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Characteristics of Hearing in Elderly People

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Abstract

The authors define the term presbycusis and discuss the prevalence of hearing loss in elderly people, its etiology, and methods of diagnostics (anamnesis, evaluation of the peripheral and central parts of the hearing system). The authors emphasize that central auditory processing disorder (CAPD) significantly impairs speech perception in elderly people and makes difficult the rehabilitation of patients with presbycusis. The possibility of improving speech intelligibility by using auditory training is considered. Improved functioning of the central auditory pathways in hearing aid (HA) users with moderate to moderately severe chronic sensorineural hearing loss (SNHL) and symptoms of CAPD was shown after the auditory training with the use of two approaches (“bottom-up” and “top-down”). The algorithm of the auditory training was designed based on distinction between nonverbal and verbal stimuli of varying complexity, as well as tasks to improve memory (e.g., memorizing poetry). The benefits of the auditory training in the rehabilitation of HA users with low speech intelligibility were demonstrated. Improvement of speech intelligibility in elderly patients with SNHL proves that plasticity of the auditory regions of the brain remains possible throughout the life. Options of the presbycusis prophylaxis are summarized.

Keywords: presbycusis, central auditory processing disorder (CAPD), diagnosis, hearing aids, rehabilitation

1. Introduction

Presbycusis is a range of hearing disorders caused by an aging process (from Greek presbus “aged” and akousis “hearing”). It is one of the most common conditions affecting older and elderly adults. Zwaardemaker was the first who has used the term “presbycusis” in 1893.

Different authors sometimes interpret this term differently. Some researchers meant (imply under this term) age-related hearing disorders caused by involuntional changes only in the cochlea, and others meant that changes involve all parts of the auditory system [1, 2]. Presbycusis is considered to be one of the forms of progressive SNHL, which is associated with age-related involuntional changes of different parts of the hearing system and is presented by symmetric pure tone audiogram with flat loss toward high-frequency range (less steep than 20 dB/oct) [3]. Numerous studies are dedicated to anatomical and functional risk factors of the presbycusis [4–9]. The significance of the presbycusis problem is determined by its social importance, lack of data about its etiology, and need for clinical practice to accurately determine an impaired area of auditory system and to identify the presbycusis genesis.

2. Prevalence

Presbycusis is a rather common disorder. According to the World Health Organization (WHO), more than 5% of global population (about 328 millions of adults) suffers from any degree of hearing loss, while among people older than 65 years of age, the prevalence of hearing loss exceeds 30% [10].

Its prevalence increases every year that may be due to the general trend of increased life duration—much more adults reach aged (from 60 to 74 years old according to the WHO classification) and senile (75 years old and more) periods. The world population is rapidly aging. At the period between 2000 and 2050, the proportion of the world's population over 60 years will double from about 11 to 22%. The absolute number of people aged 60 years and over is expected to increase from 605 million to 2 billion over the same period. The number of people aged 80 years or older will have almost quadrupled between 2000 and 2050 to 395 million [11]. Approximately one in three people in the United States between the age of 65 and 74 has hearing loss, and nearly half of those older than 75 have difficulties in hearing. Having trouble hearing can make it hard to understand and follow a doctor's advice, respond to warnings, and hear phones, doorbells, and smoke alarms. Hearing loss can also make it hard to enjoy talking with family and friends, leading to feelings of isolation.

3. Etiology

There are many causes of age-related hearing loss. Most commonly, it not only arises from changes in the inner ear as we age but can also result from changes in the middle ear, or from multiple changes that occur along the nerve pathways directed toward the brain from the inner ear. Associated medical conditions and some medications may also exert an influence. Many factors can contribute to hearing loss as you get older. It can be difficult to distinguish age-related hearing loss and hearing impairment caused by other reasons, for example, noise-induced hearing loss. Noise-induced hearing loss is caused by long-term exposure to sounds that are either too loud or last too long. This kind of noise exposure can damage the sensory hair cells of the inner ear and is responsible for hearing loss. Once these hair cells are damaged, they do not grow back, and the ability to hear is diminished.

Conditions that are more common in older people, such as high blood pressure or diabetes, can contribute to hearing loss. Medications that are toxic to the sensory cells in our ears (e.g., some chemotherapy drugs) can also cause hearing loss. Aged and senile persons have a lot of biological and social risk factors of hearing disorder development. According to some authors [3], age-related hearing loss results from biological aging process of tissue elements in the auditory system and prolonged noise exposure. SNHL is considered to be a polyetiological process with partly unidentified factors of pathogenesis. There are more than 100 causes of SNHL: infections, intoxications, acoustic trauma, genetic factors, unfounded use of aminoglycoside antibiotics, irrational treatment of acute and chronic middle ear disorders, autoimmune diseases, and so on.

Genetic determinacy of the presbycusis cannot be excluded, and diseases acquired throughout the lifetime, hemorheological changes, and other factors can trigger or exacerbate age-related hearing loss. It is difficult to define that whether or not presbycusis depends on genetic factors because other factors potentially contributing to a hearing loss development are closely associated with an aging process. Nevertheless, some epidemiological studies argue in favor of genetic influence on age-related hearing loss development, especially in the case of metabolic type of the presbycusis, according to Schuknecht [12], which is caused by the atrophy of the stria vascularis [13, 5]. Genetic factor in the presbycusis origin is acknowledged by many authors [3, 14, 15]. This fact is confirmed in our study as well. Hearing heredity is revealed to be presented more often in patients with presbycusis. Identification of genes, underlying this pathology, could be extremely helpful for many people in our aging society.

Numerous genes are responsible for functioning of the auditory system, and some of them can contribute to the presbycusis development and determine a degree and time of onset of age-related hearing loss. However, neither of them is known to be the gene responsible for the presbycusis [4, 5]. The gene of age-related hearing loss was identified in mice. This gene encodes cadherin 23 (Cdh23) and is supposed to predispose an early onset of age-related hearing loss in mice [16]. A mutation of a similar gene in human Cdh23 can incline a susceptibility to the presbycusis [17]. However, genes of monogenic deafness detected in mice are doubtfully to be the same in human.

The last gene that was considered to be a cause of the presbycusis development in human was revealed in wide genome study of age-related hearing loss, which was conducted in the House Ear Institute, Gonda Research Center for Cell and Molecular Biology, USA. Specialists from Los Angeles collaborated with Translational Genomics Research Institute and University of Antwerp (Belgium). Friedman et al. [18] studied 3434 twins aged between 53 and 67 years old—patients of eight medical centers from six European countries. After hearing assessment using routine methods, 846 pairs with one normal hearing and one hearing impaired brother or sister have been selected. Family genomes were marked by numerous genetic markers, and the comparative analysis was performed. Scientists looked for spots with different nucleotides in the same genes. And a number of such genes were revealed. After applying an excluding method, only one potential gene was left in result. It was the gene GRM7 (metabotropic glutamate receptor type 7), which takes a part in a glutamate metabolism—it encodes one of the receptors of this amino acid. Glutamate (or glutamic acid) is one of the most important excitatory neurotransmitters of the mammal's neural system. It is involved in the functioning

of different brain areas and provides neurotransmission. Studies performed on mice and humans showed that gene GRM7 is highly active in the hair cells and the spiral ganglion cells of the inner ear. The glutamate is very toxic in high concentration. Its overexciting results in neuron disruption. The excess amount of the glutamate is suspected to cause a hearing loss in twins as the study authors considered. Genetic analysis showed that after getting “protein casts” with certain variations in a gene GRM7 improperly operating glutamate receptor was obtained. It can result in the amino acid storage in the synaptic fissure and damage of the outer and the inner hair cells in the cochlea [18].

Of the genetic point of view, presbycusis is the complex pathology. In the case of monogenic disease, a simple mutation is enough to cause a clinical onset/presentation. This type of disease is easy to determine. Meanwhile, in the case of complex genetic disorder, the interaction between genetic and environmental factors is obligatory, and the only factor is not enough for disease manifestation. In the case of genetic predisposition, a degree of hearing loss and a duration of hearing impairment depend on the summary of ototoxic factors, environmental noise during lifetime, as well as acquired diseases, changes of the blood quills, and other factors contributing to hearing loss progression [19]. These studies are considered to define various factors that influence on the presbycusis development and to determine a degree of hearing disorder in aged and senile periods. They are still significant and must result in developing standards for prognosticating and preventing this pathology.

Thus, all abovementioned endo- and exogenous factors that are presented throughout the lifetime are considered to contribute to hearing disorder development in aged and senile periods. Nevertheless, hearing impairment does not occur in everyone and is affected by harmful factors.

The role of the atherosclerosis in the age-related hearing loss development has been studied since the middle of the last century. Does the severity of the atherosclerosis and the cochlear dysfunction correlate? Some authors confirm the presence of this correlation between these pathologies [20, 21]. A close interrelation between hearing loss and high serum cholesterol levels is shown in several studies, and the dependence of hearing function on some other atherogenic lipid levels in the blood is found. Inverse correlation of high significance between high-density lipoproteins (HDL) level of the peripheral blood and hearing acuity at the frequency of 4 kHz was revealed [22]. Morphological and functional damages of the cochlea and their correlations with hyperlipidemia, atherosclerosis, and endothelial dysfunction in mice are described in studies of Guo et al. [23].

Increased blood viscosity is known to influence a SNHL development. Hildesheimer et al. examined a group of 33 patients with SNHL with unknown cause; a high-blood viscosity was revealed in many of them, which was interpreted by the authors as a possible etiologic factor of SNHL [24]. Other authors also suggest that rheological properties of the blood and characteristics of the red blood cells can be considered to be a SNHL development risk factor in all patients [25].

In the majority of countries, women are registered to have longer lifespan than men that is explained by the biological distinguishing features of the female organism and differences of the atherosclerosis development process in people of different sex [26]. This mismatch has to be taken into account in the study of presbycusis problem. Efimova performed a complex

clinical and audiological examination of women of different ages: 28 elderly women with presbycusis (the main group) and 28 elderly women with normal hearing (the control group). The mean age of menopause onset was less in patients of the main group than in the control one by 3.2 ± 1.0 years, which argues in favor of the earlier aging of a whole organism including the auditory system in patients with presbycusis. The comparison of biochemical and clinical blood profiles of the main and control groups did not reveal any significant differences. The essential role of hyperlipidemia in the hearing loss progression was revealed by analysis of correlation between the lipid profile and hearing thresholds in the patients of the main group: the worse the lipid profile, the worse the hearing thresholds have been revealed [27].

Some authors mention that variable professions are not statistically associated with presbycusis [19]. However, Lopotko et al. noted that intellectuals in aged and senile periods have better hearing than people of the same age with diminished intellectual activity [3].

4. Diagnostics and clinical presentation of the presbycusis

In the middle of the last century, Schuknecht described four forms of the presbycusis: (1) sensory (caused by gradual degeneration of sensorineural elements of the inner ear); (2) neural (determined by the cell reduction in the spiral ganglion, auditory nerve fibers, and central auditory pathways); (3) metabolic (associated with atrophic changes in the stria vascularis); and (4) cochlear conductive or mechanical (associated with the process of the basal membrane thickening and loss of its elasticity). According to the author, all these forms manifest in increased tonal thresholds, and the neural one also manifests in the impaired speech intelligibility [12]. CAPD is shown to join the peripheral disorders with the aging process, so they also contribute to the presbycusis [28]. One of the keys of solving presbycusis problem is to define the proportion of peripheral and central disorders. Currently, potential role of disorders at all levels of the auditory system is taken into account, and it is realized as an integrated functional system and taken into consideration while understanding the age-related involutional hearing loss pathogenesis [29].

4.1. Asking about complaints and anamnesis

To diagnose an age-related hearing loss and to determine all risk factors of rapid hearing loss progression complete examination is necessary to begin with history taking (anamnesis), complex audiologic examination using instrumental methods in order to identify a level of a disorder, and finally, biochemical blood tests and general practitioner and neurologist consultations. All these examinations should be performed in the morning in kindly calm and comfortable conditions. The total duration of the audiological examination should not exceed 60 minutes to avoid the fatigue of a patient and loss of his attention.

While collecting a medical history, the absence of any reasons of hearing loss except of the age is noted. These patients do not have any serious somatic illnesses, middle ear pathology, professional noisy environment, or other determined reasons of the impaired hearing. Genetic factors and hearing loss duration should be taken into account while analyzing an

anamnesis. Patients with presbycusis commonly cannot determine exactly the onset time of hearing loss due to its gradual progression. The early periods of hearing impairment often remain unnoticed for a patient; meanwhile, in this period, we expect the maximal effectiveness of a therapy. That is why annual prophylactic audiologic examinations of people older than 60 years of age seem to be rational.

4.2. Evaluation of the peripheral part of the hearing system

The first step of audiological examination is the peripheral part of the auditory system functioning evaluation. Subjective examination (pure tone audiometry for auditory threshold assessment, speech audiometry, and psychoacoustic tests for recruitment identification) and objective examination (tympanometry and acoustic reflex testing) must be listed as the main methods.

Symmetric binaural pure tone audiogram with flat loss toward high frequencies is typical for patients with presbycusis. Finding out the patient's age, we are able to suggest a degree of hearing loss properly for "normal" age-related hearing loss. Commonly, hearing in women with physiologic presbycusis gradually impairs and reaches the borderline with the mild hearing loss toward 60 years old [3, 27]. The mild hearing loss was detected in 67.9% of women with presbycusis from 60 to 74 years old. The loudness recruitment phenomenon is usually presented in the case of peripheral forms of SNHL. It is the sign of damaged neuroepithelial structures of the cochlea, especially the outer hair cells. Recruitment results in exaggeration of sound perception. Even though there is only a small increase in the noise level, sound may seem to be much louder, can be distorted, and cause a severe discomfort. The measurement of an uncomfortable loudness level is one of the simplest and most informative methods to detect recruitment [30, 31].

Speech audiometry is an issue of high significance among subjective methods of aged people examination. In cases of peripheral SNHL, especially with steeply sloping audiograms or the recruitment presence, the intelligibility usually does not exceed 70–80%. If monaural intelligibility in patient with mild or moderate hearing loss is less than 50%, CAPD can be suspected. It is due to the fact that pathology of central auditory pathways is responsible for the conversion, encoding, processing, and recognizing the speech signals. CAPD leads to the appearance of additional distortions caused by impaired binaural interaction, threshold and loudness adaptation, temporal analysis, and so on. Significantly reduced intelligibility with comparatively good tonal thresholds is defined as of tonal and speech hearing dissociation (phonemic regression); age-related hearing loss often manifests this way [27, 28, 31, 32].

Impedancemetry has to be included into the list of obligatory objective methods using patient's examination. Tympanometry evaluates the middle ear condition. Age-related alterations can be observed in both the sound conductive and receptive parts of the auditory system. Sometimes the external auditory canal narrows in the isthmus area and collapses, and the epithelial migration decreases. The eardrum in aged people thickens and dims. Lipid deposits appear around the handle of the malleus and the fibrous tympanic ring. In some cases, the eardrum does not thicken but on the contrary atrophies. Age-related changes of the middle ear matter a lot and manifest in ankylosis of the joints of auditory ossicles with the development of adhesions among the eardrum, auditory ossicles and promontorium, ossification of the circular ligament,

and so on [3, 33]. However, as far as in the middle of the last century, an age-related hearing loss was already considered to be the primary consequence of degenerative alterations in sound perceptive part of the ear. The main disorders are suggested to take place in the cochlear membranes, which become rigid, thicken, and lose their form as aging progresses [29].

Changes of the spiral organ neuroepithelial elements play a leading role in the age-related hearing loss development. But according to some authors, isolated hair cell damage cannot be the only reason of selective high frequencies affected impairment in older age [34]. Involutional and dystrophic changes in the cochlea can be primary or secondary, and it is associated with blood vessel dysfunctions [35]. The reduced number of bipolar cells of the spiral ganglion can be named the steadiest morphologic manifestation of the cochlear aging in humans and animals. Changes of the auditory nerve also play a certain role in the presbycusis development [36].

4.3. The evaluation of central auditory pathways

CAPD occurs very often in elderly or senile persons, reaching up to 80% and contributing to the age-related hearing loss [28]. Stach et al. revealed CAPD symptoms in 70% of adults older than 60 years of age, and its occurrence increases with aging: adults of 50–54 years old had CAPD in 17% of cases; meanwhile, adults older than 80 years old had CAPD in 95% of cases [37]. According to Golovanova et al., 31% of elderly patients with normal hearing thresholds complained of hearing impairment, which was explained by the authors as impaired speech intelligibility caused by central auditory pathway dysfunction [38]. Australian investigators, Golding et al., also confirm the increase of CAPD occurrence associated with aging and note the prevalence of men with this pathology [39]. The difficulties of the occurrence of CAPD assessment are associated either with similarity of its symptoms with other pathologies (cognitive disorders, attention deficit, memory impairments, etc.) or with the absence of any standards of this disorder diagnostics.

Audiologic methods of evaluation of the central auditory pathway functioning are divided into behavioral (subjective) and objective. Subjective methods are subdivided into verbal and nonverbal methods. Advantages of speech tests are associated with their social significance, the ability to use them both for identifying a level of hearing pathology and for hearing aid fitting. The following speech tests are advised to use by the American work group on CAPD: (1) monaural low redundant; (2) dichotic; and (3) tests of binaural interaction [40]. The first group of tests is believed to be sensitive to auditory cortical disorders, the second is sensitive to dysfunctions of interhemispherical connections, the third is sensitive to the dysfunctions of higher auditory centers or, according to some authors, to brain stem damages [41].

Monaural low redundant speech tests evaluate the ability of the auditory system for auditory closure. There are tests with speech signals passed through filters with different cutoff frequencies, signals with distorted temporal characteristics, and tests with speech in background noise. In the tests mentioned above, the auditory closure (the ability to understand a whole word or phrase when a part of them is missing) or the ability to recognize signals in background noise are assessed [28, 32]. While testing with speech in background noise, a speech signal is presented simultaneously with a masker (different types of noise or speech signals). For Russian

language, Prof. Lopotko [30] created the Russian speech audiometric express test, during which polysyllable words are presented in the background of different noises (white noise, noise of transport, etc.). In the last year, the matrix sentence test has become rather popular, aimed to evaluate phrases intelligibility in background noise, and approbated for many European languages including Russian (Russian matrix sentence test—RuMatrix) [42]. In the presence of CAPD, intelligibility of distorted speech or speech in background noise is very poor [28].

In the dichotic tests, different speech signals, for example, monosyllable words, are presented through headphones to each ear simultaneously. In these tests, binaural integration (when a patient is instructed to repeat all signals presented to both ears) and binaural separation (when a patient is instructed to repeat signals presented only to one ear) are assessed. Numerous studies proved that in conditions of competition between right and left auditory channels, an ear that is contralateral to a dominant in the processing of presented signal hemisphere dominates. The majority of people are right-handed, and the speech center is located mainly in the left hemisphere, so the right auditory channel is dominant. This phenomenon is called “the right ear effect.” However, the right ear dominance occurs only in 80% of right-handed, while the speech center is located in the left hemisphere in 95% of right-handed people. The dominance of ipsilateral auditory pathways in some people may be the cause of this fact. A large number of dichotic test modifications were suggested as follows: dichotic digit test [43], dichotic sentence identification [44], and so on. Currently, dichotic tests are among the most popular methods to examine interhemispherical asymmetry in healthy people of different ages and in patients with central neural disorders [28, 30, 32].

In tests of binaural interaction, information is presented to each ear not simultaneously but consecutively: one part of a word/phrase is presented to one ear and the other part is presented to another. The ability of a listener to integrate signals and repeat correctly the whole income information is evaluated [41]. An example of the group tests is the audiometry with binaural alternating speech [45]. For English language, the following examples are CVC Fusion Test, during which consonants are presented to one ear, and vowels are presented to another; Spondee Binaural Fusion Test; and so on. [28].

Results of nonverbal CAPD tests are less influenced by linguistic knowledge of a patient, which is their advantage, but to perform many of them special not commercially manufactured equipment is often required [46]. One of the crucial methods of temporal processing evaluation is the Random Gap Detection Test (RGDT). It is sensitive to cortical pathologies, especially of the left hemisphere. During this test, signals (pure tones and broadband noise) with inserted pauses are presented through headphones at a comfortable loudness level [28, 47]. In the last year, indications to use subjective test diagnosing CAPD are expanded. Impaired speech intelligibility because of CAPD is proved to be one of the predictors of Alzheimer’s disease and dementia. To detect at-risk groups, some authors suggest a number of behavioral tests with high sensitivity to subclinical cognitive deficit comparing to screening cognitive tests [48–50].

Electrophysiologic (objective) audiological tests include auditory evoked potentials (AEPs), which are divided into several types by localization of generators and time of onset: cochlear potentials (are registered during cochleography), short latency (brainstem) auditory evoked potentials, middle latency AEP, long latency (cortical) AEP, cognitive potentials, and mismatch

negativity. At the moment, the unique criteria to include any type of AEP in the test battery for revealing CAPD do not exist.

Concluding the aforementioned, audiological methods for CAPD diagnosing can be divided into the following ways: speech tests (monaural low redundant, dichotic, and binaural interaction); tests assessing temporal processing; and electrophysiologic tests. Tests to perform should be chosen individually based on patient's complaints and anamnesis. Both verbal and nonverbal tests should be included. The mentioned division of the tests does not mean that tests from all groups must be used. The minimally necessary number of tests is recommended. The use of electrophysiologic tests is determined by the lack of possibility to use behavioral tests or the lack of their accuracy [40, 51]. Thus, the audiologic examination of a patient with presbycusis includes the following steps: (1) collection of complaints, anamnesis, and ENT examination; (2) pure tonal threshold audiometry in silence; (3) impedancemetry; and (4) CAPD tests.

A constant increase in number of elderly and senile people, greater demands on the quality of life in contemporary society, along with extended possibilities of audiological examination dictates a necessity to seek new approaches to the problem of age-related hearing loss. Identification of a pathology level in the auditory system with presbycusis matters a lot while choosing a further tactics of treatment and hearing aid fitting.

5. Rehabilitation of patients with presbycusis

Hearing aid fitting is the only possibility to compensate hearing loss in elderly people in the majority of cases. With the technical progress, hearing aids (HAs) become more complex devices satisfying users' needs, but often HAs do not meet high expectations placed upon it. There are data that only from 6 to 40% of patients with hearing loss use a HA [52, 53]. A number of patients completely satisfied by HA fitting results are about 20%; in elderly people, this percent is even lower, which is associated with several distinguishing features of this group [31, 54, 55]. Memory disorders, impaired ability to capture new information, cognitive disorders, impaired vision, degraded fine motor skills, and the presence of co-morbidities along with specific alterations of auditory perception are among these features [56]. Meanwhile, the refuse of patients with hearing loss to use HA is known to disturb socialization significantly, to lead to social isolation, to intensify cognitive disorders, to reduce the safety of vital activity, and to cause the essential deterioration of quality of life [57]. To evaluate the effectiveness of HA, the speech audiometry in free field is commonly used in adults along with questionnaires [58]. Together with medical parameters, social criteria (ability to practice their profession, to communicate in family without any difficulties, to lead an active social life, etc.) are evaluated. Despite high prevalence of hearing loss, few studies dedicated to the problem of HA effectiveness exist up to the moment [59].

Low effectiveness of HA fitting in elderly and senile patients was shown in our study by results of speech audiometry in 26 (21%) of 125 patients (percent of polysyllabic words intelligibility in quiet with HA was less than 70%). The analysis of results of an audiological examination allowed to conclude that the main factor reducing the effectiveness of HA use in elderly patients

was the presence and a degree of CAPD. Studies of other authors confirm this fact [28, 60]. With alterations of the retrocochlear structures, which are often associated with presbycusis, a person's ability to process and differentiate temporal and spectral properties of acoustic signals is violated, especially in conditions of perceiving speech in background noise [60].

Modern HAs are known to solve the problems of peripheral hearing loss but often not the ones of impaired speech intelligibility. Besides, HAs providing enough loudness of speech signal do not always improve signal-to-noise ratio [61], which disturb good intelligibility. Up-to-date technologies, for example, systems of noise reduction and differentiation between speech and noise, directional microphones, and the presence of various listening programs in one HA, allow a user to increase speech intelligibility with HA [62]. According to our study to increase the effectiveness of HA use by elderly patients, a complex of measures is needed including special audiological examination, therapy aimed at correction of CAPD, and HA fitting with consideration of individual features of a patient's auditory system.

Revealing CAPD before HA fitting allows an audiologist to prescribe adequate treatment, to warn a patient and his relatives about possible difficulties with HA use, to avoid excessive expectations from HA use, and to plan rehabilitation after HA fitting. To diagnose CAPD, all tests mentioned above are not necessary to perform, although all of them are performed with the use of standard equipment and do not require a lot of time. A percent of monosyllabic words intelligibility in quiet at a comfortable loudness level could serve as an express criterion to prognosticate an effectiveness of HA. Our study showed that with this percent being less than 60%, the risk of poor results from HA fitting significantly increases. A long adaptation to HA, involving not only an audiologist but also a speech therapist and a psychologist, is often required. The aim of such work is the successful use of a HA, so that in older hearing impaired patients social contacts expand, communication skills improve, and self-esteem and overall quality of life increase [59, 60].

At the moment the designed pharmacological treatment of impaired speech intelligibility associated with CAPD does not exist, this problem is being actively studied [27, 63, 64]. Despite the absence of significant success in creation of drugs for restoring speech intelligibility, improving speech signal processing in central auditory pathways is possible, thanks to the auditory training that helps to correct CAPD.

The auditory training is the complex of acoustic settings and tasks created to activate the auditory and related systems and to cause positive changes of neuronal activity and related auditory behavior. Two types of the auditory training are distinguished: (1) "bottom-up" approach (from the periphery to central parts, due to incoming sound signal) includes the improved audibility and sound quality through the use of hearing aids, FM systems and optimization of room acoustics, as well as sessions with a speech therapist to correct temporal and frequency processing, sensitivity to changes of loudness, and so on [65] and (2) "top-down" approach (from central parts to periphery involving higher functions of central nervous system) combines linguistic, cognitive, and metacognitive strategies of learning and includes special complexes to train the auditory attention, memory, linguistic and cognitive functions, musical education, and learning foreign languages.

Generally, these two approaches complement each other and must be applied together to reach maximum positive results, to improve speech intelligibility, and to compensate a residual deficit [65]. Concrete rehabilitation plan must be worked out individually depending on deficit profile of a patient, his lifestyle, social and communicative needs, presence of comorbidities, and so on. The concept of the auditory training as acoustic stimulation has been known a few centuries. At the end of 1990, first confirmations of the influence of auditory deprivation on the auditory system and proofs of plasticity inherent to the brain appeared, so the principles of the auditory training regained its development [65].

Results of last studies definitively proved that plasticity was inherent to the brain, that is, the ability of the cortex and lower levels to reorganize, and these modifications were manifested in behavioral changes [66, 67]. Although the plasticity of the brain is maximum in childhood, the ability to reorganize in the response to education persists in the mature CNS as well [68]. The auditory training leads to the reorganization of the cortex and brainstem and the increase in effectiveness of the synaptic transmission and in density of the neural tissue [66, 67, 69, 70]. Even rather peripheral processes such as determination of signal pitch can be altered during the training [71]. Cortical changes stimulated by the auditory training invade rather broad areas and remain for a long time [65]. They include four types of cortical reorganization: (1) expansion of maps, that is, areas responsible for a trained function; (2) a compensatory transmission of performing a trained function into another cortical area; (3) cross modal reorganization with involvement of cortical areas receiving an input signal from other sensory modalities; and (4) adaptation of homologous regions, that is, activation in areas in homologous regions of the contralateral hemisphere [72].

Studies on animal models proved that auditory stimulation induces alterations of inherent neural substrate. For example, tonotopic reorganization of the auditory cortex was revealed in monkeys after intensive frequency discrimination tasks. The cortical representation, the sharpness of tuning, and the latency of the response were greater for the behaviorally relevant frequencies of trained monkeys when compared to the same frequencies of control monkeys [65]. Experiences with rats showed that training-induced improvements occurred in the auditory cortex even if a damage (an impact of noise in the experiences) was done in childhood. This proves the possibility of improvement, or maybe restoration, of auditory function in adult rats even after a long time after the initial damage to the auditory cortex [73]. Another study on rats showed that the age-related deficit in distinguishing sound characteristics could also be restored by the intensive auditory training, and not only functional but also structural changes in the auditory cortex resulted from the training [74]. The human auditory system is assumed to undergo similar changes in conditions of sound stimulation.

Before studying patients with hearing loss, the auditory training was approbated in patients with normal hearing. Positive results of the training in persons with normal functioning of the auditory system (both peripheral and central) were shown: the improved results of behavioral and electrophysiological tests were observed after the auditory training to distinguish sound stimuli consonant-vowel [75, 76]. Significant improvement of speech intelligibility was observed in young persons with normal hearing after the auditory training with multiple tasks (speech in noise and accelerated speech) for 8 weeks. The improved results of behavioral tests

were confirmed by the increased sharpness of frequency tuning, especially fundamental frequency and the second harmonic [77]. Thus, the auditory training causes the changes in neural activity and improves the neural impulses, which provide coding speech signals [78]. Positive changes of mismatch negativity and increased amplitudes of P_1 , N_1 , and P_2 were revealed after the training. N_1 - P_2 potential is considered to reflect early cortical processes associated with stimulus decoding and speech detection. Mismatch negativity reflects later processes including distinguishing of speech stimuli changes. The activity of the superior temporal gyrus and planum polare of the right hemisphere on fMRI had decreased in patients after the auditory training, which reflected the enhanced effectiveness of functioning of these areas and improved ability of auditory perception [79]. Some authors consider these improvements to occur only for the trained sound stimulus, and others consider to spread on other stimuli [80]. Neurons of the auditory cortex, which are selectively tuned to some frequencies or amplitudes, were found to be able to change their selectivity after the behavioral auditory training [81].

It can be said that we form our brain as we form our muscles. These data open up new possibilities for rehabilitation, particularly the possibility to train patients' own central resources. Although the compensation of the peripheral deficit (the increased intensity of input signal) dominates in rehabilitation of elderly patients, the role of deficit-specific, intensive auditory training should not be underestimated.

In case of concurrent attention, deficits or intellectual disorder cognitive trainings are also used [65]. Compensatory training belongs to "top-down" approach designed to minimize the impact of auditory processing deficit that persists after the modification of acoustic environment and the auditory training. Compensatory training includes providing information on strategies of communication aimed at strengthening the use of central cognitive resources (linguistic strategies, memory, ability to problem solving, exercises on vocabulary expansion, development of active listening, and training of concentration). General recommendations on lifestyle such as preservation of intellectual activity, maintaining physical activity, minimizing chronic stress, and healthy nutrition are helpful to reduce a risk of development of cognitive deficit [28]. The effectiveness of the auditory training is explained by the fact that neuroplasticity is not completely lost with the aging process, though gradually decreases [60]. The central auditory system in elderly persons preserves its ability for training-induced alterations, which entails the possibility to improve speech intelligibility, especially in noisy environment [65].

In the laboratory of hearing and speech (Saint-Petersburg, Russia), a program of the auditory training with the use of two approaches "bottom-up" and "top-down" was evaluated. The aim of the study was to design an optimal algorithm of the auditory training for adults with SNHL and poor speech intelligibility in noise. Twenty-nine patients, HA users with moderate to moderately severe SNHL and symptoms of CAPD, including poor speech intelligibility in noise, underwent this auditory training: 12 young patients (from 19 to 22 years old) and 17 elderly and senile patients (from 60 to 83 years old). An examination before the training included the pure tonal audiometry, tests evaluating central auditory pathway functioning, and speech audiometry in free field by means of the Russian Matrix sentence test (RUMatrix). The auditory training was conducted individually by a speech therapist and included a distinction between nonverbal and verbal stimuli of varying complexity, as well as tasks to improve memory (e.g., memorizing poetry).

Nonverbal training included the following tasks: (1) to distinguish stimuli by pitch with sets of 18 musical sounds of different pitches. Increase of the stimulation complexity—from the set “1 instrument—1 pause” to the set “3 instruments—2 pauses”; (2) to detect silent pause between two sound signals—three variants (tonal signal, noise signal, and vowel); and (3) to evaluate rhythmic pattern of three signals (long or short).

Verbal training included the following tasks: (1) to distinguish a rhythmical pattern of 15 sequences of three syllables/phonemes (vowel “A,” syllables “MA,” and “PA”) of different duration or intensity; (2) to perceive acoustically similar words and syllables with a choice of the correct word from 6 to 12 homonyms (“dom-tom” and “gora-kora”); (3) to distinguish syllables with a choice from two syllables (“ba-va” and “ga-da”), in more complex variants—from four to eight syllables; and (4) to perceive speech in background speech noise with identifying all vowels presented (eight variants in the set) or words (20 in the set), in the complex variant—to identify the predetermined signal by a speaker’s voice (vowels or words spoken by male or female voice) in background speech of another speaker.

Classes lasted for 60 minutes and were carried out twice a week. The course of the auditory training took 8–10 weeks. A percent of correct answers and time of reaction were compared in the beginning and at the end of the training when analyzing the results. After the training, the significantly improved ($p < 0.01$) perception of verbal and nonverbal signals was revealed both in young and elderly HA users (a percent of correct answers increased by $24.4 \pm 5.2\%$ and $15.3 \pm 6.4\%$ accordingly; decrease of time of reaction in the range from 0.4 to 1.6 seconds). Besides, RuMatrix in quiet and noise, performed with hearing aids in free field before and after the training, was used to assess the effectiveness of the training. Signals were presented from a loudspeaker located at an angle of 0° relatively to a patient’s head (frontally) on 1 m distance. The effectiveness of the training was evaluated by calculating the difference between first and last results. Significantly improved speech intelligibility ($p < 0.05$) both in quiet and in noise was revealed after the training. According to the results of the RuMatrix in quiet, the intensity, at which 50% sentence intelligibility level was achieved, was 44.5 ± 11.4 dB SPL before the training and 43.5 ± 12.5 dB SPL after the training. The difference of the results is significant ($p < 0.05$). According to the results of the RuMatrix in noise, signal-to-noise ratio, at which 50% sentence intelligibility level was achieved, was 1.5 ± 5.5 dB SNR before the training and -0.33 ± 5.5 dB SNR after the training. The difference between the results is also significant ($p < 0.05$).

Based on the study, improved functioning of the central auditory pathway was shown after the auditory training, so it is appropriate to include it in the rehabilitation of HA users with low speech intelligibility in noise. The following algorithm of the auditory training was designed: (1) the distinction between nonverbal signals with changes in their duration, frequency, and intensity; (2) recognition of speech stimuli of varying complexity, including speech in background noise; and (3) tasks to improve memory. An important aspect of training was a gradual complication of tasks in the process of each session and from lesson to lesson [82].

Improvement of speech intelligibility in elderly patients with SNHL proves that plasticity of the auditory regions of the brain remains possible throughout the life. Stimulation-induced plastic changes in the central auditory pathways were proved by other researchers too [28]. According to some researchers, the decreased latency time and decreased variability between peaks of auditory evoked potentials were revealed in elderly after the course of the auditory

training and accompanied by improved speech intelligibility in noise and short-term memory [28]. As shown by our study, improvement of neuronal functioning can be proven by the results of behavioral tests, which were also noted by a number of foreign authors [77].

Neuronal changes depend on the activity of training and amount of stimulation, and the sooner the stimulation begins after the detection of impaired intelligibility, the best results can be expected, however, to start training is never too late [65].

One of the basic principles of the auditory training must be concordance between the used material and age and linguistic skills of a patient. If the materials and tasks exceed the cognitive and linguistic skills of a patient, he/she will have no interest in the training, and there will be no progress. In contrast, material for adult training should not be childish and too simplistic. Motivation is also one of decisive factors in the training success. To increase the motivation, patients should understand the principles and the theory of action of the auditory training.

The use of a various tasks, the variation of a stimulus in the auditory training helps to maintain a patient's attention, increases motivation and makes the training more efficient. The complexity of tasks during the training can vary automatically: as soon as a patient reaches the predetermined level, the task becomes more difficult. Careful monitoring of a patient's progress is important. For each patient, an individual profile of functional deficit, which reflects the processing of information in the central auditory pathways, cognitive and language skills, should be developed, and an emphasis on training deficit skills should be done while planning the rehabilitation.

6. Possibilities of the presbycusis prophylaxis

At the moment, the presbycusis is irreversible; therefore, the prevention of age-related hearing loss must be paid attention to. First of all, it is necessary to educate the population about harmful factors affecting hearing throughout the life, such as ototoxic drugs, noise exposure, vibrations, and others. Audiological care in case of SNHL should be aimed at the enhancement of nonspecific resistance of excitable structures of the auditory analyzer to general pathological damaging factors—tissue hypoxia, oxidative stress, and extinction of the action of endogenous neurotrophic factors [30, 83].

Due to the fact that with age-related hearing loss, it is impossible to obtain gains in tonal hearing, and special emphasis is done on means of improving the auditory attention (the functions of the central auditory pathways), which allows to compensate for the lack of auditory acuity and enhance the efficacy of the hearing aid. If CAPD causing poor speech intelligibility is detected, the auditory training is appropriate.

7. Conclusion

Constantly growing number of aged and senile people, increasing demands to the quality of life in modern conditions, as well as enhancing of audiological examination opportunities

requires the necessity of searching the new approaches to the problem of age-related hearing impairment.

Presbycusis does not develop in all people. Genetic mechanisms are considered to be the crucial cause of age-related hearing loss development. Different diseases acquired throughout the lifetime and other factors can contribute to hearing loss progression in the case of hereditary predisposition to presbycusis.

Assessment of pathology level in the auditory system in patients with presbycusis is essential during the choice of further treatment and hearing rehabilitation. Therefore, it is necessary to use various audiologic methods during elderly people examination, including tests to evaluate the central auditory pathways. Elderly patients often suffer from impaired speech intelligibility, especially in background noise. This is one of the central auditory processing disorder symptoms. Currently, there are no data about significant achievements in development of drugs, improving speech intelligibility. According to research on brain neuroplasticity, specially designed auditory training programs have been shown to be able to refine speech signals' processing in central auditory pathways even in aged people. Auditory training designed with consideration of the individual features of auditory deficit should be included into rehabilitation programs of aged people with speech intelligibility disorders.

Conflict of interest

There are no conflicts of interests.

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