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The Biophysical Modeling of the Human Hearing

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Abstract

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. 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. Loudness on one hand depends on the physical intensity, and on the hand on the frequency of sound. However, identical changes of intensity correspond to non-identical changes of sound sensation, since as discussed previously the ear is only able to receive physical stimuli across 13 orders of magnitude. The vibrating amplitude of air in the case of sounds which are just audible is extremely small i.e. about ten times smaller than the diameter of hydrogen atom (10^{-11} m). There are three tiny bones (malleus, incus, stapes) in the tympanic cavity between the eardrum and the oval opening. the voice guidance system of the middle ear: it causes a pressure increase of 24.5 + 2.2 = 26.7 dB.

Keywords: Anthocyanin; Hepatoprotection; Signaling Pathways.

1. INTRODUCTION

The connection between the organism and the environment is made through the analysers, real information channels, which receive, lead and integrate the excitations in the environment as specific conscious sensations.

The anatomical-physiological apparatus of sensations is called analyzer and it is made of three parts, tightly connected between them: the receiver or the analyser's peripheral segment, the afferent pathway which takes the excitation to the cerebral cortex and the cortical segment of the analyser [1].

The peripheral segment – the receiver:

– Is represented by specialized structures integrated in the sense organs;

– Stimulated by the variation of an energy form and finally the action potential (nervous inflow) which propagates in the following segment;

– The receiver – it only performs a gross analysis.

The intermediary – leading segment is formed of:

– Direct pathways – they are specific pathways, with a few synapses, through which the nervous impulses are lead rapidly and they are projected in the cortical areas, in specific areas;

– Indirect pathways – nonspecific nervous pathways, with a lot of synapses and through which the nervous inflows are led slowly, in the cortical areas, where they project diffusely and non-specifically.

The central segment is represented by two types of cortical areas:

– Primary cortical area, where the fibres of the leading pathway are projected;

– Secondary cortical area connected with the primary area.

The ear transforms soft mechanical vibration of air particles into electrical signals, which reach the appropriate part of the cerebral cortex for further processing by means of auditory nerves. [2] The cerebrum interprets these complicated signals by determining pitch, tone, loudness, and placement of the sound source.

2. ANATOMICAL STRUCTURE OF THE EAR

The structure of the ear is shown in Figure 1.

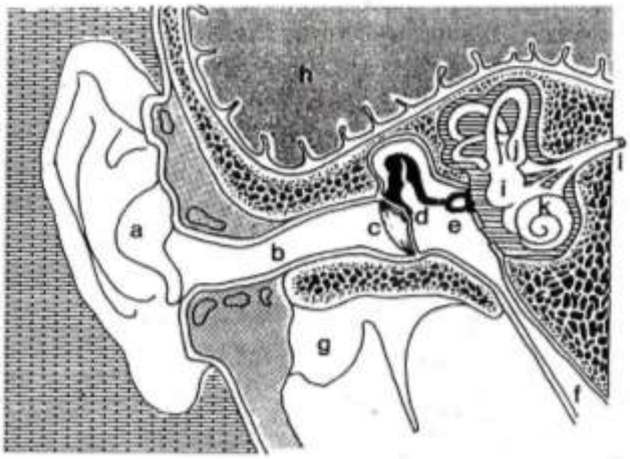


Figure 1. Schematic section of the ear.

Symbols: a: auricle, b: external auditory canal, c: eardrum, d: middle ear with auditory bones, e: stapes in the oval window, f: Eustachian tube towards the oral cavity, g: and its black patched area) bone, h: brain, i: vestibula, j: semicircular canals, k: cochlea (white parts are membranous, hatched parts are a bony maze), l: nerve running to the brain.

It is our {auditory} organ of hearing [3] to perceive speech and music.

3. THE CHARACTERISTICS OF THE SOUND WAVES

The waves can be classified in two big categories:

– longitudinal waves when the oscillations of the particles take place in the direction of propagation of the wave;

he phase velocity c for longitudinal waves in a solid medium is given by the following formula:

$$c = \sqrt{\frac{E}{\rho} \cdot \frac{1}{(3-6)\mu}}$$

where: E - modulus of elasticity, ρ - density, μ - Poisson's ratio. [4]

– Transversal waves when the oscillations take place on a perpendicular direction on the one of the propagation of the wave.

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. [5] Using the value interval of the Poisson number, the ratio of the velocities of the two phases changes in the following interval:

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

The sounds are longitudinal waves which propagate in continuous environments and if they reach the human's hearing organ, in certain conditions, they produce hearing sensations. The description and the characterization of the sounds is based on three main characteristics: height, intensity and quality, to which the following physical sizes correspond: frequency, amplitude and harmonic constitution. [6]

The height of a sound is determined by the frequency of an acoustic wave (**ν**), namely the number of oscillations that the sound wave performs in the time unit. The higher the sound frequency, the „higher" the human ear perceives them.

According to the frequency, the sounds classify as follows:

- infrasounds, $\nu < 16$ Hz;
- proper sounds, 16 Hz $< \nu <$ 20 kHz,
- ultrasounds, $\nu >$ 20 kHz.

The infrasounds and the ultrasounds cannot be perceived by the human ear.

The frequency range of hearing varies greatly from individual to individual; it is rare for a person to be able to hear the full hearing range of 16 to 20,000 Hz. The ear is relatively insensitive to low-frequency sounds; for example, at 100 Hz its sensitivity is roughly 1,000 times lower than at 1,000 Hz. The sensitivity of high-frequency sounds is greatest in infancy and gradually decreases throughout life, making it difficult for an adult to hear sounds above 12,000 Hz.

Loudness mainly depends on the sound pressure, but the duration and spectrum of the sound also influence the development of loudness sensation. The sense of pitch depends mainly on frequency, but shows a slight dependence on sound pressure and duration. Table 1 illustrates the dependence of sound sensation quality on physical parameters.

Table 1. *Dependence of sound quality on physical parameters. + = weakly dependent ++ = moderately dependent, +++ = highly dependent.*

Physical Parameter	**Subjective Quality**			
	Loudness	**Base tone**	**Tone**	**Durability**
Intensity	+++	+	+	+
Frequency	+	+++	++	+
Spectrum	+	+	+++	+
Duration	+	+	+	+++

4. THE HUMAN HEARING SYSTEM

The human auditory system is a complex acoustic, mechanical, hydrodynamic electrical transducer, nerve conduction and brain structure. Not only does it respond to a number of stimuli, but it also accurately identifies the base tone (sound quality) and the pitch, but even the direction of the sound source. Much of the hearing function is performed by the organ with which we hear, that is the ear, but recent research has highlighted the extent to which hearing depends on the data processing that takes place in the central nervous system.

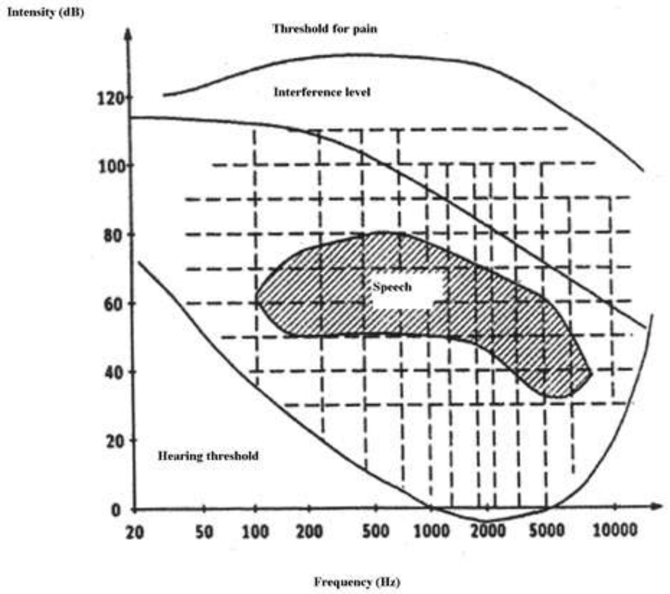


Figure 2. *The frequency and intensity sensing range of hearing*

The range of sound pressure stimuli to which the ear responds is very wide. The energy content of a particularly loud sound is about (10^{12}) greater than that of the weakest but still audible sound. At certain sound frequencies, the displacement of the eardrum is less than 10^{-11} m. The frequency and intensity sensing range of hearing is shown in Figure 2.

Hereinafter, we will confine ourselves to gas space, because the most significant chapter of mechanical waves is sound waves. The result obtained will also be valid for a liquid or solid state as far as the shape of the wave equation is concerned, but the properties of the medium must be duly taken into account. In a gas space, the change in volume and density caused by the sound wave takes place at such a high rate that there is practically no time for heat exchange, so the wave propagation is treated as an adiabatic process. The Poisson equation is valid:

$$p \cdot V^{\gamma} = \acute{a}lland\acute{o},$$

where: p – pressure, V – volume,

$$\gamma = \frac{C_p}{C_V}$$

– ratio of isobar to isochoric molar heat. With logarithm, then differentiation and Taylor decomposition (disregarding the whole mathematical derivation) we get:

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

It is a three-dimensional wave equation that gives the acoustic pressure in a flexible, homogeneous, and isotropic medium over space and time. With some modifications, we get to:

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

The differential equation is the desired wave equation depending on the velocity potential of the particle. This differential equation can be written for each sound wave.

5. THE OUTER EAR

The external auditory canal starts in the middle of the eardrum and leads from the side to the middle, leading to the middle ear. It is approx. 22 to 26 mm long, 7 to 9 mm in diameter and approx. 1 cm^3 in volume. We distinguish between external cartilaginous and internal bony parts. The cartilaginous part is a continuation of the cartilage of the auricle, while the bony auditory canal is formed by the os temporale. The wall of the external auditory canal forms an acute angle with the eardrum. Its inner surface is lined with skin folding over from the auricle, which also reaches the outer surface of the eardrum.

The external auditory canal is not completely straight, but is slightly bent in an S-shape. This curvature can be straightened by pulling the auricle backwards, upwards and outwards, and then the eardrum can also be examined on a living person with the help of a funnel. Hair follicles are also present at the auditory canal entrance. There are a number of sebaceous glands in the skin of the external auditory canal, the secretions of which are yellowish-brown in color (earwax), which, if they accumulate, can lead to hearing loss.

The outer ear begins to form intrauterally at 4–6 weeks of age, from the 6 dorsal tubers of the first gill arch. The final size is reached by the age of 9.

The skeleton of the auricle is made up of flexible cartilage that connects the connective tissue and outer skin to the skull bones. The shape of the auricle is determined by the cartilaginous vase. It covers the cartilage skeleton as a direct continuation of the skin, head, and facial skin. Its shape and size vary from individual to individual. Under the skin, clinging to the cartilage, we find short muscles, which, however, are completely insignificant in terms of function in humans, but in some they are not completely diminished and are able to move the auricle. In old age, overproduction of growth hormone results in acromegaly and this results, in an increase in the cartilage skeleton of the auricle in both women (5%) and men (18%).

6. THE HUMAN EARDRUM

The boundary between the outer and middle ears is formed by the eardrum, which is approx. 9 mm in diameter, slightly oval, moderately elastic plate. Its thickness is 0.1 mm; its tensile strength is 100 kPa. It has a surface of 85 mm^2, of which only 55 mm^2 can be used for hearing. Its periphery forms a bony ring. Its outer surface is covered with skin in the continuation of the skin of the auditory canal, while the inside is covered by the mucosa of the tympanic cavity. The eardrum is like the diaphragm of a speaker. The eardrum is normally silver gray, shiny.

Between the two epithelial layers is a circular and radially running collagen fiber skeleton. The eardrum is inclined in both the craniocaudal and antero-posterior directions, making an angle of 55° with the plane of the external auditory canal. The handle of the malleus is attached to its inner surface. On the eardrum, the handle of the malleus in the form of a white stripe causes a slight protrusion on the outer surface: stria mallearis. The upper, triangular part is weaker, translucent, the inner connective tissue layer is missing, while the others are denser parts. The two parts are separated by oblique wrinkles.

The eardrum can be divided into four quadrants: anterior-lower, anterior-upper, posterior-lower, and posterior-upper quadrants. The so-called light cone reflex can be seen on the anterior-lower quadrant, behind which the promontory is located in the tympanic cavity. This area is the usual site of paracentesis. Behind the anterior-upper quadrant is the opening of the Eustachian tube. Behind the posterior-bottom quadrant we find the round window. Behind the posterior-upper quadrant is the chorda tympani.

The eardrum is a two-dimensional surface and here its wave propagation can be characterized using Bessel functions. Bessel functions are particularly important for solving wave propagation problems and for static potential problems.

The Bessel differential equation is:

$$x^2 \frac{\partial^2 y}{\partial^2 x} + x \frac{\partial y}{\partial x} + \left(x^2 - a^2\right) y = 0$$

; where: a – integer 0, 1, 2.

7. THE MIDDLE EAR

The middle ear consists of the tympanic cavity. It is a cavity in the shape of a prism inside the pyramid. Six of its walls are usually described: Paries jugularis. The lower wall separates it from the fossa jugularis visible from the outside at the base of the pyramid. Paries tegmentalis. The upper wall is formed by the tegmen tympani of the temporal bone. It borders the cranial cavity. Paries caroticus. The anterior wall is behind the canalis caroticus. Paries mastoideus. The posterior wall faces the processus mastoideus. There is a larger opening in it that leads to the cavity system of the processus mastoideus. In addition, a small, conical protrusion (erninentia pyramidalis) is visible, through which the tendon of a small muscle (musculus stapedius) appears. The outer wall (aries membranaceus) is mostly made up of the eardrum. The inner wall (paries labyrinthicus) separates it from the inner ear. There are two small openings on it: the upper oval window, the lower circular window. The former fits the base of the stapes, while the latter is closed by a connective tissue membrane, the membrana tympani secundaria.

At the corners of the anterior and inner walls, a bony canal runs towards the top of the pyramid: the canalis musculotubarius. The canal is divided by a thin bone plate into an upper smaller and a lower larger part. There is small muscle in the upper half of the canal, while the lower, larger passage is the initial, bony section of the Eustache tube.

In the middle ear there is an air column of length d between the eardrum and the circular window, which is an integer (n) multiple of the half-wavelength ($\lambda/2$) of the standing wave formed here. Frequency of vibrations (ν_n) in the air column of the middle ear.

$$\upsilon_n = n \cdot \frac{c}{2d}$$

where c – speed of sound wave propagation in the air. The significance of the air column in the middle ear is minimal, because it is mainly the auditory ossicles that play a role in this.

8. AUDITORY OSSICLES

There are three tiny bones in the tympanic cavity between the eardrum and the oval opening.

a) Malleus 6–8 mm. The head (capitulum), the neck (collum) and projections can be distinguished on it. The strongest of the latter is the handle (manubrium), which has merged with the eardrum, causing stria mallearis on it.

b) Incus 7 mm. A body and two protruding crura can be separated on it. The body forms a joint with the head of the malleus. Its short crus points backwards, its long crus runs parallel to the handle of the malleus, behind this formula. The lower part widens (processus lenticularis) and forms a joint with the head of the stapes.

c) Stapes 3x3 mm^2. On the third auditory bone, a head (capitulum), two crura and a base (basis) are distinguished. The head fits into the lenticular process of the incus and the base fits into the oval window.

The auditory bones are connected through joints to each other. The handle of the malleus has grown together with the eardrum, and the base of the stapes is secured to the oval window by a circular strip. In this way, the bones connect the eardrum to the inner ear. The vibrations of the eardrum are taken over and transmitted to the inner ear. If the eardrum moves as a result of the vibration of the sound waves, the base of the stapes will be pressed or retracted into the fenestra oval. [22]

The muscles of the tympanic cavity. In the tympanic cavity we find two fine little striated muscles. The stapes muscle (m. stapedius) is a 6.3 mm long muscle that originates from the pyramidal process of the tympanic cavity and adheres to the neck of the stapes. It is innervated by the facial nerve. It pulls the stapes out and back. The tensor tympani is a 25 mm long muscle that originates in the musculotubarius canal and adheres to the root of the malleus handle after a break of nearly 90°. Its nerve is the branch of the trigeminal nerve. It pulls the malleus up and inwards. The two muscles contract together, making the auditory bone chain tighter. The function of said muscles reduces sound transmission, so they have a protective effect, but they also have a tuning role, as their increased contraction ensures that the ear adapts to high tones, and their relaxation ensures that the eardrum adapts to deep tones.

The muscles of the tympanic cavity as well as the ligament systems of the auditory ossicles hold the auditory ossicles in a special position.

It is true that the pressure of the fluid system of the inner ear increases with the increased tone of the muscles, but this phenomenon has no significant effect on the sound transmission.

Another specific formula of the tympanic cavity is the Eustache tube (tuba auditiva), the narrow channel that connects the tympanic cavity to the pharynx. A bony and cartilaginous section can be distinguished on it.

9. BIOPHYSICAL MODELING OF THE SOUND CONDUCTION OF THE AUDITORY OSSICLES

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.

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 auditory ossicles can be considered as rigid bars and thus the sound waves propagate in a longitudinal form. In this case, the wave equation

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

The phase velocity c for longitudinal waves in a solid medium is given by the following formula:

$$c = \sqrt{\frac{E}{\rho} \cdot \frac{1}{(3-6)\mu}}$$

where: E - modulus of elasticity, ρ - density, μ - Poisson's ratio.

With their reflex contraction, the m. stapedius and m .tensor tympani stiffen the auditory bone chain (70–80 dB sound above the hearing range) and reduce the amplitude of the system vibrations (~ 10 s delay) - the reflex mainly reduces the transmission of deep sounds – n. facial paresis – causes hyperacusis.

The stapes base moves around two axes:

for weaker sounds - rotates around its transverse axis (Fig. 3.a.);

Figure. 3.a.

– in case of a strong sound - it moves around its longitudinal axis, then the amplitude of vibration is smaller (Fig. 3.b).

Figure. 3.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.

10. THE STRUCTURE OF THE INNER EAR

The inner ear, just like the middle ear, is hidden in the temporal bone. 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*),

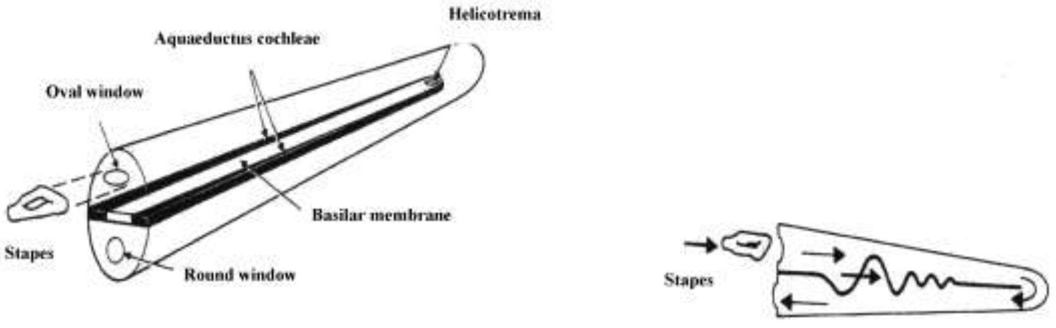
b) membranous labyrinth (*labyrinthus membranaceus*).

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.



(a) (b)

Figure 4. *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.*

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.

Georg von Békésy also determined this progressive wave experimentally (Figure 5.). The relative amplitude of the displacement of the basilar membrane serves as a function of the distance from the stapes for many different frequencies.)

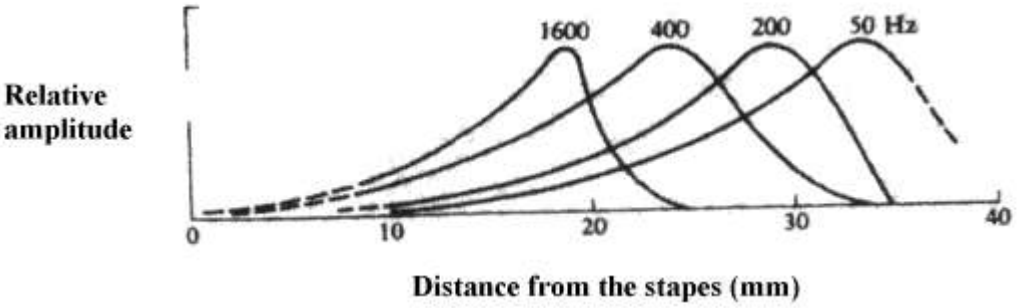


Figure5: The relative amplitude of the displacement of the basilar membrane serves as a function of the distance from the stapes for many different frequencies.

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.

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.

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.

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. Low frequencies produce the waves with the largest amplitude where the membrane is loose at the distal end. 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.

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. (Fig.6.) 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.

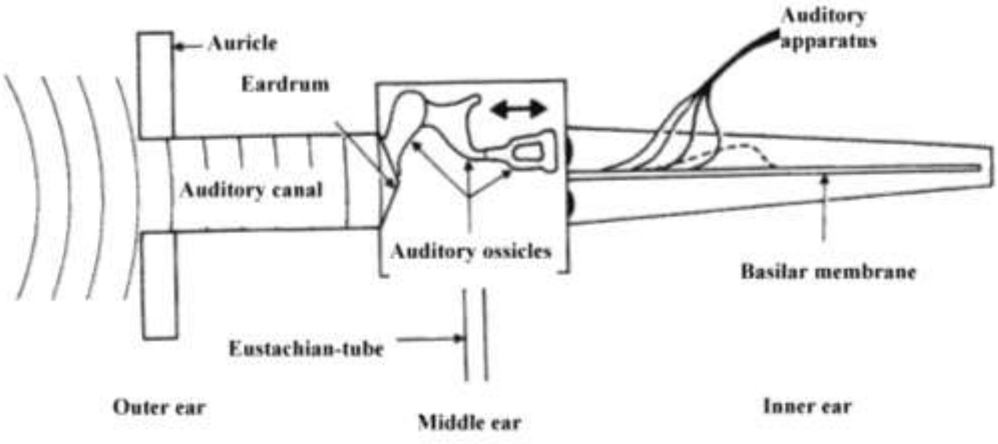


Figure6. A schematic representation of the ear that illustrates the entire hearing mechanism.

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. 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.

12. 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.

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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