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REMOTE MONITORING OF HEARING FROM THE POSITION OF PERSONALIZED MEDICINE

Introduction. *At the current stage of society's development, an increasing number of people suffer from hearing loss. Hearing plays an important role in the combat fitness of the military. Hearing loss can be prevented by regular testing. But in field conditions, it is impossible to conduct an audiometric study based only on standard methods.*

The purpose of the paper *is to develop methods for hearing loss evaluation based on tonal threshold audiometry using the client-server system, which provides remote communication between a patient and a physician.*

Methods. *To check the hearing ability, the results of the current audiogram are compared with the user's personal norm. In case of deviation from the norm the doctor is notified. He uses this information system to adjust the treatment.*

Results. *Developed information technology provides the opportunity of remote monitoring of the hearing condition and correction of treatment. It is demonstrated that the determination of the patient's personal norm can be carried out by calculating the median from the user's audiograms obtained with a smartphone and head phones.*

Conclusions. *The information system, which ensures the implementation of the proposed procedures, can be used on a mid-range smartphone running the Android operating system.*

Keywords: *information method, audiogram, population and personal hearing norms, client-server information technology, mathematical model, remote communication patient-physician.*

INTRODUCTION

Over time, an increasing number of people suffer from hearing loss. According to WHO forecasts, by 2050 more than 700 million people will suffer from hearing loss [1]. Deterioration of hearing often leads to the inability to perform professional duties and negatively affects the quality of life.

The fact is that the human brain creates a predictive model of what it expects to hear in the message [2]. The advantage of this is that when we cannot fully hear a phrase, we reproduce the missing part quite accurately. If a person's hearing has significantly deteriorated, then the interpretation of what is heard using the old model leads to a large number of errors [3].

Mathematical models of auditory perception of sound signals are presented in works [4, 5]. Each of the models shows a direct dependence on time, amplitude and sound intensity. Using these parameters during hearing testing, it is possible to determine the area of a person's hearing aid that has been affected by certain factors (ear disease or complications after the disease, head injuries or long-term exposure to strong noise and vibrations due to the specifics of work etc.).

Military personnel are at high risk of hearing loss due to the sounds of artillery weapons and other noises. Hearing problems reduce the military's combat fitness. If a soldier cannot correctly interpret an order, it not only puts him at risk, but also affects the safety of other soldiers and sometimes civilians.

To reduce the risk of developing hearing loss, military personnel must undergo regular audiometric testing and, if necessary, undergo an individual rehabilitation program. And constantly monitor the dynamics of treatment. But in field conditions and in conditions of constant hostilities, it is impossible to conduct an audiometric study and remotely monitor the dynamics of treatment using only standard methods.

The purpose of the paper is to develop methods for diagnosing the state of hearing based on tonal threshold audiometry using a client-server system that provides remote contact between the patient and the doctor.

BASIC PREREQUISITES

Before proceeding to solving the given problem, let us recall the information known from the scientific literature, which will be needed for further research.

The human inner ear is a pair of multifunctional hearing organs that capture sound information, amplify it and transmit it to the brain in the form of electrical impulses. The anatomy of the ear consists of many functional elements, each of which plays a separate role (Fig. 1).

One of the main elements of the ear is the so-called bacillary membrane, which is located in the cochlea of the inner ear, separating two of the three channels (stairs) that stretch along the entire length of the spiral of the cochlea. The bacillary membrane (Fig. 2) is a place where the primary frequency analysis of a complex sound wave is carried out.

The maximum amplitudes of oscillations correspond to those regions of the basilar membrane that is responsible for the frequency spectrum of perceived sound [6]. A more accurate selection of the sound range is related to the work of the central nervous system (CNS) [3]. Two standing waves are formed on the

basilar plate: a wave that occurs in the space of the tympanic stair (Fig. 1) and a wave that occurs in the space of the cochlear duct [4].
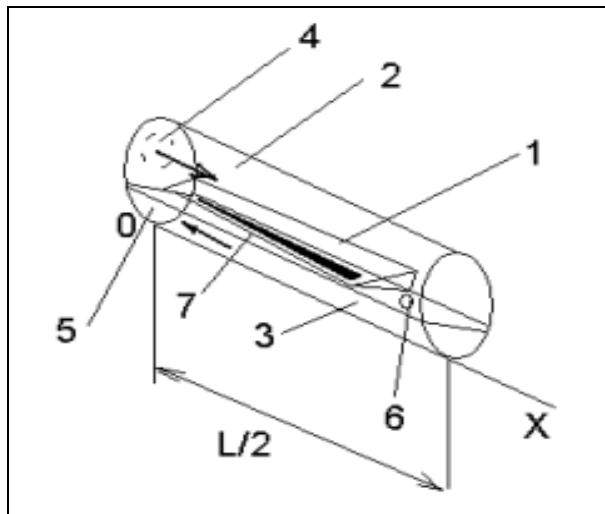

Fig. 1. Scheme of the human inner ear: 1 — cochlear duct, 2 — vestibular stairs, 3 — tympanic stairs, 4 — oval window, 5 — round window, 6 — helicotrema, 7 — basilar membrane.
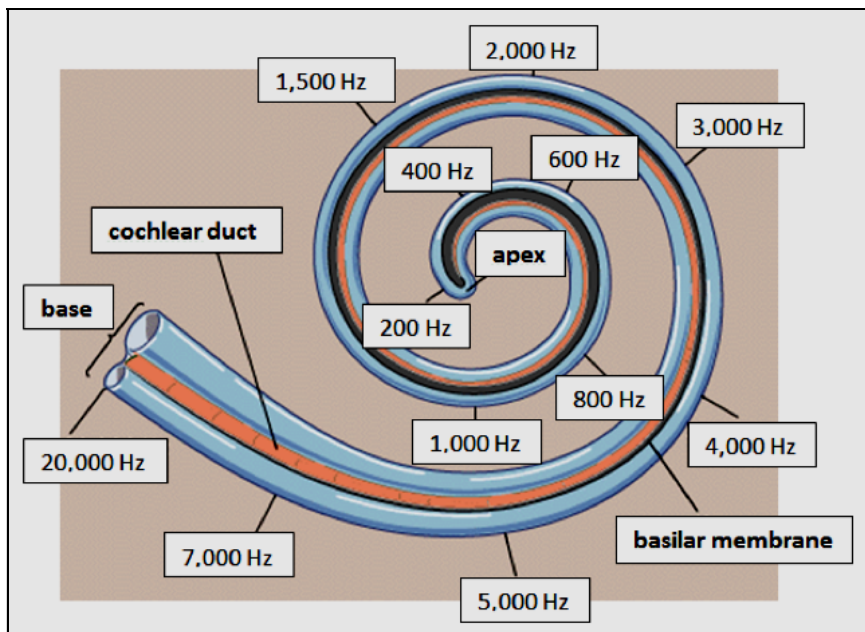

Fig. 2. Areas of the basilar membrane that are excited by frequency fluctuations

According to the principle of superposition, the total displacement of standing waves is equal to:

$$S = 2A(\cos \frac{\omega t}{V} + \cos \frac{\omega(t-X)}{V_1}) \sin \omega t , \qquad (1)$$

where A is the amplitude of oscillations in the sound wave, ω is the circular frequency of the wave, V is the speed of the sound wave in the endolymph, V_1 is the speed of the sound wave in the perilymph, X is the coordinate counted from the oval window, t is time, l is the total length of the vestibular and tympanic stairs, which is approximately twice the length of the cochlear passage.

According to (1), during the addition of standing waves a separate maximum appears, the location of which on the basilar plate and the shift (sharpness) $B(\omega, X)$ depend on the frequency ω of the perceived sound and the coordinates X. Such a dependence can be constructed [4] according to the formula:

$$B(\omega, X) = 2A(\cos \frac{\omega t}{V} + \cos \frac{\omega(l-X)}{V_1}). \qquad (2)$$

A slightly different model is presented in [5]:

$$y(x, t) = \sin (\frac{2\pi x}{\lambda}) \cos (2\pi ft), \qquad (3)$$

where λ is the wavelength, f is the frequency of the wave, $\sin (\frac{2\pi x}{\lambda})$ describes the sinusoidal shape of the signal with the wavelength λ, $\cos (2\pi ft)$ describes the up-down oscillation of each segment of the wave at the frequency f .

According to the formulas above, the volume of sound perceived by a person depends on its frequency, as well as its intensity. Therefore, the state of auditory perception (acuity of hearing) can be checked by the method of determining auditory sensitivity to sound waves of different frequencies f (Fig. 3).
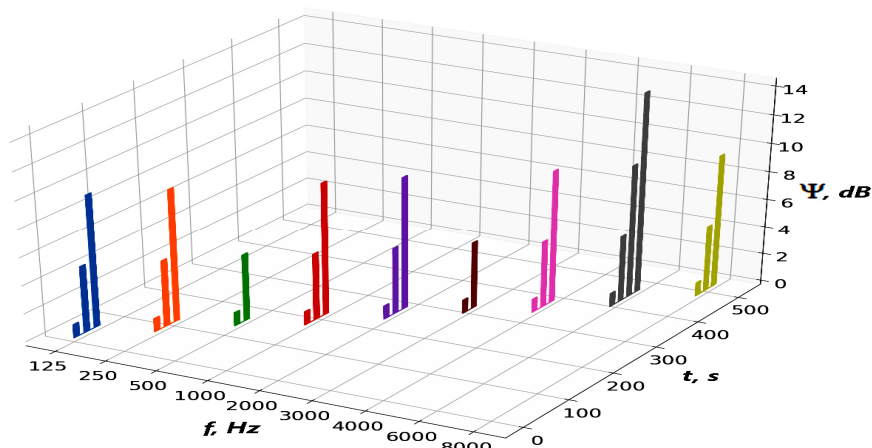

Fig. 3. Spectral characteristics of the sound wave at frequencies f perceived by the patient
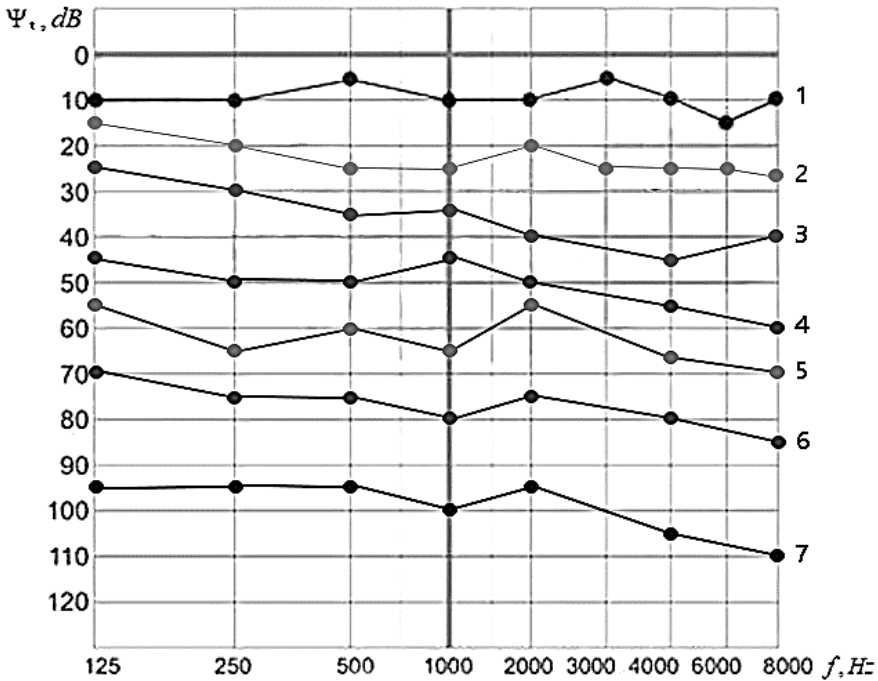
Fig. 4. Degrees of hearing loss: 1 – normal hearing threshold, 2 – minimal hearing loss, 3 – mild hearing loss, 4 – moderate hearing loss, 5 – severe hearing loss, 6 – profound hearing loss, 7 – deafness

The result of testing the state of hearing is an audiogram ψ_t — a curve of the threshold of auditory perception, on the ordinate axis of which the level ψ of intensity of tones in dB that the patient feels, and on the abscissa axis f — the frequency of these tones in Hz, is plotted. The patient's task is to record the initial perception of sound vibrations at a specific moment in time t. The graph of the sound wave generation process, taking into account the patient's perception of the signal, generates an audiogram $\psi_t = \psi(f)$.

For illustration in Fig. 4 examples of real audiograms that correspond to different degrees of hearing loss are shown. In medical practice, it is customary to distinguish [7] minimal hearing loss (16–25 dB), mild (26–40 dB), medium (41–55 dB), severe (56–70 dB), profound (71–90 dB) and deafness (more than 90 dB).

Since the transition from one degree of hearing loss to another occurs quickly enough under the condition of constant action of hearing impairment factors, it is necessary to carry out constant monitoring and timely intervention of a specialist in case of detection of hearing loss.

APPARATUS FOR CARRYING OUT AUDIOMETRY

The standard procedure for checking the state of hearing involves the use of an audiometer [8]. The audiometer makes it possible to perform a check using the following methods [9]:

• tone threshold audiometry [10];

• suprathreshold audiometry [11];

• speech audiometry based on a pre-recorded speech signal in conditions of interference [12].

To check the condition of hearing in children, additional methods are used [13, 14].

The development of elements of digital computing technology has led to the creation of portable audiometers [15], and modern information technologies make it possible to remotely check the condition of hearing. In the market of medical equipment, there are many software applications for conducting an audiometric examination on a smartphone.

Table 1 presents the generalized results of a comparative analysis of the modern market of audio metric systems based on available publications [18–25].

Most of the known portable audiometers use tone threshold and speech audiometry in noise as testing methods. Such methods have the lowest risk of harming the user's hearing [16, 17], as they will not exceed the permissible norms for frequencies and hearing thresholds.

The conducted analysis shows that the existing software tools on the smartphone are sufficiently reliable and widely used by the world community. However, software applications only show the user the test result in the form of a graph of the current audiogram ψ_t and a short conclusion for ψ_t:

$$\begin{aligned} &\text{Physiological norm if } \psi_t \in \Omega, \\ &\text{Deviation from the norm if } \psi_t \notin \Omega, \end{aligned} \tag{4}$$

where Ω — generally accepted medical norm.

Table 1. Analysis of existing applications for hearing testing

Software application	Hearing Test (Petralex)	Hearing Test (Lemonapps)	Hearing Test (Mimi)	Hearing Test (E-audiologia)	Hearing Test (Audio Cardio)	Hearing Test (Pidgey)
Full hearing testing	+	-	+	+	+	+
Headphone calibration	-	-	-	+	-	-
Instruction	+	+	+	-	+	-
Saving the results	+	-	+	+	+	+
Registration	+	-	+	+	+	-
Change user	-	-	-	-	-	-
Analysis of results	+	+	+	+	+	-
Description of results	+	+	+	+	-	-
Construction of an audiogram	+	-	+	+	-	+

Since some people have an ear for music, while others, due to the constant interaction of noise or other factors, do not perceive a sound signal at all frequencies [1], an important element of the modern hearing diagnostic system should be an individual approach taking into account the hearing characteristics of a particular person.

PERSONALIZATION OF DIAGNOSTIC SOLUTIONS

Let's consider the approach to making diagnostic decisions, which is based on the main principle of personalized medicine — to treat the patient, not the disease, taking into account the individual characteristics of the organism. This approach is based on the general method of making personalized diagnostic decisions proposed in [26].

Let's assume that the patient has the opportunity to independently register multiple audiograms over a sufficiently long period of time using his smartphone

$$\psi = \{\psi_1, \psi_2, \ldots, \psi_N\}. \tag{5}$$

Each individual audiogram $\psi_n \in \psi_2$, $n = 1, \ldots, N$ from the set (5) characterizes the minimum sound ψ intensity level (dB) that the patient hears with the ear at fixed frequencies $f_1, f_2, \ldots, \psi_M$ (Hz), i.e. ψ_n is a vector

$$\psi_n = \{\psi_{n1}, \psi_{n2}, \ldots, \psi_{nM}\}, n = 1, \ldots, N, \tag{6}$$

whose components ψ_{nm} correspond to the minimum intensity levels of sounds heard by the patient at frequencies f_m, $m = 1, \ldots, M$.

In the simplest case, the number M of fixed frequencies in (6) can be small, for example, $M = 3$ provided that $f_1 = 100$ Hz, $f_2 = 500$ Hz and $f_3 = 1000$ Hz [7].

The proximity of two audiograms f_m, $m = 1, \ldots, M \in \psi$ and $\psi_v \in \psi$, $\mu = 1, \ldots, N$, $v = 1, \ldots, N$ from the training sample (5) will be estimated by the value

$$L_{\mu v} = \frac{1}{M} \sum_{m=1}^{M} \left| \psi_\mu(f_m) - \psi_v(f_m) \right|, \tag{7}$$

which determines the average difference of the minimum sound intensity levels heard by the patient at the corresponding frequencies f_m, $m = 1, \ldots, M$. It is clear that the value $L_{\mu v}$ has the properties of a metric:

- $L_{\mu v} \geq 0$, and $L_{\mu v} = 0$ only if $\mu = v$;
- $L_{\mu v} = L_{v\mu}$;
- $L_{\mu v} \leq L_{\mu\gamma} + L_{\gamma\mu}$, where $\gamma = 1, \ldots, N$.

Let's form a square matrix of distances $L\mu v$, $\mu = 1, \ldots, N$, $v = 1, \ldots, N$ between all pairs of elements of the set (5):

$$R\begin{pmatrix} L_{11} & L_{12} & \ldots & L_{1N} \\ L_{21} & L_{22} & \ldots & L_{2N} \\ \ldots & \ldots & \ldots & \ldots \\ L_{N1} & L_{N2} & \ldots & L_{NN} \end{pmatrix}. \tag{8}$$

The matrix R makes it possible to determine two integral quantities: the personalized reference audiogram $\psi_0 \in \psi$, which is closest to all other observations $\psi_n \in \psi$ from the set (5), i.e.

$$\psi_0 = \arg \min_{1 \le j \le N} \sum_{i=1}^{N} L_{ij} \qquad (9)$$

and the average deviation $\overline{L}$ of the results of observations, which is calculated by the formula

$$\overline{L} = \frac{1}{N^2 - N} \sum_{\mu=1}^{N} \sum_{\nu=1}^{N} L_{\mu\nu} . \qquad (10)$$

The standard ψ_0 can also be defined as a M — dimensional vector $\psi_0 = (\psi_{01}, \psi_{02}, \ldots, \psi_{0M})$ whose components ψ_{0M}, $m = 1, \ldots, M$ are the medians of the corresponding values $\psi_{1m}, \psi_{0m}, \ldots, \psi_{Nm}$ of observations from the training sample (5). In this case, the reference vector $\psi_0 = (\psi_{01}, \psi_{02}, \ldots, \psi_{0M})$ does not necessarily belong to the set ψ.

If the random variables $\psi_{1m}, \psi_{0m}, \ldots, \psi_{Nm}$ are distributed symmetrically with respect to the mode (for example, according to the normal law), then the components of the standard $\psi_0 = (\psi_{01}, \psi_{02}, \ldots, \psi_{0M})$ can be estimated by the arithmetic mean of the corresponding values. In this case, you can use the recurrence relation

$$\psi_{0m}^{(n)} = \psi_{0m}^{(n-1)} + \frac{1}{n}(\psi_m^{(n)} - \psi_{0m}^{(n-1)}), \; n = 1, 2, 3, \ldots \qquad (11)$$

with the initial condition $\psi_{0m}^{(0)} = 0$.

Ratio (11) makes it possible to constantly refine the standard in the course of data accumulation, without saving the entire array of observations $\psi_m^{(1)}$, $\psi_m^{(2)}$, $\psi_m^{(3)}, \ldots$, $m = 1, \ldots, M$. In a similar way, it is possible to calculate the value $\overline{L}^{(n)}$, which, like and $\psi_{0m}^{(n)} = (\psi_{01}^{(n)}, \psi_{02}^{(n)}, \ldots, \psi_{0M}^{(n)})$, tends to a stable value with an increase in the number of observations.

Integral quantities ψ_0 and $\overline{L}$ characterize the individual characteristics of a specific person's hearing: the standard ψ_0 reflects the **central tendency** of the results of observations ψ_1, ψ_2, ψ_3 and the value $\overline{L}$ is the degree of variability of these observations.

Such information makes it possible to make a personalized decision about the patient's current condition according to the rule:

$$\text{Personal norm if } L_{t0} \le \lambda\overline{L},$$
$$\text{Attention if } L_{t0} > \lambda\overline{L}, \qquad (12)$$

where

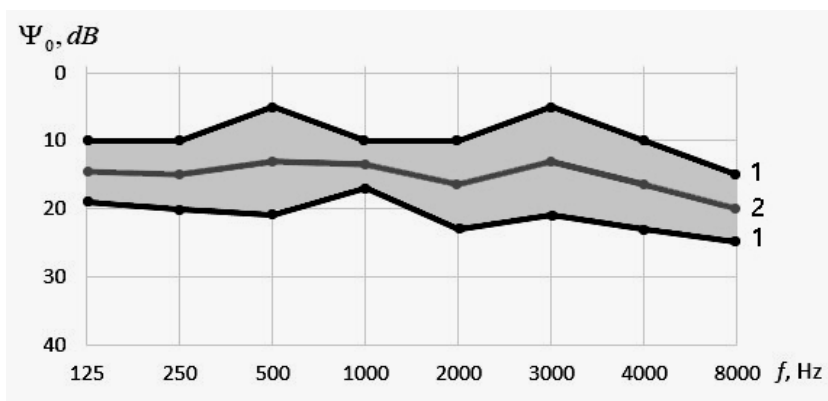$$L_{t0} = \frac{1}{M} \sum_{m=1}^{M} |\psi_t(f_m) - \psi_0(f_m)| . \qquad (13)$$

Fig. 5. The idea of building a personal norm of the user 1 — audiograms from the training sample, 2 — personal norm of the user ψ_0

If the average difference in the deviations of the components of the current audiogram $\psi_t(f_1)$, $\psi_t(f_2)$,…, $\psi_t(f_M)$ from the corresponding components of the standard $\psi_0(f_1)$, $\psi_0(f_2)$,…, $\psi_0(f_M)$, and $\lambda \geq 1$ is the coefficient that provides the desired compromise between the sensitivity and specificity of diagnostic solutions.

It is clear that additional information according to the rule (12) makes it possible to make more informed decisions than the decision according to the rule (4), which is based only on the results of the current observation $\psi_t = (\psi_t(f_1), …, \psi_{0t}(f_1))$ with the population norm Ω adopted in medical practice.

In addition, the analysis of the reference audiogram $\psi_0 = (\psi_0(f_1), …, \psi_0(f_1))$ with the population norm Ω makes it possible to assess the risk of the possible development of pathology according to the rule.

$$\text{Low risk of pathology if } \psi_0 \in \Omega,$$
$$\text{High risk of pathology if } \psi_0 \notin \Omega. \tag{14}$$

Rule (14) is fundamentally different from rule (4), because the diagnostic decision is made not according to the current observation ψ_t, but according to the standard ψ_0 calculated using the results of multiple observations for a specific patient. Thus, the proposed approach, in contrast to the traditional one, ensures the adaptation of the diagnostic rule to the individual characteristics of the organism of a particular user, which increases the reliability of the made decisions.

STRUCTURE OF THE INFORMATION SYSTEM

On the basis of the conducted research, an information technology for remote monitoring of the hearing condition was developed based on the client-server architecture (Fig. 6).

The client parts of the information system are represented by a mobile application for the patient and a WEB application for the doctor, which are implemented in the Java programming language using the Android Studio and IntelliJ IDEA development environments. Interaction with the database takes place using the SQLLite DBMS.

Signal generation in the mobile software application is done using the AudioTrack stream from the android.media library. The WEB application for the doctor was implemented using the Spring framework.

Figure 7 shows the use-case diagram of the developed information system. As you can see, every user regardless of role must be registered, due to which the doctor is linked to the patient. This is necessary so that the doctor receives the data of the hearing test analysis of only a specific patient.

Figure 8 presents a diagram of the interaction sequence between user ("Patient" role in the mobile software application) and the information system.

A smartphone with an Android operating system version 4.0 (or higher) and standard headsets are used for hearing testing. Before starting the test the system will check whether the main phones are connected and the volume level, which should be maximum.

During audiometric testing, a sound signal is generated alternately in the left and right ears at each frequency (Fig. 5). Discrete signal growth of 5 dB occurs with a delay of 1000 milliseconds. This interval is necessary to reduce the error during testing taking into account the user's reaction.
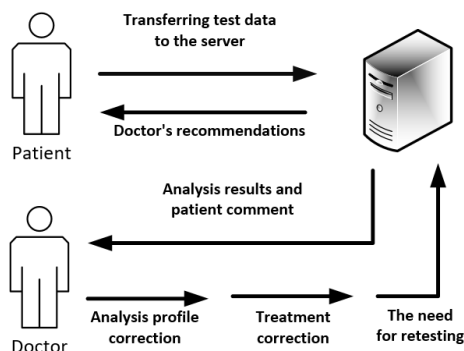

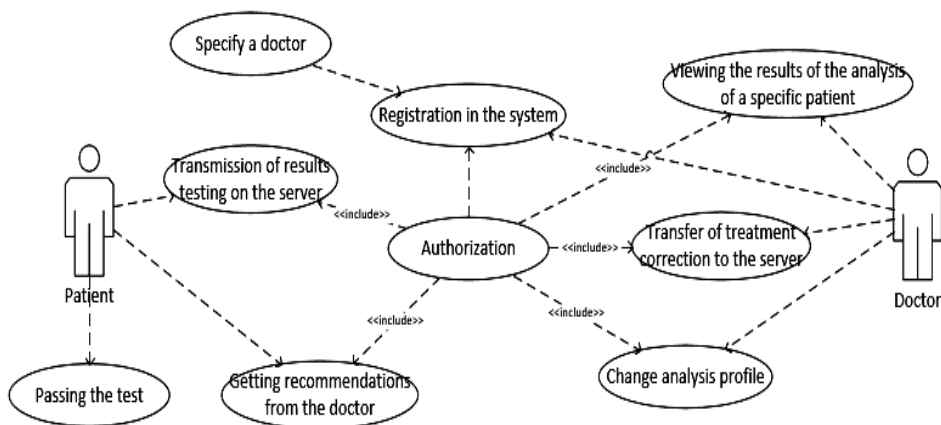***Fig. 6.*** Structural diagram of information technology

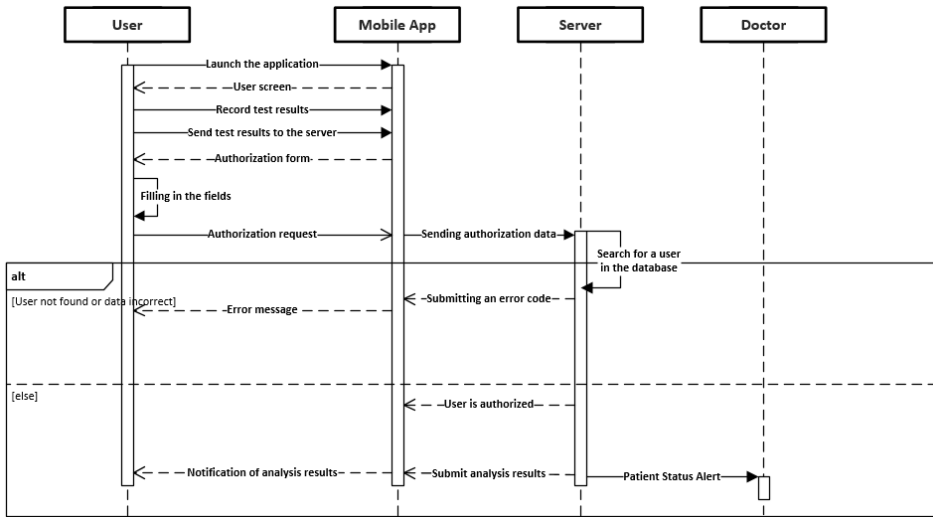***Fig. 7.*** Use-case diagram of information technology

Fig. 8. Diagram of the sequence of interaction of the patient with the information system
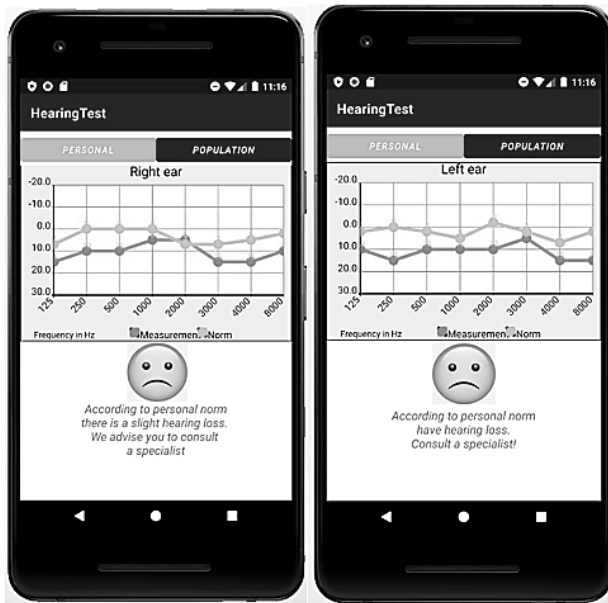

Fig. 9. The result of the analysis of the user's current audiogram according to the personal norm

The current results of the audiogram, as well as a comment from the patient, will be transferred from the user's smartphone to the server. The user will be shown the result according to the population norm.

Calculations regarding the current test results according to the population norm [27, 28] are displayed on the smartphone screen (Fig. 9). A deviation of the sensitivity threshold of more than 10 dB in two or more points of the audiogram is considered significant [29]. If there is an Internet connection, such information is sent to the server and transmitted to the doctor.
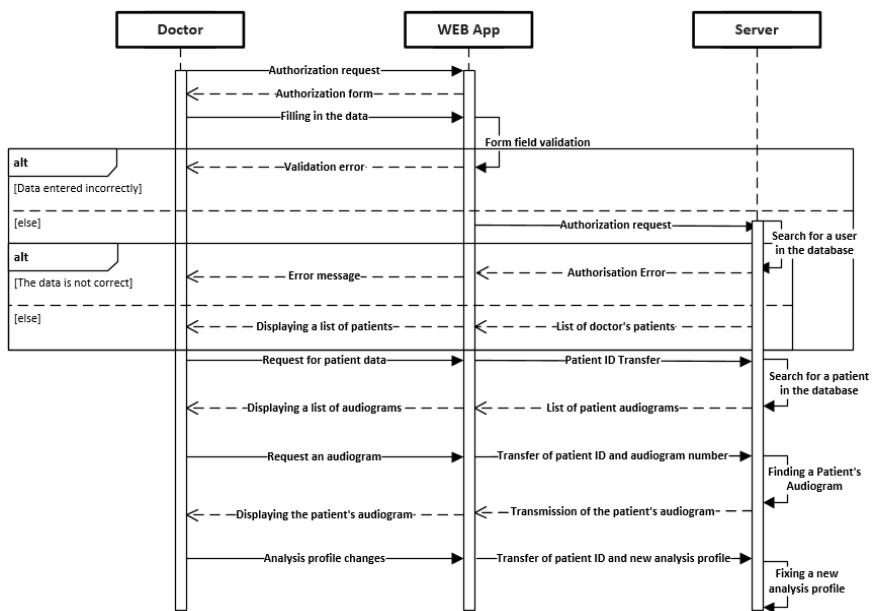
Fig. 10. Diagram of the sequence of the doctor's interaction with the information system

The main problem solved by the server is the automatic calculation of the personalized norm according to the proposed approach. If the deviation of the current audiogram deviates from the personalized norm by more than 5 dB at least two frequencies, then the relevant information is sent to both the patient and the doctor.

To respond to notifications from the server, the doctor uses the WEB application according to the sequence diagram (Fig. 10).

The WEB application will allow the specialist to:

– view the test results of a specific user;

– add to the system the results of the audiogram, which were made by professional equipment, and assign them to the user's personal norm;

– change discrete signal growth in dB (if more detailed testing is required);

– set the limits of deviation from the norm at each frequency separately for the left and right ears (first and second levels of permissible deviation and personal norm);

– write a comment-response to specific testing about the need for additional user actions;

– after making changes, request the server to re-analyze the test result.

The server records the changes in the testing methodology provided by the doctor and, if necessary, issues a request about the need to repeat the hearing test. Otherwise, the analysis profile is saved for subsequent testing.

If there is a comment-answer from the doctor, when the smartphone is connected to the Internet, the patient's software application receives the doctor's recommendations. At the same time, the software application has the ability to function even without an Internet connection, providing the user with limited information according to the population norm, which is important in conditions of lack of communication. When the connection is restored, all new test results are transferred to the server.

CONCLUSION

The article proposes an information technology that enables remote monitoring of patients' hearing. The client-server structure of the system enables the doctor to make corrections in the patient's hearing rehabilitation method taking into account the individual characteristics of his organism.

Interaction between a doctor and a patient provides an opportunity to set the necessary discrete growth of the test signal and set other individual characteristics. The patient software application for registration and transmission of the current audiogram to the server is implemented on a smartphone running the Android operating system.

The advantage of the developed system in comparison with existing on the market of medical equipment is the automatic calculation of the personal norm of a specific patient, which will be determined as the median of the collection of audiograms from the training sample. This ensures the practical realization of the main principle of personalized medicine — to treat the patient, not the disease, taking into account the individual characteristics of the organism.

REFERENCES

1. World Health Organization. Hearing screening considerations for implementation, 54 p.
2. Larry Medwetsky. Understanding the Fundamentals of the Audiogram…So What?. Convention "Hearing Loss Association of America". URL: https://www.hearingloss.org/wp-content/uploads/HLM_JulAug2014_LarryMedwetsky_Audiogram1.pdf?pdf=2014-hlm-ja-lmedwetsky.
3. National Health and Nutrition Examination Survey (NHANES). Audiometry procedures manual. 2003, 111 p.
4. Varfolomieiev A., Lysenko O. An improved algorithm of median flow for visual object tracking and its implementation on ARM platform. *Jourmal Real-Time Image Process*. 2016, 11, pp. 527–534. URL: https://doi.org/10.1007/s11554-013-0354-1
5. Bisgaard Nikolai & Vlaming, Marcel & Dahlquist Martin. Standard Audiograms for the IEC 60118-15 Measurement Procedure. *Trends in amplification*. 2010, No. 14, pp. 113–20. DOI: 10.1177/1084713810379609.
6. Lin Y., Abdulla W.H. Principles of Psychoacoustics. In: Audio Watermark. Springer, Cham. 2015. https://doi.org/10.1007/978-3-319-07974-5_2
7. "AURORA Hearing Rehabilitation Center" LLC Medical Center. Audiogram — what is it?. URL: https://aurora.ua/articles/audiohrama-shcho-tse-take/. (in Ukrainian).
8. Health and Safety Authority (HSA). Guidelines on Hearing Checks and Audiometry Under the Safety, Health and Welfare at Work (General Application) Regulations 2007, Control of Noise at Work, 2007.
9. Paul J. Govaerts. Audiometric Tests and Diagnostic Workup. 2003, pp. 33–48. DOI: 10.1201/9780203913062.ch2.
10. Soer M. Pure tone audiometry. Open access guide to audiology and hearing aids for otolaryngologists. 2014.
11. Occupational Safety and Health Administration (OSHA). Hearing Conservation. 2002.
12. Bright K., Eichwald J., Hall J. Childhood Hearing Screening. *American Academy of Audiology*. 2011.
13. Stavrakas M., Kyriafinis G., Tsalighopoulos M. Diagnosis and Evaluation of hearing loss. Digital Tools for Computer Music Production and Distribution. Hershey, PA: IGI Global. 2016, pp. 31–50. URL: https://doi.org/10.4018/978-1-5225-0264-7.ch002
14. Minnesota department of health. Hearing Screening Training Manual. 2022.
15. Lysenko O. M. Portable multifunctional system of objective auditory screening based on modern DSP and "network-on-crystal" technologies. Science and innovation of KPI named after Igor Sikorsky. 2014. (in Ukrainian).

16. Melo I., Silva A., Camargo A. and al. Accuracy of smartphone-based hearing screening tests: a systematic review. Systematic Review. *SciELO*. 2021, No 34. URL: https://doi.org/ 10.1590/2317-1782/20212020380

17. Potgieter J., Swanepoel W., Myburgh H. and al. Development and validation of a smartphone-based digits-in-noise hearing test in south african english. *International Journal of Audiology*. 2016, No 55. URL: https://doi.org/10.3109/ 14992027.2016.1172269

18. Leonidas A., Paulina T., Ruben C., Altamirano C, Sebastian F.. Methods used in mobile applications for the diagnosis of hearing loss: A systematic mapping study. *KnE Engineering*. 2020, pp. 89–107. URL: http://dx.doi.org/10.18502/keg.v5i1.5923.

19. Sousa K., Swanepoel W., Moore D., Smits C. A Smartphone National Hearing Test: Performance and Characteristics of Users. *American Journal of Audiology*. 2018, No 27, pp. 448–454. URL: https://doi.org/10.1044/2018_AJA-IMIA3-18-0016

20. Khazan A., Luberadzka D., Rivilla D. Home-Based Audiometry With a Smartphone App: Reliable Results?. *American Journal of Audiologia*. 2021, No 31, pp. 914–922. URL: https://doi.org/10.1044/2022_AJA-21-00191

21. Yesantharao L., Donahue M., Smith A. and al. Virtual audiometric testing using smartphone mobile applications to detect hearing los. *Investigative Otolaryngology*. 2002. URL: https://doi.org/10.1002/lio2.928

22. Mahomed-Asmail F., Swanepoel W. Mobile phone audiometry. *Open access guide to audiology and hearing aids for otolaryngologists*. 2013.

23. Patel K., Thibodeau L., McCullough D. Development and Pilot Testing of Smartphone-Based Hearing Test Application. *International Journal of Environmental Research and Public Health*. 2021. URL: https://doi.org/10.3390/ijerph18115529

24. MWM Mustafa. High-Rated Hearing Test Android Mobile Applications: Are they Appropriate for Action?. *Otolaryngology Open Access Journal*. 2022, No 7. URL: https://doi.org/10.23880/ooaj-16000249

25. Bright T., Pallawela T. Validated Smartphone-Based Apps for Ear and Hearing Assessments: A Review. *JMIR Rehabilitation and assistive technologies*. 2016, No 2. URL: http://dx.doi.org/10.2196/rehab.6074

26. Fainzilberg L.S. Generalized Approach to Building Computer`s Tools of Preventive Medicine for Home Using. *International Scientific Technical Journal «Problems of Control and Informatics»*. 2022, No 1, pp. 136–158.

27. Mazur G. Digital Multimeter Principles. American Technical Publishers. 2010, 182 p.

28. Wang, M., Ai, Y., Han, Y. et al. Extended high-frequency audiometry in healthy adults with different age groups. *Journal of Otolaryngology - Head & Neck Surg.* 2021, No 50. URL: https://doi.org/10.1186/s40463-021-00534-w.

29. Fainzilberg L., Kharchenko A. Determination of the Personal Hearing Standard in the Audiometer on a Smartphone. *Proceedings of XI International Scientific and Practical Conference "Modern Scientific Research: Achievements, Innovations and Development Prospects" (Berlin, April 24–26, 2022)*. Berlin, Germany: MDPC Publishing, 2022, pp. 33–39.

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ДИСТАНЦІЙНИЙ МОНІТОРИНГ СТАНУ СЛУХУ З ПОЗИЦІЙ ПЕРСОНАЛІЗОВАНОЇ МЕДИЦИНИ

Вступ. *На сучасному етапі розвитку суспільства все більша кількість людей страждає від погіршення слуху. Слух відіграє важливу роль у бойовій придатності військового. Попередити втрату слуху можливо регулярним проходженням тестування. Але в польових умовах неможливо проводити аудіометричне дослідження тільки на основі стандартних методів.*

Мета статті *— розвиток методів діагностики стану слуху на основі тональної порогової аудіометрії за допомогою клієнт-серверної системи, що забезпечує дистанційний контакт пацієнта та лікаря.*

Методи. *Для оцінювання стану слуху здійснюється порівняння результатів поточної аудіограми з персональною нормою користувача. У разі відхилення від норми, сповіщається лікар, який за допомогою інформаційної систему корегує лікування.*

Результати. *Розроблено інформаційну технологію, яка забезпечує можливість дистанційного моніторингу стану слуху та корекції лікування. Продемонстровано, що побудову персональної норми пацієнта можливо здійснити шляхом вирахування медіани колекції аудіограм користувача, отриманих під час тестування слуху за допомогою смартфону та головних телефонів.*

Висновки. *Інформаційну систему, яка забезпечує реалізацію запропонованих процедур, можливо використовувати на смартфоні середньої потужності під керуванням операційної системи Android.*

Ключові слова: *інформаційна система, аудіограма, популяційна та персональна норми слуху, клієнт-серверна інформаційна технологія, математична модель, дистанційна взаємодія пацієнт-лікар.*