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Mechanisms of Hearing - Part Three

Myjkowski Jan

Retired physician, Specialist in otolaryngology – pensioner, Myjkowski Jan, Poland.

***Corresponding Author:** Myjkowski Jan, Retired physician, Specialist in otolaryngology pensioner, Myjkowski Jan, Poland. Tel No: 48-782 449 179.

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Abstract

Introduction

The theory of hearing, promulgated by Georg von Bekesy in 1928 under the name of the traveling wave theory, was created in the time of a lower level of science. It has been revised and supplemented over many decades, but the foundations of the theory have remained unchanged. These are the fluid hydrodynamics of the inner ear, wave resonance, mechanical amplification or the tip-links mechanism. The said mechanisms must be consistent with hearing of all animals worldwide. They do not explain all hearing problems. Presented is some information about sound waves, related to hearing; in addition, the importance of inertia in the ear is also highlighted. In the concluding section exposed are the problems of Bekesy's theory of hearing - viz. of the traveling wave, and they point to the need of having this theory revised.

Arguments in Support of Revising the Hearing Theory

A sound wave is a displacement of energy without transporting the mass of the environment. Those are vibrations of particles propagating in an elastic medium. Each particle makes an oscillating motion around its equilibrium position, transferring energy to a neighboring particle. The energy transfer occurs at a rate that depends on the elasticity of the environment. The energy of the sound wave, absorbed by the eardrum, is the source of the wave energy conducted through the ossicles of the middle ear to the oval window, and directly from the eardrum and ossicles to the osseous housing of the cochlea, and further on to the receptor. The vibrating stapes base induces vibrations in the fluid adjacent to the stapes base. A sound wave is created in the fluid, travelling to the cupula, and further on to the round window. There is neither fluid mass movement nor fluid flows.

A sound wave has a period of oscillation and an amplitude of excursion. As the amplitude changes, the sound pressure changes, proportionally to the amplitude of the excursion. The energy of the wave is proportional to the square of the deflection. The intensity is, therefore, proportional to the square of the wave pressure [1]. Maximum pressure of sounds loud to the ear = approximately 28 N/m2 = 28 Pa. (This is the difference between atmospheric pressure = 100 000 Pa, and the sound). 28 Pa converted to the excursion/displacement amplitude = 10-5 m = 100 000 nm. Minimum pressure - hearing threshold = 2.0 x 10-5 Pa = 8 x 10-12 m = 8 pm = 0.008 nm. The intensity spread of a sound wave perceived by the human ear is 12 million times, and can only exist in the case of energy quantization. Only receptors with their receptor fields are responsible for the intensity resolution, transmitting information to the centre. Stapes vibrations produce sound waves in the fluid of the vestibular canal, and transmit the wave energy to the osseous housing of the cochlea [2]. The pathway of sound wave energy transmitted to the round window is not the signal pathway to the receptor.

It is assumed that a sound wave has no mass and is not subject to the law of inertia. This view requires verification. The measure of inertia is the mass of a vibrating element that retains speed and acceleration. Vibrating particles in a sound wave have a speed as well as a positive and negative acceleration. They consist of at least 2 atoms of an elastic medium. An average mass of atoms of vibrating particles = 10-24 to 10-23 g. The mass of even a large number of atoms of vibrating molecules, multiplied by the acceleration and amplitude, is itself of little significance. With a large increase in amplitude, and especially in the frequency, it can make a difference - it is an added value. Inertia is proportional to the square of the frequency and directly proportional to the amplitude and to the vibrating mass. A sound wave carries energy without carrying the mass of the environment. There are no fluid flows in the inner ear. The forward motion of vibrating particles is equal to the amplitude of the sound wave and its frequency, followed by a backward motion phase of the same amplitude due to the elasticity of the environment. Inertia is the product of acceleration and mass. This is one of the reasons for the need of increased energy of high-frequency and high-amplitude waves for their conduction.

The main problem of inertia in the ear concerns vibrating elements that have a mass, such as the middle ear bones. The graph of the harmonic oscillation is a sinusoid. The circular frequency is calculated - $\omega = 2\pi$ x f (f-frequency). The velocity in harmonic motion is A x ω (A-amplitude). Acceleration in wave motion : a = $\omega 2$ x A = $(2\pi$ x f$)2$ x A. Force required to cause motion and acceleration : F = a x m (a = acceleration, m = oscillating mass). Total energy in simple oscillating motion E = m x $\omega 2$ x A2 divided by 2. From this formula, it follows that the total energy of a wave is proportional to the square of the frequency and proportional to the square of the amplitude.

A vibrating body must perform some work against the elastic resistance force of the environment, and overcome the resistance of the pseudo forces of the vibrating mass (inertia). If it does the work, it must have some energy supplied. Without new energy supplied, the amplitude of the wave decreases. It is assumed that the time after which the amplitude of the oscillation decreases "e" times - this is the relaxation time. The value "e" = 2.71872 - is the base of the natural logarithm. Damping the vibration reduces the relaxation time. Damping is the inverse of relaxation. Damping and relaxation are relevant in determining the natural vibration of a given body, capable of entering in resonance - e.g. the basilemma. The natural vibration is determined for a body free of damping. In the inner ear, the vibrations of the basilemma are strongly damped by the fluid on either side of the basilemma. Resonance of the forcing wave with the forced wave occurs in the absence of damping of the forced wave. With such an intensive damping of the vibration of the basilemma by the fluid on either side of the vibrating membrane, resonance with accurate transmission of information is unlikely to occur.

In the ear, large masses have the eardrum and the ossicles, vibrating as a whole up to a certain frequency limit (according to Bekesy 2400 Hz). Assuming the mass of the middle ear ossicles with mucous membrane = 70 mg, (malleus 25 mg, anvil 30 mg, stapes 3 mg, in total 58 mg, + mass of mucous membrane, part of the mass of the ossicle ligaments + part of the mass of the ring ligament, totaling 70 mg [3]. It is possible to calculate the inertia, for each frequency and wave intensity, of this oscillating mass. Inertia = mass x acceleration:

Exemplary Quantities:

1000 Hz - 0 dB - inertia 27.6 - 60 dB - 27606 - 80 dB - 276068 g/mm x sec2

4000 Hz - 0 dB - inertia 441.7 - 60 dB - 44170 - 80 dB - 4417100 g/mm x sec2

10000Hz - 0 dB - inertia 2760 - 60 dB - 2760688 - 80 dB-276066880 g/mm x sec2 0

dB = 0.01 nm, 60 dB = 10 nm, 80 dB = 100 nm

One of the pillars of Bekesy's traveling wave theory is cochlear fluid hydrodynamics. "Hydrodynamics describes the phenomena associated with fluid flow, with a strict description of these phenomena being limited to laminar flows" [4]. In the inner ear, laminar flows do not exist. There is a wave motion in a fluid with the amplitude of the wave excursion limited to the magnitude of the amplitude of the excitation wave, taking into account damping and energy losses in the energy transfer pathway. High frequencies cannot be conducted by vibrating elements having a large mass. In contrast, a sound wave, having the mass of vibrating particles at atomic mass level, can be transmitted through any medium, except vacuum. This may explain the lack of high-frequency conduction after stapedotomy when sound waves are transmitted by the piston only to the fluids of the inner ear. The piston vibrates together with the ossicles, increasing the vibrating mass, which has a decisive effect on the inertia of the high frequencies.

We can hear high frequencies and other mammals can hear up to 100 kHz; there must be another mechanism for transmission to the high-frequency receptor. Such a transmission route is through the osseous housing of the cochlea [5]. There is a transmission of high-frequency wave energy from the eardrum, middle ear ossicles and oval window directly to the cochlear osseous housing. If a part of the wave energy is conducted to the cochlear fluids and to the round window, this energy does not play a role in the transmission of information to the receptor. It may have a role in the annihilation of excess energy, constantly flowing into the ear. The energy of a sound wave disappears on its way from the external auditory canal to the round window about one million times (the amplitude for a 90 dB wave and 8 000 Hz wave disappears 1,000 times!). The amplitude of a 90 dB wave is 500 nm, on the round window it is 0.5 nm. The human threshold wave is 0.01 nm. The owl can hear very well, and its threshold wave = 0.001 nm. This wave will also fade away on its way to the receptor through the cochlear fluid. Such a fading sound wave cannot produce a wave traveling on the basilemma because it is 100 times smaller than the diameter of the atoms that make up the basilemma structure (10-10 m). It is not possible to transmit accurate information with such a gigantic energy decay? Many factors influence the disappearance of a sound wave in cochlear fluids: time, energy dissipation, fluid viscosity, particle friction, frequency increase, absorption attenuation, reflection attenuation, wave dispersion in a fluid containing mineral particles, destructive interference.

Doubts of Bekesy's Traveling Wave Theory

- A threshold wave of 0.01 nm at the entrance, fading several hundred times en route, tilts or bends the auditory cell hairs 10 000 times thicker than the sound wave at the entrance.
- The middle ear lever mechanism reduces the vibration amplitude but increases energy.
- Quiet sounds are amplified 40 dB (10 000 times), but we still hear them as quiet.
- OHC contraction only amplifies quiet tones, and depolarization and OHC contraction is the same for loud tones that do not require amplification.
- OHC contraction amplifies entirely new waves, not only

silent ones, on the basilemma.

- Resonance of a longitudinal wave with a transverse wave is difficult or impossible to communicate quickly and accurately.
- Energy quantification is not provided by fluid flows, auditory cell hairs or cadherin tip-links [6].
- Myosins are responsible for closing the mechanosensitive potassium ion channels up to 100 kHz. This is impossible.
- The duty cycle of the ion channels of the auditory cell membrane lies within 3-4 ms. Cell depolarization and cell contraction depend on these channels. Nevertheless, theory holds that OHCs can contract up to 100 kHz.
- The receptor receives a signal lasting tenths of ms, which can correspond to up to 1 period of a wave. How does the resonance transmit information during 1 period? [7].
- The signal path time from the external auditory canal to the auditory nerve = 1.5 - 1.9 ms. In contrast, when counted together, the signal paths through the cochlear fluids and the basilemma are 5 - 6 ms.
- There is a lack of detailed description of mechanisms at the molecular and electron level [8].
- Lack of high frequency transmission after stapedotomy.
- Blocking of both windows precludes the formation of a wave running on the basilemma. Frequency and intensity resolution is preserved in severe hearing loss.

Those Bekesy traveling wave problems are sufficient to implement a revision of the age-old hearing theory. Problems of this type do not apply to the new Sub molecular Theory of Hearing.

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