum which receives the energy of a sound wave, transmitting it to the middle ear ossicles. Vibrometric studies on the eardrum, the stapes base and the fluid at the beginning of the vestibular canal are presented. Differences in signal amplification on the way to the receptor are pointed out. It was hypothesized there is another signal pathway to the auditory receptor bypassing the cochlear fluid and the basilemma. The pathway leads through the osseous housing of the cochlea.

Hearing Mechanism

The eardrum is an important mechanism and the first stage of the signal pathway to the receptor. A thin, flaccid membrane connected to the malleus has a high capacity to absorb sound wave energy. If 99.9% of the energy of an incident sound wave is reflected, in the case of the eardrum, the reflection of the wave energy is small and depends on the frequency of the wave. Laser Doppler vibrometry studies have shown that for a 90 dB wave, corresponding to an amplitude of 500 nm at the entry at 2-3 kHz - vibrations of the eardrum are on an average 100 nm/Pa [1]- which corresponds to 80 dB. As the frequency increases, the amplitude of the eardrum deflections decreases to 10 nm/Pa – which corresponds to 60 dB. The two mechanisms, described by Bekesy, responsible for amplifying sound wave energy in the middle ear are implausible. The difference in surface area of the eardrum and stapes base in a ratio 55:3.2 is supposed to act as a mechanical transformer, increasing the transmission of sound wave energy between the air and fluid of the inner ear. The value of this amplification is approximately 17 times.

According to theory, the conical shape of the basilemma gives an additional twofold amplification. Then, there is also an amplification due to a 1.3 : 1 lever mechanism, which leads eventually to a total amplification of about 44 times [2]. On a logarithmic scale, this is about 33 dB. The energy of a sound wave is quantized [3]. By quantized energy we should understand that the differences in energy levels are defined by the smallest indivisible portion of energy called a quantum of energy or its multiple (in optics it is a photon). The energy difference cannot be continuous, it must be stepwise. It is difficult to achieve quantization of energy in a lever mechanism.

If the difference in the surface area between the tympanic membrane and the stapes plate should be taken into account, in the case of stapedotomy, the diameter of the plunger is 0.4 mm - the surface area of the plunger is 0.502656 mm^2. A 55 mm^2 tympanic membrane should be amplified by about 100 times, in addition to the amplification caused by the lever mechanism. For a 6 mm diameter piston with an area of 1.080976 mm^2, an amplification should be about 55 times in addition to the lever mechanism. According to the publication, changing the diameter of the piston does not cause such differences in the gain. As about the lever mechanism, a shorter anvil leg frame results in a reduction of the wave amplitude in a ratio of 1.3 : 1. A reduction of the wave amplitude reduces the wave energy in proportion to the square of the wave excursion. Therefore, whence is the assumption that this mechanism increases the energy of the wave in a ratio of 1.3 ;1 times. An increase in force measured in Newtons will not increase the amplitude of the wave measured in nanometres, responsible for the transmission of auditory information. Up to a frequency of 2400 Hz, the malleus has the same vibration amplitude as the eardrum.

If, according to vibrometric testing of a 90 dB input sound wave, the malleus has a vibration amplitude of 100 nm, corresponding to 80 dB - it is difficult to agree with the thesis that the input wave or 80 dB wave at the eardrum, conducted through the ossicles is increased by 33 dB, or about 44 times. A proof that the thesis of such an amplification is incorrect is provided by vibrometric studies on wave amplitudes at the stapes base on the side of the inner ear and in the initial section of the vestibular canal fluids [4]:

Frequency-------base --------- vestibule

1000 Hz--------5.09 nm--------0.275 nm

4000 Hz--------1.37 nm--------0.00886 nm

8000 Hz--------0.0905 nm-----0.00153 nm

The study was performed for a 90 dB (500 nm) input wave at the entry.

Such a large decrease in the wave energy transferred to the cochlear fluids may be due to the structure of the oval window - bone and connective tissue - length 2.24 mm, width 1.4 mm, ring width 0.1 - 0.04 mm, ring thickness 0.2 mm. It is influenced by the length of the annular ligament, which is a linear elastic material to a deflection of about 100 nm, with a stiffness of about 1200 N/m and a calculated modulus of elasticity, approx. 1.1 MPa [5]. The vibrations of the stapes base through the annular ligament are transmitted to the bone of the cochlear housing. Swaying movements of the stapes amplify the transmission of vibrations to the bone. During rocking movements, a part of the base generates a forward motion of the wave, while at the same time, the remaining part of the stapes generates a backward motion. Sound waves traveling in opposite directions in the same plane undergo destructive interference. The formation of a wave traveling on the basilemma is questionable or impossible.

Transmission of accurate information is impossible, too. At high frequencies, a signal takes a different route to the receptor, as evidenced by our hearing, and the very good hearing of animals receiving sound waves up to 100 kHz [6]. A decrease in the amplitude of the wave transmitted to the cochlear fluids, proportional to an 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. The circular window has a diameter of 1.2 mm, the thickness of the circular window membrane is 0.05 mm. The circular window is 20 times more susceptible to vibrations than the oval window. Therefore, when the chain of ossicles in the middle ear is broken, but the eardrum is preserved and the mobility of both the windows is maintained, there is a large hearing loss of 40-60 dB – yet the hearing will remain. In the cochlear fluids, a retrograde wave is generated from the circular, vibration-prone window. There is no wave traveling on the basilemma from the oval window to the cupula. Frequency and intensity resolution are preserved with no basilar membrane involvement.

It should be noted that these vibrometric studies involved a 90 dB wave, whereas the threshold of human hearing is 0 dB, i.e. a wave at the entrance = 8 pm [7] or slightly above. f such a small wave is already fading on its way to the vestibular, similarly to the 90 dB wave, the energy is unlikely to reach the receptor through cochlear fluids and basilemma. Vibrometric studies have shown that the amplitude of a 800 Hz and 90 dB wave from the external auditory canal to the circular window fades about 1000 times, and the energy of this wave fades approx. a million times! This is not the path of the signal to the receptor, but is a clear indication of the disappearance of energy in the inner ear when vibrations involve elements having mass. A sound wave that caries certain energy has no mass and does not suffer such losses on its path through the bone of the cochlear housing. A human being hears waves above the auditory threshold, which can imply that the path of this wave does not pass through the cochlear fluid and basilemma, either. It passes through the cochlear housing bone at a speed of 3-4 thousand m/s directly to the receptor.

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