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Review Article

The Biophysical Function of the Human Inner Ear

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Abstract:

The ear transforms soft mechanical vibration of air particles into electrical signals, which reach the appropriate part of the cerebral cortex for processing by means of auditory nerves. The process of the hearing is next: the eardrum vibrates from the sound waves; auditory ossicles amplify the stimulus; in an oval window, the vibration is transmitted to the fluid space of the inner ear; iIt vibrates the basilar membrane; what is pressed against the membrane tectoria; the stereocilliums of the hair cell bend, ion channels open; hair cell depolarizes; stimulus is dissipated in cerebrospinal fluid VIII (vestibulocochlearis); temporal lobe primary auditory cortex (Brodman 41, 42); association pathways: speech comprehension (Wernicke area). For the rising prevalence of psychoses (mental disorders) in the last decades among townspeople, these stimuli – as compared to the abandoned environment – and the adaptation to them may also play a definite role. The man, therefore, enjoying worths and conveniences of the civilization has to size every opportunity to get into the open, to compensate the monotony of the external stimuli, in a word, to grant his organism those stimuli which he claims as a biological creature. This human demand – it seems – is such a great physiological need that our organism cannot be without even in the evening. At least this turns out according to the researches relating sleep and dreaming.

Key words: békésy's theorie; cochlea; auditory ossicles

Introduction

The hearing analyser consists of two main systems: the peripheral hearing system, formed of the outer ear, the middle ear and the inner ear and the central hearing system, which contains the nervous pathways which ensures the transmission of the nervous influx and the hearing area where the information is analyzed and the hearing sensation is generated [1]. The peripheral hearing system achieves the functions of transmission of the sound vibration, the analysis of the acoustic signal and the transformation of the acoustic signal in nervous inflow and the generation of the nervous response.

The man's hearing organ is the ear and it serves as equilibrium organ [2]. The ear has three parts: the outer ear, the middle ear and the inner ear (labyrinth).

The anatomical structure of the ear is shown in Figure 1.

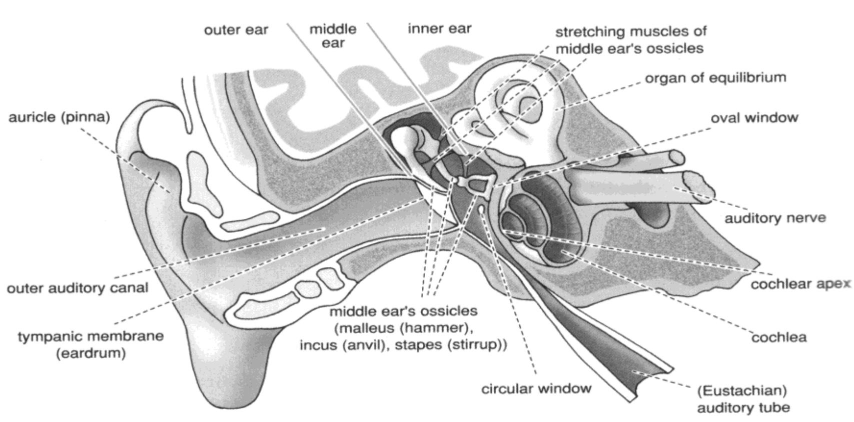

Figure 1: *Anatomical structure of the ear*

The Structure of the Inner Ear

The inner ear, just like the middle ear, is hidden in the temporal bone [3]. It contains the receptors of the hearing and balancing device.

The inner ear consists of two parts: 1. labyrinth (labyrinthus), 2. Internal auditory canal (meatus acusticus internus).

In the creation of the labyrinth we distinguish between bony and membranous parts:

a) bony labyrinth (labyrinthus osseus),

b) Membranous labyrinth (labyrinthus membranaceus).

The bony labyrinth is nothing more than the protective case of the membranous labyrinth. The membrane labyrinth, which contains the stimulus-absorbing devices, fits into this cavity system.

The bony labyrinth consists of a central cavity, also known as a porch (vestibulum), the originating bony semicircular canals (canalis semicircularis) and the cochlea [4].

The vestibulum is a small, smooth-walled cavity that is connected to the cochlea forward and to the semicircular canals to the rear. Its lateral wall borders the tympanic cavity and shows the oval opening of the fenestra. Its medial wall separates it from the internal auditory canal [5]. There are three depressions in it: at the back we find the recessus ellipticus, at the front we find the recessus sphericus, and at the bottom there is the recessus cochlearis.

Semicircular canals (canalis semicircularis). Three semicircular canals originate from the vestibule and return to the same place. Each of the three semicircular canals lies in a plane perpendicular to each other. A distinction is made between superior (canalis semicircularis superior), posterior (canalis semicircularis posterior) and lateral (canalis semicircularis lateralis) canal [6]. The superior canal lies in the frontal plane, the posterior in the sagittal plane, and the lateral in the horizontal plane. The crura of each canal are not the same. We distinguish between a broader (crus ampullare) and a narrower (crus simplex) crus. The three arch passages enter the vestibulum with only five openings because the crus simplex of the superior and posterior canals merge with each other before the opening.

Figure 2. shows the cross-section of the cochlea along its entire length with three different chambers: the scala vestibuli, the scala tympani, and the cochlear duct.

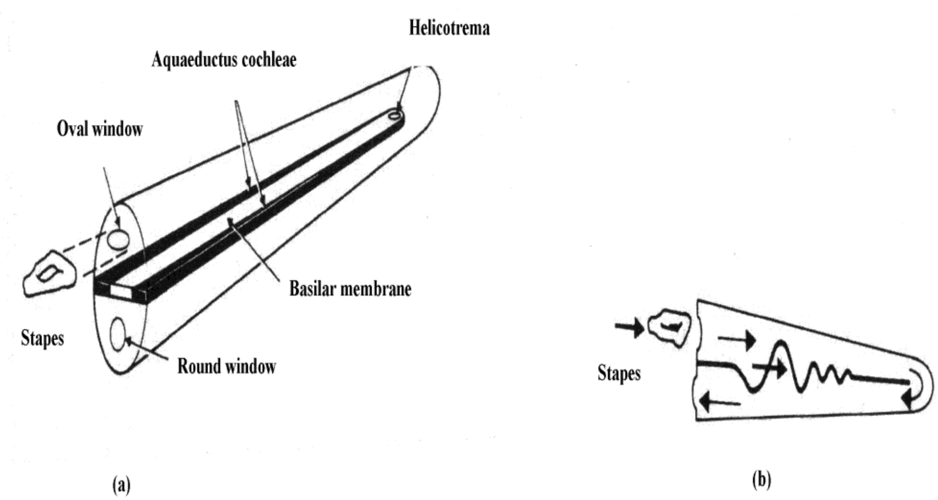

Figure 2: *Schematic diagram of the cochlea (a) and the part cut from the cochlea (b)*

The cochlea is filled with fluid and surrounded by a solid, bony wall. It contains two types of fluid: perilymphet (in the scala vestibulit and scala tympanit canals) and endolymph (in the cochlea); the total capacity of the cochlea is only a fraction of a drop. Perilymph is similar to spinal fluid, while endolymph is similar to intracellular fluid. The two fluids are separated by two membranes: the Reissner membrane and the basilar membrane. The Reissner membrane is very thin, approx. two cells thick.

The propagation of the waves

The wave propagates in the perilymph in two ways: longitudinally and transversely [7]. The phase velocity of longitudinal waves is determined by the following formula:

$$c_l = \sqrt{\frac{E}{\rho_0 \cdot (3-6\mu)}}$$

Where: E – modulus of elasticity, ρ_0 – density of perilymph, μ – Poisson’s number, the value of which varies between 0.3 and 0.45. The phase velocity (c) of the transverse wave is calculated by the following formula:

$$c_l = \sqrt{\frac{E}{\rho_0 \cdot (3-6\mu)}}$$

Comparing the two formulas, we can conclude that the phase velocity of longitudinal waves is always higher [8]. Using the value interval of the Poisson number, the ratio of the velocities of the two phases changes in the following interval:

$$c_l / c_t \in \left[2{,}15 - 9{,}7\right]$$

Georg von Békésy [9] also determined this progressive wave experimentally (Figure 3.). The relative amplitude of the displacement of the basilar membrane serves as a function of the distance from the stapes for many different frequencies.)

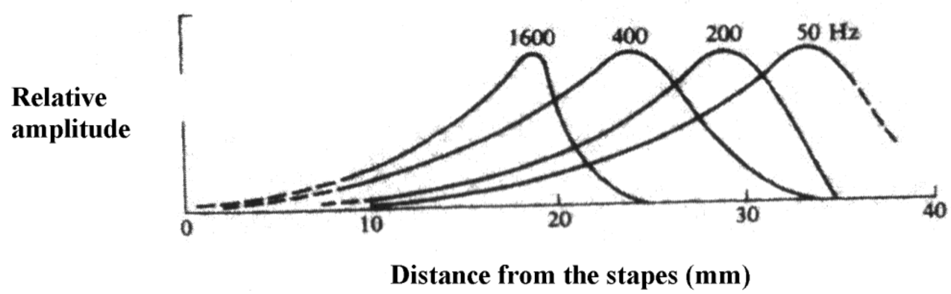

Figure 3: *The relative amplitude of the displacement of the basilar membrane serves*

As a function of the distance from the stapes for many different frequencies.

Of course, the wave equation is also valid for the inner ear

$$\nabla^2 \Phi = \frac{1}{c^2} \cdot \frac{\partial^2 \Phi}{\partial t^2}$$

Hankel functions are used more in theoretical developments and in solving equations of advanced wave propagation [10, 11].

The Organ of Corti

The fine and complex organ of Corti rests on the basilar membrane, and is an approx. 3 cm long gelatinous paste. It is the “headquarter of hearing” that consists of several rows of tiny hair cells. Each hair cell has a number of cilia that bend when the basilar membrane responds to a sound. The deflection of the cilia is likely to stimulate the hair cells, which in turn stimulate the neurons in the auditory organ [12].

In order to understand how the basilar membrane vibrates, look at the expanded and simplified version of the cochlea in Figure 2. The cochlea here appears as a conically tapering cylinder, which is divided into two parts by the basilar membrane. (Since the cochlear duct is quite thin, we can ignore this – as a first approach – consider the two parts separated by a single membrane instead.) At the beginning of the thicker end of the cylinder is an oval and round window closed by a thin membrane, and near the distal end of the basilar membrane is a small hole, the helicotrema, which connects the two scala vestibuli, the scala tympani chambers. The fluid transmits pressure waves to the end of the membrane [13].

As the stapes moves toward the oval window, hydraulic pressure waves are rapidly transmitted in the scala vestibular chamber, inducing waves in the basilar membrane. High-frequency sounds cause the largest amplitude displacement of the basilar membrane near the oval window, where the basilar membrane is narrow and rigid [14]. Low frequencies produce the waves with the largest amplitude where the membrane is loose at the distal end (see Figure 3.). This results in an initial not yet high-resolution frequency analysis in the cochlea, although the base tone is determined by the central nervous system, where data from the auditory nerve is processed.

The conversion of the mechanical vibrations of the basilar membrane into electrical impulses takes place here in the inner ear. When the basilar membrane vibrates, the “hairs” of the hair cells bend, creating nerve impulses that are transmitted to the brain. The density of the generated pulses depends mainly on the intensity, but also less on its frequency [15].

The entire hearing mechanism is illustrated in Figure 4. Sound waves propagate further into the ear canal, stimulate the eardrum, and create mechanical vibrations in the middle ear. The stapes transmit the vibration to the oval window and cause a pressure change along the cochlea in the cochlear fluid, which in turn creates mechanical vibrations in the basilar membrane. Vibrations of the basilar membrane stimulate the hair cells to excite impulses and the nerve impulses generated in the hair cells are transmitted to the brain through the auditory nerve fibers.

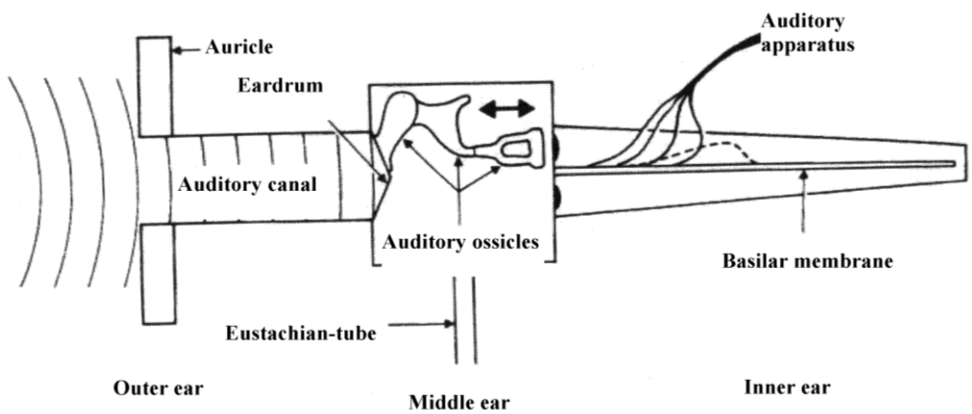

Figure 4: *A schematic representation of the ear that illustrates the entire hearing mechanism.*

Sound waves from the outer ear cause mechanical vibrations in the middle ear and eventually nerve impulses that, interpreted as sound, pass through the brain.

Some of the sounds reach the inner ear with the vibrations of the skull and cheekbones. This is called bone conduction hearing. Hearing by bone conduction plays an important role in speech. Buzzing sounds or clicking of the teeth can be heard almost entirely by bone conduction. (If we cover our ears with our fingers, so standing in our way to the air, the buzz will sound louder.) During speech or singing, two different sounds can be heard, one by bone conduction and the other by air conduction [16]. Our own recorded voice may sound very unnatural to ourselves, just because the sound coming through the air was recorded by a microphone, while we are used to hearing both components of our own voice. When two pure sounds are so close to each other at a frequency that a significant overlap appears in their displacement amplitude curves of the basilar membrane, they lie on the same critical band. There are 24 critical bands between 16 and 16,000 Hz.

Biophysical modeling of the sound conduction

It plays an acoustic role, transforming external sound vibrations, amplifying them and then transmitting them to the fluid system of the inner ear. It protects the inner ear from excessive sound effects [17].

The deflections of the eardrum are transferred to the base of the stapes by the lifting action of the auditory bone chain. Due to the fact that the functional surface of the eardrum is 55 mm^2 and that of the stapes base is 3.2 mm^2, the pressure at the base of the stapes is 18 times higher than that of the eardrum (55: 3.2 = 17). This ratio corresponds to a 24.5 dB increase in sound pressure. To this must be added 2.2 dB, since one crus of the auditory bone chain (one arm of the elevator) is one handle of the malleus, the other crus (the other arm of the elevator) is the long crus of the incus, 1.3 times longer than the handle of the malleus. Thus, the voice guidance system of the middle ear: It causes a pressure increase of 24.5 + 2.2 = 26.7 dB. From all this we can conclude that the middle ear acts as a mechanical transformer.

The stapes base moves around two axes: [18] for weaker sounds - rotates around its transverse axis (Figure. 5.a.);

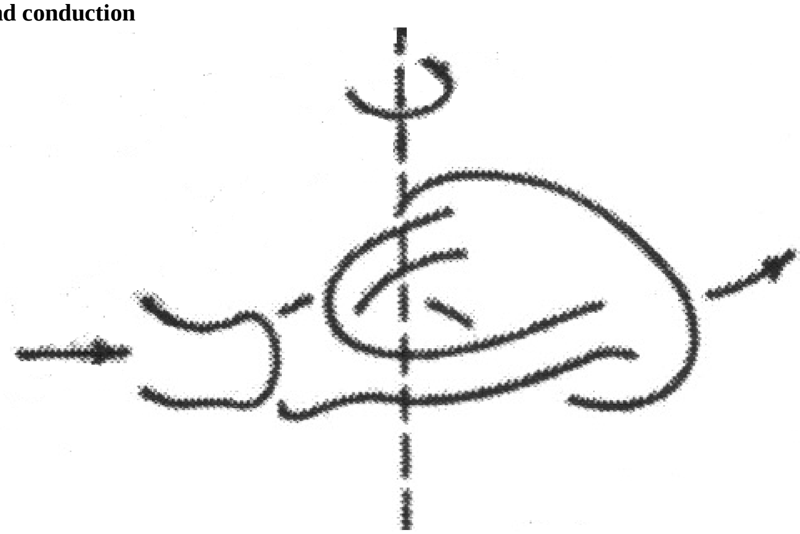

Figure. 5.a: *In case of a strong sound - it moves around its longitudinal axis, then the amplitude of vibration is smaller (Figure. 5.b).*

Figure. 5.b: *We have three (3) auditory ossicles because, with their spatial location, the middle ear is able to amplify weak sounds and at the same time is able to attenuate high-intensity sounds [19].*

Masking

When an ear is exposed to two or more different sounds, one can mask the other in the traditional sense. In the case of a simultaneous sound effect, the simultaneous *masking* is perhaps best explained by the fact that the hearing range of the weaker sound is raised by the louder sound, and the extent of this also depends on the frequency of the two sounds. Clear sounds, complex sounds, narrow and broadband noises can all mask other sounds in different ways [20].

Some interesting conclusions can be drawn from the relevant masking attempts:

1. Clear sounds that are closely related in frequency overlap more than sounds that are widely spaced in frequency.

2. A clear sound masks higher frequency sounds better than lower frequency sounds.

3. The higher the intensity of a masking sound, the wider the frequency threshold it is able to mask.

4. Narrowing by narrowband noise has the same properties as masking by a clear sound; again high frequency sounds are covered more effectively than those with a lower frequency than the masking noise.

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