SIMULATION MODELING OF AUDITORY FUNCTION

Ass. Prof., Dr. Eng. Donii O.[1], Dr. Med. Pisanko V.[2], Ass. Prof., Dr. Eng. Kulinich A.[1], Ass. Kotliar S.[1]
National Technical University of Ukraine "Kyiv Polytechnic Institute named after Igor Sikorsky" - Kyiv, Ukraine[1]
SI"O.S.Kolomiychenko Institute of Otolaryngology Of National Academy of Medical Science of Ukraine - Kyiv, Ukraine[2]
Email: dosha@iff.kpi.ua

Abstract: The hypothese concerning encoding of information in the peripheral part of the human's auricular analyzer are presented. A brief critical analysis of contemporary trends in theoretical concepts concerning principles of work of the cochlea of the inner ear are conducted . Prerequisites for the construction of an alternative theory of coding of information in it are formulated in order to optimize the design and software of cochlear implants. The principle of constructing an imitation model of the generation of electric signals formed in the cochlea of the inner ear are proposed.
KEYWORDS: *COCHLEAR, INNER EAR, BASILAR MEMBRANE, HEARING, SIMULATION MODELING*

1. Introduction

Hearing plays an important role in the development of speech, intelligence and formation of the human's psyche. The information which is received through hearing, is not less important than the information which is perceived by sight. Loss of functions of hearing by a human largely limits his/her communication and leads to serious psychological and moral problems. Therefore, the task of full or partial, but socially adequate, recovery of hearing is an urgent one. To solve this problem hearing aids, as well as cochlear implants, are used in modern medicine. The task of hearing aids is simple and consists in shaping the frequency response of the amplifier to compensate for a decrease in the sensitivity of the patient's auditory system in a certain range of frequency. Implants of cochlea are constructed on the principle of separating the audio signal into several signals in separate frequency bands, followed by further direct electrical stimulation of the auditory nerve by each of them. They are used in case of violation of the peripheral part of the auditory analyzer, more specifically - of the patient's inner ear. Nowadays medicine has made significant progress in the use of cochlear implantation. Surgical techniques of their implantation are well established. However, there are certain difficulties related, mainly, with the perception of signals from the implant. These difficulties are caused by principles of implants' work, which are based on a fairly rough analysis of the audio signal's spectrum and selection of several frequency channels, each of which excites a certain portion of the auditory nerve. This ideology of the cochlear implantation is based on the current understanding of work of the peripheral part of the auditory analyzer, which is based on theory of Békésy [1], concerning the running wave on the basilar membrane (BM), and on "frequency-place" principle. There is enough experimental data that can be interpreted as a confirmation of this theory. However, there are also experimental data which contradict it [2]. One can say that today there is no consistent view on the functioning of the cochlea of the inner ear and representation of the audio signal in the structures, which stimulate the auditory nerve. Therefore, in this paper, a brief critical analysis of contemporary trends in the theoretical concepts of the peripheral part of the auditory analyzer is given and prerequisites are formulated for the construction of an alternative hypothesis on the coding of information in auditory analyzer . Creation of the experimentally proved theory on the basis of this hypothesis will provide an opportunity for further critical rethinking of principles of the cochlear implants' design in order to improve the adaptation of patients with deafness caused by damage of the inner ear's cochlea.

2. Preconditions for resolving the problem

One of the known effects, inexplicable from the standpoint of the theory of "frequency-place" is the binaural effect. Evaluation of the time difference of arrival of the same wave's phases to both ears may occur, evidently, only in the brain centers, that means that the periodic nature of the sound process should somehow appear in the neural processes of the cortex. Meanwhile, the theory of "frequency-place", as the theory of "peripheral analyzer" refers assessment of sound solely to the excitation of nerves in the given area of the cochlea. This leads to the emergence of new theories of hearing. One of such theories is the theory of G. Fletcher [3]. According to this theory,it is not individual strings of basic membrane respond to the audio waves, but peri - and endolymph of the cochlea do this. Plate of the stapes transmits sound vibrations of the cochlea's fluid to the BM, at that the maximum of amplitude of these oscillations at higher tones lies closer to the base of the cochlea, at lower ones - closer to its top. Nerve fibers which end in the main membrane, including the organ of Corti (according to some authors) resonate only at frequencies above 60 - 80 Hz. There are no fibers, which receive more lower frequency on the main membrane. Nevertheless, feeling of heights up to 20 Hz is formed in the brain. It appeares like the combination of high tone harmonies. Thus, from the Fletcher hypothesis's viewpoint, perception of the low tones' pitch is explained by perception of the whole complex of harmonic overtones, and not only by perception of the frequency of the main tone, as it was usually taken so far. And as content of overtones to a large extent is dependent on the intensity of the sound, then it becomes clear a close relationship between the three subjective qualities of the sound - its height, volume and timbre. All these elements, each of them individually, are dependent on the frequency, strength and composition of the sound's overtones. According to the Fletcher's hypothesis, resonant properties are inherent to the mechanical system of the cochlea as a whole, not just to the main membrane's fibers. Under the influence of a certain pitch, not only fibers, which resonate with this frequency, oscillate, but the entire membrane as well, and also this or that amount of fluids in cochlea. High tones force to drive only a small mass of liquid near the base of the cochlea, low ones - are fixed closer to helicotrema. Fletcher also overcomes the main difficulty of the resonance theory associated with explanation of a large range of volume. He believes that the volume is determined by the total number of nerve impulses, coming to the brain from all the excited nerve fibers of the basal membrane. Fletcher's theory, in general, does not deny existence of "frequency-place" theory and it can be attributed to the theories of "peripheral analyzer".

Theories of "central analyzer" or so-called "telephone theory", form another group of theories [4]. According to these theories, audio vibrations are converted by cochlea into synchronous waves in the nerve and transmitted to the brain, where their analysis and perception of level of tone takes place. J. Ewald's theory, which was proposed in the late of 19th century, also belongs to this group of theories. According to this theory, under effect of the sound, standing waves are formed in the cochlea with a length which is determined by the frequency of the sound. The level of the tone is determined by the perception of the shape of the pattern of the standing waves. The feeling of a certain tone corresponds to the excitation of one part of the nerve fibers, and the feeling of a different tone corresponds to the excitation of an another part. Analysis of sound is performed not in the cochlea but in the central areas of the cortex. Ewald succeded to build a model of BM, with the size which approximately corresponded to the real ones. In his experiments the entire membrane began to vibrate when it was excited by the sound. The "audio picture" appeares in the form of standing waves with the length, which is as smaller, as the sound is higher. Despite the successful explanation of some embarrassing particulars, Ewald's theory (as well as other theories of "the central analyzer") hardly corresponds to the latest physiological researches of the nerve impulses' nature. In the [3] the dual point of view is expressed, namely, the explanation of the perception of high tones is given in the sense of "peripheral analyzer" and of low ones - from the perspective of "the central analyzer.

American researchers, who first-ever implanted microelectrodes in cat's cochlea, registered electrical potentials which arised in the cochlea [5]. Based on their observations, they created an electrophysiological theory of hearing. According to this theory, every hair of hair cells of organ of Corti is similar to the piezoelectric crystal. As it is known, these crystals have an interesting property - upright they are neutral, but when they are bent even a little bit then electric charge appears immediately. In case of fluctuations of BM, hair cells, naturally, begin to oscillate also. But the tectorial membrane pushes on top of the hair, they bend, causing an electrical charge. Thus, under the influence of the deformation of receptor cells' hairs in sync with the sound's vibrations, the electrical energy is released, and biological currents appear. These biological currents stimulate the thinnest endings of branches of auditory nerve, which criss-crosses the hair cells. Through this nerve and conductive pathways of medulla oblongata excitation is transferred to the cortex of the temporal lobes of the brain, where the analysis and synthesis of audio stimuli takes place.

Thus, at the moment it is common to speak about the duality of the mechanisms of perception of the pitch: in the high-frequency range the most acceptable is the principle of "place", in the area of lower frequencies - a modified principle of "bursts". Despite the long history of the discussions on the principles of the functioning of the auditory system as a whole and its peripheral parts in particular, and the availability of a huge number of researches related to the study of the perception of pitch, it is obvious that the mechanism of coding the information in the peripheral part of the auditory analyzer is not completely elucidated and requires further intensive research.

3. Formulation of a hypothesis for model development

From the perspective of physics, dynamic range of 125 dB is a unique parameter of the human auditory system. Thus, the maximum amplitude of the audio signal at the system's input (eardrum) differs from the minimal amplitude in trillion times. Such value of the dynamic's range leads to suggestion that there is not only one, but several mechanisms of perception of the sound in the peripheral part of the auditory analyzer, which is consistent with the views of a number of scientists. For example, it is known [6], that the subcutaneous plate of stirrup at high intensity of the input's signal, close to the maximum intensity, moves from the translational vibrations to the vibrational-rotational ones, thus preventing the entire system of middle and inner ear from the mechanical damage. Then this is logical to assume the existence of several reactions to sounds, which are differrent not only by frequency, but also by intensity. Thus, it is interesting to compare processes of formation of auditory images in the cochlea of the inner ear at maximum and minimum levels of input signals.

Taking into account the assumption that there are several mechanisms of the inner ear's functioning while converting sounds of different intensity into the electrical activity of the auditory nerve, let us consider the mechanical processes in the cochlea when it is exposed to weak (low intensity) beeps.

As it was mentioned above, Békésy G. substantiated hypothesis, called the "theory of running waves", which states that the vibrations are distributed through BM in the form of running waves having a maximum of the envelope at a certain point of membrane, whose place varies depending on frequency of the acting signal . A number of authors who used different methods for registration of membrane's oscillations, experimentally confirmed the basic provisions of G. Békésy's hypothesis [7 - 10]. However, direct observations of BM's vibrations, executed by G. Békésy, were carried out at a power of the sound of 90 - 120 dB. Using an extrapolation of the existing experimental data it is possible to calculate that the amplitude of BM's movement in the place of the running wave's envelope's maximum is about 10^{-12} sm [1, 7]. This value is much smaller than the amplitude of the thermal motion of the molecules of cochlea fluids. Furthermore, in order to have any fluctuations of BM, the pressure of sound's signal must overcome cochlea's elasticity and its inertia of rest. And, obviously, because of its stiffness, it will not respond to such a small amount of energy. So, it can be postulated that BM is stationary at low intensities of the sound's signal. And this gives a basis to suppose the absence of influence of BM's mechanics on the analysis of the sound's information at small acoustic signals. At the same time, the presence of a running wave can say about ability of the cochlea's structures to absorb the excess of energy at high levels of the sound.

This assumption, as well as high sensitivity of acoustic analyzer, give reasons to look for other mechanisms of perception of the sound in the cochlea, especially at low levels of intensity of acoustic signals. In a number of works [8, 9], where the amplitude-frequency characteristics of the BM's vibrations were investigated, it turned out that they are less selective than it was expected based on the values of differential threshold of frequency. This allowed to suppose the presence of so-called "the second filter", which is located, according to the researchers' viewpoint, at the junction of the tectorial membrane - wax cells of the organ of Corti or hair cells - the fibers of the auditory nerve Ψ [11 - 13], although such a filter was not detected experimentally [11]. Also in the work [14] the hypothesis is suggested concerning the existence of molecular resonance mechanism, which is localized in the tectorial membrane. Due to different speeds of sound's movement in the perilymph and in the tectorial membrane, concentration of the acoustic energy takes place in the latter, resulting in the conversion of mechanical energy into biochemical one through resonance and movement of ions, which cover complex of the tectorial membrane - the hair cells of organ of Corti. There is a hypothesis, according to which the flanking sprouts of Deiters cells and cuticular region of the hair cell form a pair, called "Auron" by the authors, that makes primary frequency analysis of sounds using resonant oscillations (hypothesis of "auron resonance"). A number of authors [4, 15] express the opinion that the frequency analysis in the cochlea is carried out by means of resonant vibrations of the hair cells and the tectorial membrane. These assumptions are confirmed by correlation between the lengths of hair cells' stereocilia and characteristic frequencies [4, 15]. Thus, modern researches have led to the need for a thorough study of the "thin" structures of the organ of Corti.

Imagine the possible mechanism of the cochlea's mechanical part under the influence of weak acoustic signals (0-20 dB above threshold). In this case, taking into account the above mentioned extrapolation, let us assume that BM is immovable. If we are adhere to the concept of a mechanical nature of transformation of sound's vibrations into receptors' potentials of the hair cells, it is necessary to find in the structure of the organ of Corti those oscillating elements, that have to "feel" the impact of such a small incentive. To do this, we consider a schematic cross-sectional view of the organ of Corti in a single turn of the cochlea (Figure 1). The figure shows that the hair cells are connected with the tectorial membrane (this is confirmed experimentally by [1]), and the latter, in turn, is fixed in such a way that it can form a very sensitive lever system in vertical direction regarding to the BM's plane. The schematic connection of the covering membrane with hair cells is shown in Figure 2, at that it is assumed that the hair cells have their own elasticity (coefficients K_j). When the mechanical structure of the cochlea's membrane was studied, it was found that the tectorial membrane really moved easily in the direction which is perpendicular regarding to BM [1].

In the experiments described in the works of [16], it is shown that the stereocilia of hair cells are rather hard. It can be assumed that they alone or in a bundle together with the mass of the coating membrane form sensitive, and perhaps the resonance system. In the [4, 15], for example, the possibility of resonance in such a system is shown. This is confirmed also by the structure of the coating membrane: it consists of thin transverse fibers, which generally have a radial direction along the axis of the cochlea, and there is a transparent gluing substance between the the fibers [17]. Reissner's membrane is a very thin film of the same elasticity over the entire length. At that, its elasticity is small in comparison with the elasticity of BM, through which transmission of oscillations passes freely. Its role is to separate endo- and perilymph and it seems, that id does not participate in the analysis of vibrations.

Based on the above mentioned facts, one can imagine a process of the membranes' vibrations in the cochlea un terms of action of acoustic signals with low levels of sound's pressure as follows: sound's pressure is transferred to a tectorial membrane through the perilymph, endolymph and Reissner membrane. Because of its structure, tectorial membrane responds to minimum pressure by substantial displacement in a plane, which is perpendicular to the BM, as compared with the displacement of MB (or its absence) at the samelevels of input signals. The mass of the tectorial membrane and elasticity of the hair cells can form the sensitive system, which reacts to this movement. Moreover, taking into account the structure of the tectorial membrane, it can be assumed, that together with the hair cells, it forms the whole system of sensitive elements , which, in principle, can work as unbound tuned resonators. Taking into account calculations contained in [4, 15], their amplitude and frequency characteristics will be sharper than the same specifications for MB. BM in this case remains stationary and does not participate in the analysis of signals with such levels. It is obvious, that while increasing the sound's level, starting from some particular magnitude of the acoustic signal, vibrations of the BM become relevant and can not be ignored anymore. In this case the nature of excitation of hair cells, which determines the information transmitted by the auditory nerve, is to be altered.

This situation can be considered in more details. Under the influence of a weak signal BM is stationary. Sound's pressure, according to the laws of physics, is transmitted through the perilymph in all directions. At that, if the forward movement of the stapes is very slow (very low frequency), a column of liquid should overflow from channel to channel through helicotrema without creating significant pressure on the side walls. In this case, hair cells do not respond to the signal. By increasing the speed of movement of the stapes (increasing the frequency of the signal) perilymph does not have time to go through an opening with a limited area (gelikotrema) and the radial component of pressure arises, which affects the complex " tectorial membrane - hair cells", generating an electric signal (it is possible that the area of helicotrema defines the lower boundary of perception of the signal). This pressure should be distributed over the entire length of the channel, that corresponds to the assumptions of the "telephone theory"

Thus, when the input signal has low intensity, the dotted excitation response of hair cells is possible. However, considering the fact, that pressure in liquid circulates in all directions simultaneously, and that the helicotrema restricts the flow of the perilymph from channel to channel, one may assume the simultaneous stimulation of hair cells in the area of a certain length.

The increase in signal intensity leads to the excitation of BM's vibrations and the appearance of a running wave on it. A running wave should lead to the displacement of structures of organ of Corti and irritation of hair cells throughout its whole length, not just at the point of its maximum amplitude. So, it is possible to propose a hypothesis about the formation of a some spatio-temporal pattern, which represents the excitation of the auditory nerve. At that, taking into account the form of envelope of a running wave, the excitation should reflect the reaction of hair cells in three spatial coordinates, as well as changes in the spatial "images" in time. Thus the spatial-temporal signal, having four coordinates: length, width, depth and time, is formed. Obviously, in such way principle of "frequency-place" and elements of the telephone theory are combined.

Considering the mechanisms of forming the excitation in the cochlea of the auditory analyzer, the question must arise about the nature of the signal applied to the input of the system in experimental studies. Usually it is a pure tone, which represents a sine wave with a certain amplitude and frequency. It is believed that the "frequency-place" principle works in this case. When the composite signal is supplied, then since the Helmholtz times in most studies it is suggested that the ear analyzes in this or that way its spectrum, represented as a set of sinusoids. However, representation of the composite signal as a set of sine and cosine, which is widely used in electronics and acoustics, is a comfortable way, but not the only one. For example, according to the approximation theorem of Weierstrass any complex function can be approximately described by a polynomial of degree n, i.e. as a sum of exponential functions with different coefficients of [18]. And taking into account the fact that in the natural environment you can hardly meet pure tones, the natural response of the auditory system is the analysis of complex sounds. It is doubtful the possibility of the membrane of the cochlea of the inner ear to decompose non-periodic audio signal in Fourier series. Thus, it is not necessarily that the inner ear works as a spectrum analyzer, allocating and fixing the harmonic components of the audio signal. Hence the assumption arises (which supports the expressed above hypothesis) that the audio signal is not decomposed in the inner ear into components, but is perceived as a whole. Of course, the principle of "frequency-place" can not be denied, as it was confirmed experimentally. However, its confirmation was received when exposed to high intensity signals.

4. Computer model of signal formation in the cochlea

These assumptions should be confirmed by experimental verification. At the same time, it should be noted that the experimental study of structures (and particularly of "thin" structures) of the inner ear's cochlea in real objects are very labour-consuming and not very informative, even when using modern technology and equipment. Therefore simulation is one of the main methods of investigation of the inner ear. Unfortunately, among a large number and variety of existing models of cochlea, there are just a few of them which take into account not only the behavior of the BM, but also of other membranes, but even at that case they are used only with the aim to clarify its vibrational characteristics.

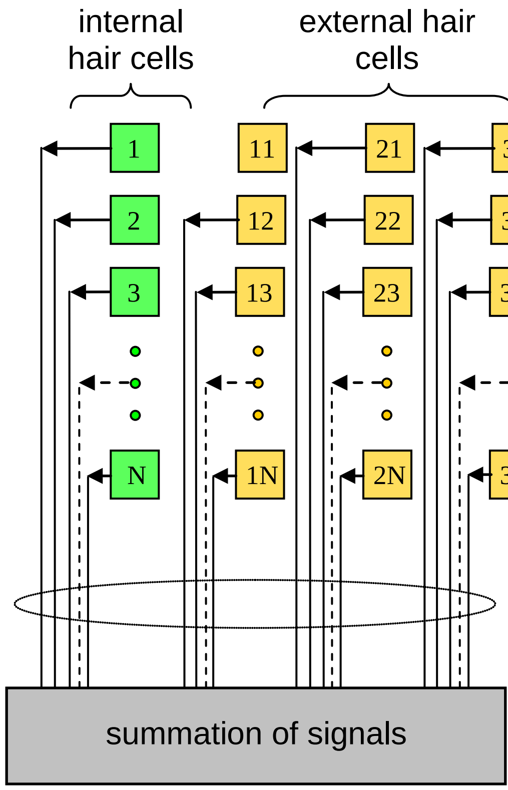

Fig. 1. *Structure of the imitation model of the inner ear function*

Taking into account complexity of the structure of the inner ear's cochlea, simulation modeling is conveniently chosen as a method of constructing of the model, since this technique was developed for studying of complex systems. Organization of hydromechanical part of the cochlea is complex, not linear and poorly researched. However, its response to the sound signal causes the excitation of hair cells, both internal and external. This excitation forms a common electrical signal, which is transmitted to the upper parts of

the brain along the auditory nerve. Based on the proposed hypothesis of the formation of some spatio-temporal pattern of oscillations in the cochlea, it is possible to model different variants of hair cells' excitation, and, accordingly, of their reaction as an aggregated electrical signal. This electrical signal can be registered in a real experiment. Comparing signals which were simulated by the model with the experimentally recorded ones, one can select the most similar ones and thereby make a conclusion about the real mechanisms of the inner ear's functioning. A simplified diagram of the model of the formation of an electrical signal of the hair cells' reaction to an external signal is shown in Fig. 1. Inner and outer hair cells are denoted by multicolored squares. In this variant, each cell (which can be regarded as a sensor) generates a single pulse regardless of the parameters of the input signal. All pulses which were generated at a given moment of time are summed in the summation block. Thus, a signal is generated, which is similar to that one, which can be registered in a real experiment.
The fragment of output results of modeling of hair cells' excitation under influence of the input signal which was generated by means

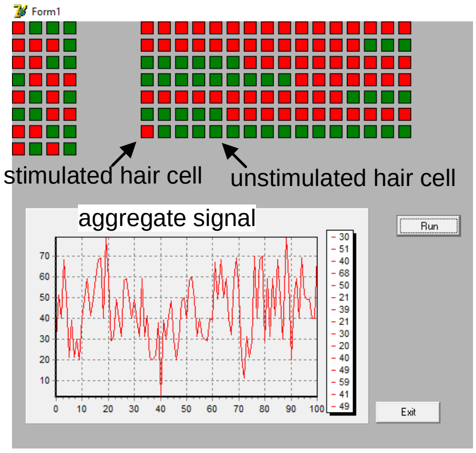

Fig. 2. *The computer simulation result of the formation of an electrical signal at the "exit" of the cochlea of the inner ear*

of the generator of random numbers is presented in Fig. 2. As it can be seen from Fig. 2, the resulting signal is similar to the microphone potential which was measured in a real experiment. Thus, one can see the prospects of developing of this approach for modeling of the auditory function. One can draw a conclusion about the principles of coding of information in the peripheral part of the human auditory system by analyzing the mechanisms of functioning of the inner ear's cochlea from the point of view of existing theories and developing models of signals that stimulate hair cells and comparing the results of modeling with the results of the experiment. Moreover, it seems expedient to select tests of subjective and objective researches of hearing, on the basis of which it is possible to create an adequate model of inner ear's functioning both in conditions of norm and pathology. This will deepen our knowledge of coding of auditory information and optimize design and software of cochlear implants on their basis. In case of confirmation of mechanisms of the inner ear's functioning in framework of the above mentioned hypothesis, the design of cochlear implants must be based on other ideas about coding of signals in the peripheral part of the auditory analyzer other than decomposition of the input signal into several frequency ranges.

5. Conclusion

1. The hypothesis of stimulation of hair cells of the inner ear's cochlea is proposed, in which the formation of a spatio-temporal picture of excitation as a reaction to an external sound signal is suggested. This hypothesis makes it possible to explain the sensitivity of the auditory analyzer at low intensities of input signal and, on the whole, does not contradict to the existing ideas about mechanisms of hearing's perception.
2. An imitation model of formation of an electrical signal of the hair cells' reaction to an external signal is proposed, in which each cell generates a pulse and all pulses are summed in the summation block. In this way the electric reaction of a cochlea is simulated, which is similar to that one, which can be recorded in a real experiment.
3. It seems appropriate to conduct tests of subjective and objective researches of hearing for the analysis of modeling results on the basis of which the adequacy of the proposed hypothesis of functioning of the inner ear can be confirmed in conditions of norm and pathology. This will allow to deep knowledge about coding of auditory information and optimize on this basis design and software of cochlear implants.

6. Literature

1. Bekesy G. Experiments in Hearing. N.Y., McGraw-Hill, 1960.
2. Rubinshtein S.L. Foundations of General Psychology, St. Petersburg, Peter, 2002. (Russion)
3. Fletcher H. On the dynamics of the cochlea. - J. Acoust. Soc. Amer., 1951, v. 23., p. 637 - 645.
4. Zwislocki, J.J. Theory of cochlear mechanics. Hear. Res., 2, 1980, P. 171 - 182.
5. Kiang N.Y-S., Watanabe T., Thomas E.C., Clark L.F. Discharge patterns of the single fibers in the cat's auditory nerve. Cambridge, Massachusetts. 1965.
6. Gelfand S.A. Hearing: An Introduction to Psychological and Physiological Acoustics, Marsel Dekker, INC, New York and Basel, 1981.
7. Johnstone B.M., Taylor K.J., Boyle A.J. Mechanics of the guinea-pig cochlea. J. Acoust. Soc. Amer., 47, 1970, p. 504 - 509.
8. Johnstone B.M., Yates G.K. Basilar membrane tuning curves in the guinea pig. J. Acoust. Soc. Amer., 55, 1974, p. 584 - 587.
9. Kohllöffel L.U.E. Observations of the mechanical disturbances along the basilar membrane with laser illumination. In: Basic mechanisms in hearing. New York; London, 1973, p. 95 - 117.
10. Rhode W.S. Some observations on cochlear mechanics. J. Acoust. Soc. Amer., 64, 1978, p. 158 - 176.
11. Labutin V.K., Molchanov A.P. Models of the mechanisms of hearing. M., 1973. (Russion)
12. Duifhuis D. Cochlear linearity and second filter: Possible mechanisms and applications. J. Acoust. Soc. Amer., 59, 1976, p. 356 - 358.
13. Hall J.L. Spatial differentiation as an auditory "second filter": assesment on a nonlinear model of the basilar membrane. J. Acoust. Soc. Amer., 61, 1977, p. 520 - 524.
14. Naftalin L., Path F.R.C. The Peripheral Hearing Mechanism: A Biochemical and Biological Approach. Annals of Otology, Rhinology & Laryngology, v. 85, №1, 1976, p. 38 - 42.
15. Zwislocki, J.J. Five decades of research on cochlear mechanics. J. Acoust. Soc. Amer., 67, 1980, p. 1679 -1685.
16. Flock A. Physiological properties of sensory hairs in the ear/ In: Psyhophysics and physiology of hearing. London, 1977.
17. Vinnikov Y.A., Titova L.K. Corti's organ. Histophysiology and histochemistry. M.-L., 1961. (Russion)
18. Fikhtengolts G.M. Course of differential and integral calculus. FIZMATLIT, v. 3, 2001. (Russion)