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Graphical Method of Effectively Estimation of Hearing Organ Rehabilitation

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Abstract—Purpose. The purpose of this study is to analyze the usage ability and effectiveness of a new graphical method of estimation of presence of a difference between healthy and non-healthy hearing organ of a biological object during rehabilitation from the influence of an ototoxic influence. Said method is designed to provide higher analysis speed and possibility of its application of all medical personnel.

Material & Methods. During data preparation 41 experiment was conducted. A total of 3936 measurements was made, 96 for every experiment. Each measurement was conducted on one ear of a guinea pig via implementation of a distortion product otoacoustic emission. Out of said 41 experiment 40 were conducted upon test groups with different medicament influence and 1 was done as a referential to normal state of a hearing organ. In each experiment measurements were distributed between 6 frequency bands (2 kHz, 4 kHz, 6 kHz, 8 kHz, 10 kHz, 12 kHz) – 16 measurements per each. Then mean value and standard error in each band for each experiment were calculated. Obtained values were used in a presented method to find differences between them. Later statistical analysis was implemented to check method for reliability. In statistical analysis normality of distribution of results in groups was calculated and depending on it parametric or non-parametric difference test were applied. Reliability of said methods was also tested via implementation of Sokolov's criterion.

Results. Implementation of proposed method showed that for each frequency band results were divided into two large groups – normal (containing experiment 1) and deviating. Differences between two groups are next – normal group has higher mean values, lower standard errors in experiments in it and results are less scattered on a grid. Reliability of a proposed method was tested in three different tests – presence of statistically meaningful differences between mean values of experiments in normal and deviating group, presence of a statistically meaningful differences between measurements in experiment 1 and experiments in deviating group and its correlation with results of usage of a Sokolov's criterion. Tests confirmed the reliability of proposed method and had shown that it even has advantages over already used methods – be it higher susceptibility or simplicity of its implementation.

Conclusion: testing of a new method had shown that it's reliable due to the results of conducted test series for every frequency band. Apart from easiness of implementation and increase of speed of analysis of results proposed method also has higher sensitivity that some already existing methods of analysis test results of state of a hearing organ in biological object.

Keywords — otoacoustic emission; distortion product; biological object; objective audiology, machine learning.

I. INTRODUCTION

In the modern world there is constant increase in the number of congenital and acquired as a result of urban, epidemiological[1], military[2] and environmental problems hearing loss and hearing organ diseases. This fact is a reason for ever-growing concern and therefore either development of a new test methods or upgrading of existing one is needed.

One of the most prominent testing method for a hearing loss diagnostics is distortion product otoacoustic emission – DPOAE[3]. Said method is objective in its nature and therefore allows to bypass limitations of a subjective ones[2] – the need to rely on the response of a testing subject.

In the United States of America, via the implementation of DPOAE, the connection between low levels

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of response to its signals and a high chance of stroke has been established for a part of the population[4].

Said otoacoustic emission may also be a marker of hearing status for people in occupations that involve exposure to significant noise levels[5]. It is know that cumulative exposure to ototoxic drugs and noise also causes hearing loss as measured by otoacoustic emission[6].

Via usage of a DPOAE, the presence of an ototoxic effect in a cobalt femoral implant was established [7]. Also implementation of a DPOAE testing methods allows quick and reliable study of an influence of ototoxic or possible ototoxic substances on human health[8].

Another case of ototoxic effect estimation via DPOAE can be the study of effect of Carbon monoxide poisoning, especially on its early stages[9].

Observation of the clinical usage of otoacoustic emission of different types in a hospital for 3 years[10] had shown the possibility of usage of OAE as an “acoustic fingerprints”.

Additionally, study[11] had shown that DPOAE testing results can be used to estimate different risk factors for increasing severity of a diabetes of the first type in the department of it causing sensorineural hearing loss. These risk factors include higher age, lower level of education, previous continuous exposure to high noise levels, prolonged disease duration, presence of different diabetic complications.

Noteworthy is the fact that prolonged mask use, which was common during the time of a COVID pandemic[12], can damage the outer cells in the cochlea of the inner ear, causing hearing damage.

In regard to the COVID-19 virus it can be said[13] that it can cause cochlear damage which impairs hearing ability, especially at high frequencies.

A. Purpose

Purpose of the study is to estimate effectiveness and reliability of proposed graphical analysis method of evaluation of hearing organ in biological object test data, obtained via implementation of distortion product otoacoustic emission.

B. Implementation of the method

Implementation of graphical analysis method of evaluation of hearing organ in biological object test data can be presented by portable, standalone device. Addition of this method will allow to increase speed of analysis and will enable all medical personnel directly in the medical facility to conduct needed tests.

Instrument will adapt existing workflows via adding additional steps and its new workflow will begin with DPOAE data acquisition to immediate displaying

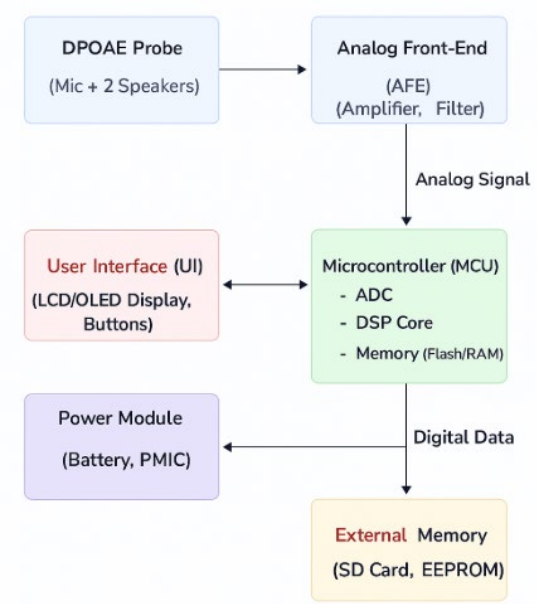

Fig. 1. Block diagram of hardware architecture

the obtained result on a "Mean Value vs. Standard Error" scatter plot.

Required architecture to realize this objective is presented on the block scheme on Fig. 1.

Blocks on are as follows: DPOAE Probe. A medical-grade DPOAE probe serves as the primary data acquisition interface. It contains a microphone for the registration of the otoacoustic emission signal and two miniature speakers for the delivery of the stimulating tones (f1 and f2).

Analog Front-End (AFE). The AFE is a critical component responsible for the pre-processing of the weak microphone signal. This block includes a Low-Noise Amplifier (LNA) to increase the signal amplitude without significant degradation of the signal-to-noise ratio, and a band-pass filter precisely tuned to the distortion product frequency (2f1 - f2) to isolate the signal of interest from extraneous noise.

Microcontroller (MCU). The central processing unit is a microcontroller. The selection criteria for the MCU needed are based on the presence of key integrated parameters:

An integrated Analog-to-Digital Converter (ADC) with a resolution of at least 16 bits, ensuring accurate signal digitization.

A set of Digital Signal Processing (DSP) instructions for the high-speed execution of the required mathematical operations.

Sufficient on-chip Flash Memory for the storage of the operating firmware, the referential group dataset, and measurement results.

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User Interface (UI). A color Liquid Crystal Display (LCD) or Organic Light-Emitting Diode (OLED) display facilitates user interaction and the graphical representation of results. They require high resolution to provide user with readable and easily accessible information. Navigation is conducted via several integrated buttons or a touchscreen interface.

External Memory. The system provisions for data logging and export via an external memory slot, such as for a Secure Digital (SD) card. This allows for the storage of a large number of patient results for historical tracking or subsequent analysis on a personal computer.

Power Module. A rechargeable battery unit, managed by a Power Management Integrated Circuit (PMIC), ensures the autonomous operation of the instrument in a clinical setting.

Proposed solution for MCU unit is STM32F407VE [14], presented on Fig. 2 which features Arm® 32-bit Cortex®-M4 CPU with FPU, Adaptive real-time accelerator (ART Accelerator) allowing 0-wait state execution from flash memory, frequency up to 168 MHz, memory protection unit, 210 DMIPS/1.25 DMIPS/MHz (Dhrystone 2.1), and DSP instructions; Up to 1 Mbyte of flash memory. Up to 192+4 Kbytes of SRAM including 64-Kbyte of CCM (core coupled memory) data RAM, 512 bytes of OTP memory, flexible static memory controller supporting Compact Flash, SRAM, PSRAM, NOR and NAND memories and LCD parallel interface. Usage of this model allows for application of selected periphery (display, memory, buttons) and presents calculation power required to apply proposed method.

II. Materials and Methods

A. Participants

Data, presented in the research, was obtained on the basis of the O. S. Kolomiychenko Institute of Otolaryngology of the National Academy of Sciences of Ukraine using the Otoread device of the Interacoustics company (Denmark) and all mentioned experiments were conducted following national regulations and ethical standards of the Declaration of Helsinki.

Fig. 2. STM32F407VE unit

The OtoRead™ device, in its "Screener+" [15] licensed version, offers next options for hearing screening using two key methods: Distortion Product Otoacoustic Emissions (DPOAE) and Transient Evoked Otoacoustic Emissions (TEOAE).

- DP (Distortion Product) Testing Options

This mode is designed for a quick and accurate assessment of the outer hair cell function of the cochlea within a specific frequency range.

Protocols: 2 fixed protocols – DP 2s and DP 4s.

Frequency Range: 2 - 5 kHz.

Stimulus Level: 65/55 dB SPL (Sound Pressure Level).

Signal-to-Noise Ratio (SNR): 6 dB.

"PASS" Criterion: A response is registered at 3 out of 4 tested frequencies.

Testing Time: 2 or 4 seconds per frequency.

- TE (Transient Evoked) Testing Options

This mode provides a comprehensive assessment of the cochlea's condition across a broader frequency spectrum and is ideal for general screening.

Protocols: 2 fixed protocols – TE 32s and TE 64s.

Frequency Range: 1.5 - 4 kHz.

Stimulus Level: 80 dB pe SPL (peak equivalent Sound Pressure Level).

Signal-to-Noise Ratio (SNR): 4 dB.

"PASS" Criterion: A response is registered at 3 out of 6 tested frequencies.

Testing Time: 32 or 64 seconds (maximum total testing time).

During the research, the results of the hearing examination of the biological object - the guinea pig, were assessed using the method of assessing the activity of the inner ear. In order to replace the human auditory canal during the study of the state of hearing, the auditory canal of guinea pigs, in particular domestic guinea pigs (Latin Cavia porcellus), was used. This was due to the fact that the auditory organ of the guinea pig is built almost identically to the human one[16] - although there are some differences in the structure of the hypotympanum and mesotympanum, where the round and oval windows are located at different levels, and the bone system has an additional ligament[17].

B. Study design

Data measurements were as following: each ear of a biological object (guinea pig) was tested via implementation of distortion product otoacoustic emission, where sound pressure value of distortion product was estimated.

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The obtained data is divided into experiments, each of which includes a group of results of examination of both ears of eight test subjects for six different frequencies: 2, 4, 6, 8, 10 and 12 kHz. Thus, each experiment represents a sample of 96 results grouped by frequency ranges for the specified six frequencies.

A control group, which was not exposed to medication, was separated from the total set of test subjects. The results of the hearing evaluation of this group were accepted as the norm for further studies. A total of 40 experiments were conducted with drug exposure and one to establish the initial normal value – experiment №1. For each frequency range in each experiment, 16 measurements were made, so a total of 3936 measurements were collected, 656 samples were collected for each of the used frequencies.

C. Statistical analysis

The obtained results were processed as follows: for each frequency range of each experiment, the average value of the amplitude of the sound pressure level obtained during the experiment was calculated. After that, deviations from the sample mean were determined for each frequency, and confidence intervals were constructed. The confidence interval indicates the range of values within which the result of the next identical experiment may lie within a probability of 95%.

In this study, standard normal distribution is σ=1.96≈2 at significance level of p=0.05. This means that means that **95% of the values** of a normally distributed random variable lie within the interval ±1.96 standard deviations from the mean[18]. If power of method allows it, lower value of p will be used, which will also be specified. Sigma [19] is calculated according to formula (1) or (2)

$$\sigma_x^2 = \frac{\sum(\bar{x} - x_i)^2}{n-1}, \quad (1)$$

$$\sigma_x = \sqrt{\frac{\sum(\bar{x} - x_i)^2}{n-1}}, \quad (2)$$

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}, \quad (3)$$

where expression(3) is the average arithmetic value of the sample, n is the number of results in the sample, x_i is the i-th member of the sample.

The given algorithm was used both for the assessment of normal and experimental (with drug exposure) experiments.

Statistically meaningful differences between two groups was calculated via implementation of parametric – Student's t-criterion [20] and non-parametric Mann–Whitney U-test [21] methods.

For estimation of the presence of normality distribution of features in the aggregate data group were used graphical method, Shapiro-Wilk method [22] and skewness estimation[23]. If two out of 3 aforementioned criterions are positive, the distribution is considered normal.

For estimation of correctness of the test, its power was used. Power is the probability of avoiding a Type II error (a 'false negative'), where you mistakenly conclude there is no effect when one is actually present (Type I and Type II Errors and Statistical Power).

Power estimation of Shapiro-Wilk method for asymmetric distributions is presented on Fig. 3.

For Student's t-test power curve[24] is presented on Fig. 4.

In turn Mann-Whitneys power ([25]) is shown on Fig. 5, where blue curves are for Mann-Whitney test and numbers in legend refer to the standard deviation.

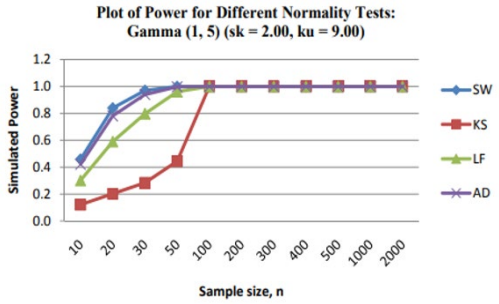

Fig. 3. Comparison of the power of the Shapiro-Wilk (SW), Lilliefors (LF), and Kolmogorov-Smirnov (KS) tests.

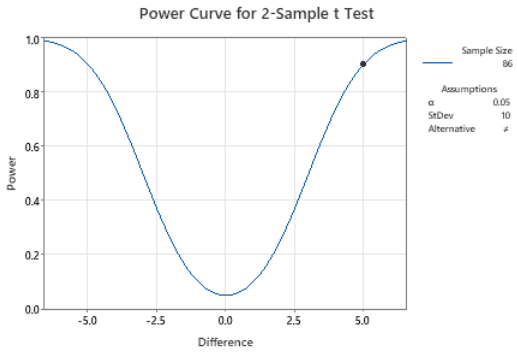

Fig. 4. The power curve of the Student's t-test

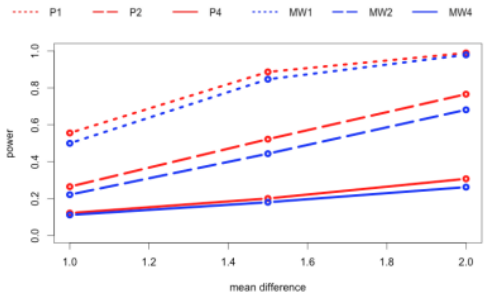

Fig. 5. The power curve of the Mann-Whitneys test (blue curves).

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Statistical analysis was performed via usage of JASP and Open Office data products.

III. RESULTS

New proposed method serves the estimation presence of a medical effect of a drug used to change the hearing level of a biological object. Said method is based upon utilization of the ratio of the mean value in the group to the standard error in it. Example of graphic representation of a “2 kHz” frequency groups results is presented on Fig. 6.

In this example is visible a clear divide between two major groups. Said groups can be described as follows – group one has more grouped results, lower deviation in a group and a higher mean result in a group. Second group on the contrary has lower mean values, higher standard error and the results are scattered.

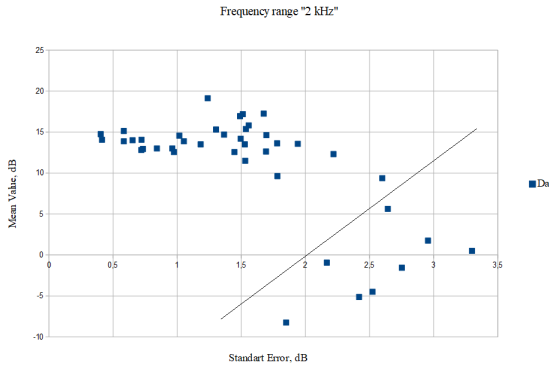

Fig. 6. Distribution of results in 2 kHz frequency range

TABLE 1. EXPERIMENTS IN THE SECOND (DEVIATING GROUP), NAMES AND NUMBERS

Experiment name	Experiment number
therapeutic action for 14 days during intra\tympan	1
therapeutic action for 14 days during intra\peritone	2
therapeutic action for 14 days during v/m	3
gentamicin 7 days after	4
therapeutic action for 7 days during intra/tympan	5
therapeutic action for 7 days during v/m	6
therapeutic action for 7 days during intra\peritone	7
gentamicin 14 days after	8

There were ten experiments in the second group. Their names are presented in a Table 1. All of them were obtained via usage of ototoxic influence.

Executed statistical analysis provided evidence of the presence of a statistically meaningful differences between two groups. Results from specialized statistical software are presented in Table 2. It is important to say that the results of the referential experiment №1 were considered normal and were present in group one and therefore it is named “Normal” for all other groups too. For the future references said results will be presented as “Test №1”.

In previous test data assessment sessions were used next methods:

- Usage of Sokolovs criterion[26];
- Application of a parametric and non-parametric analysis methods.

So, need arises to estimate if a new method provides corresponding results to the aforementioned tests. First step in it will be usage of Sokolovs criterion. As stated in [26], Sokolovs criterion values for different frequencies are as shown in Table 3.

In accordance with presented data results of the test group were analyzed and it was estimated, that for 2 kHz group mean sound pressure levels were lower than aforementioned criterion for 3 experiments. For proposed graphical method ten experiments were in a deviating group, and said 3 experiments were among this group (numbers 5-8). For the future references said results will be presented as “Test №2”.

Next step of method testing was conducted as a comparison of a parametric and non-parametric statistical analysis methods utilization results with proposed graphical method test results. Obtained from comparison data is shown in a Table 4. In all experiments presence of a statistically meaningful difference with experiment №1 was confirmed. For the future references said results will be presented as “Test №3”.

Validity of a presence of a difference between two experiment groups for 2 kHz frequency band – normal and deviating was concluded via application of aforementioned three criterions – complete results are presented in Table 5.

TABLE 2. STATISTICAL TEST RESULTS FOR 2 KHZ GROUP

Group Descriptives							T-Test		
	Group	*N*	*Mean, dB*	*SD, dB*	*SE, dB*	*Coef. of variation*	*t*	*df*	*p*
2 kHz	Normal	33	13.979	1.989	0.346	0.142	15.276	39	p < .001
	Deviating	8	-1.563	4.364	1.543	-2.793			

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TABLE 3. FREQUENCY CHARACTERISTIC OF THE TEST ACCORDING TO Y. K. SOKOLOW, SUPPLEMENTED FOR HIGH FREQUENCIES

Frequency, kHz	2	4	6	8	10	12
The upper limit of the confidence interval, dB					-5,46	-5,97
Sound pressure level, dB	-4,34	-4,95	-4,92	-6	-6,37	-6,88
The lower limit of the confidence interval, dB					-7,29	-7,80

TABLE 4. COMPARISON BETWEEN STATISTICAL ANALYSIS AND PROPOSED GRAPHICAL METHOD

Experiment number	Presence of a statistically meaningful difference with experiment №1
1	Present
2	Present
3	Present
4	Present
5	Present
6	Present
7	Present
8	Present

TABLE 5. COMPLETE TEST RESULTS FOR NEW METHOD, 2 KHZ FREQUENCY BAND

Test number	Test №1	Test №2	Test №3
Result	Difference present, p<0,001	3 results out of 8 are below criterion (Experiments №6-8)	Difference present in 8 out of 8 expe–riments

TABLE 6. COMPLETE TEST RESULTS FOR NEW METHOD, 4 KHZ FREQUENCY BAND

Test number	Test №1	Test №2	Test №3
Result	Difference present, p<0,001	8 results out of 8 are below criterion	Difference present in 8 out of 8 experiments

Same tests were conducted also for another 5 frequency bands. The results for frequency band “4 kHz” are presented in Table 6. Distribution of a results in it is shown on a Fig. 7.

Another observed difference is for test №2, where all experimental results were below criterions value. For the test N3 difference was present in all experiments.

Observed in this frequency band deviating group is different from previous one – standard error in it does not differ from “Normal” group.

Graphs of all other frequency groups are presented on Fig. 8.

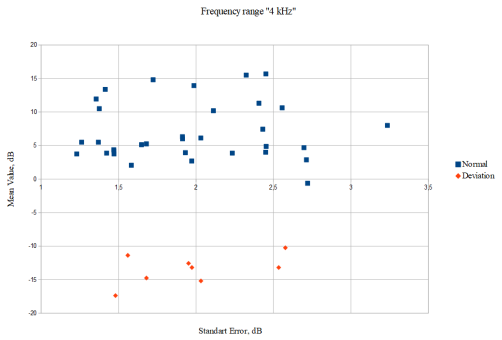

Fig. 7. Distribution of results in 4 kHz frequency range

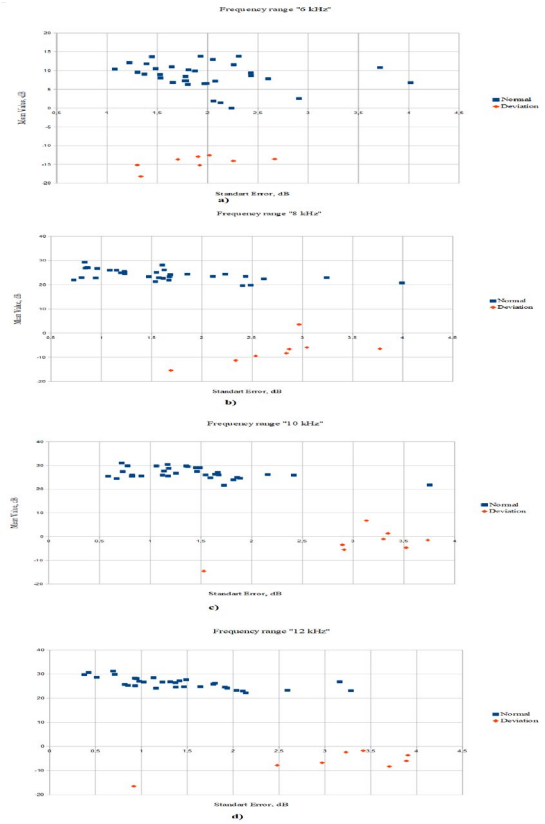

Fig. 8. Distribution of results in 6 kHz frequency band (a), in 8 kHz frequency band (b), in 10 kHz frequency band (c), in 12 kHz frequency band (d)

Fig. 3 shows that apart from 6 kHz frequency band all deviating groups have higher standard error, while other two parameters (mean values in groups and scattering) were present. Results of conducting of tests №2 and №3 for said frequency bands are presented in a Table 7. From said table it is possible to see that in majority of cases all three test were passed, but for some cases with Sokolov’s criterion only part of experiments had mean value below needed point. In conclusion, it’s possible to see that three tests for frequency bands 4-8 kHz were passed, but for test №2 frequency bands 2 kHz, 10 kHz and 12 kHz had at least 5 more results which exceeded Sokolov’s criterion but were in deviating group each. In general, for all frequency bands 8 same results were determined to be in deviating group.

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TABLE 7. COMPLETE TEST RESULTS FOR NEW METHOD, 6-12 KHZ FREQUENCY BAND

Test number	Test №1	Test №2	Test №3
Frequency band 6 kHz	Difference present, p<0,001	8 results out of 8 are below criterion	Difference present in 8 out of 8 experiments
Frequency band 8 kHz	Difference present, p<0,001	6 results out of 8 are below criterion (experiments №4 and 5 are above criterion)	Difference present in 8 out of 8 experiments
Frequency band 10 kHz	Difference present, p<0,001	1 result out of 8 is below criterion (experiment №8)	Difference present in 8 out of 8 experiments
Frequency band 12 kHz	Difference present, p<0,001	3 results out of 8 are below criterion (experiments 3, 7, 8)	Difference present in 8 out of 8 experiments

IV. DISCUSSION

The issue of healing from and rehabilitation after ototoxicity substances exposure due to medical, occupational, environmental or other factors is at priority due to growing number of cases nowadays. Currently, number of clinical studies of a minimization of the ototoxic effects are ongoing, however there is a need for improvement in the used methods of study not only to better understand the mechanism behind ototoxicity in wide array of individuals with differing values of hearing loss [27] but to improve healing process as well.

One of the prominent methods to evaluate the effectiveness of healing, rehabilitation or severity of hearing loss during ototoxicity exposure is distortion product otoacoustic emissions. Said method are more effective then classical pure tone audiometry tests [28] and can be used in number of situations apart from healing – for example, the search of hidden hearing loss due to prolonged high noise levels from the factories [29]. Apart from factories some studies [30] also had found the possibility for implementation of said otoacoustic emissions not only in factories, but also in clinical environments with high levels of noise exposure.

Out of the ways of improvement of distortion product otoacoustic emissions method of monitoring of the hearing organ of biological object is optimization of rate of amplitude of stimulus signals and relations of frequencies of said signals. It was found that for different frequency bands different frequency ratios must be used to obtain the largest DPOAE levels when hearing organs are tested for calculation of ototoxic influence[31].

Noteworthy is also new method of analyzing of obtained otoacoustic emissions data via implementation of trained models which can simplify calculation of results of ototoxic treatment[32].

Apart from usage of learned models, sometimes deep-neural-networks are implemented. Also said networks can differ in their efficiency depending on their architecture, and be effective not only in working with already acquired data, but also for modelling back-propagation system [33].

Novel ways of implementation of OAE include usage of some type of emissions for creation of the new types of biometric data[34].

All aforementioned facts highlight the need for upgrading existing and creating new methods of working with obtained via usage DPOAE data, one of which is presented in this study.

Further research on this topic involves creating a physical prototype of the device. Such device can be a useful tool in medical procedures not only aiding the personnel by providing a reliable and precise data but also speeding up the whole process resulting in better patient care.

CONCLUSIONS

Presented in the study results show that proposed graphical analysis method can be used for estimation of the effectivity of rehabilitation of a hearing organ of biological object due to its distinction in highlighting differences between data groups which had been subjected to the influence of ototoxic drug and ones which either had not or had ototoxic influence on them mitigated.

Further analysis had shown that results, obtained by graphical method, correlates well with statistical analysis conducted both on pair of normal and deviating experiment group, and on pairs of an experiment №1 (normal value) and experiments in deviating group for each frequency band.

At the same time differences were observed for implementation of Sokolov's criterion, where proposed graphical method had found additional differing from normal value results for frequency band of 2 kHz – 5 more results which values are above criterion, band of 8 kHz - 2 more results above criterion, band of 10 kHz - 7 more results above criterion, band of 12 kHz - 5 more results above criterion.

Summarizing everything aforementioned – proposed graphical method correlated perfectly with statistical methods of finding differences between values in data groups and provided more results for majority of frequency bands (high-frequency ones) then method utilizing Sokolov's criterion.

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A promising direction for further research is prototype development of the proposed device, the main advantages being reliability and completion speed.

CONTRIBUTION OF AUTHORS

Pareniuk A.– sources preparation.

Pareniuk D.– statistical analysis, writing.

Rudenka K.– experimental data obtaining.

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Графічний метод оцінки ефективності реабілітації слухового органу

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Анотація—Метою даної роботи є аналіз можливості використання та ефективності нового запропонованого графічного методу оцінки наявності різниці між здоровим і хворим органом слуху біологічного об'єкта під час реабілітації від ототоксичного впливу. Вказаний метод призначений для забезпечення більшої швидкості аналізу, підвищення його якості та можливості його застосування всім медичним персоналом – як лікарським, так і сестринським.

Матеріал і методи. Під час підготовки даних було проведено 41 експеримент. Всього було виконано 3936 вимірювань, по 96 для кожного експерименту. Кожне вимірювання проводилося на одному вусі морської свинки шляхом використання отоакустичної емісії на частоті продукту спотворення. Із зазначених 41 експерименту 40 були проведені на піддослідних групах з різним впливом медикаментів (як ототоксичний, так і лікувальний), а один проводився як референтний – для демонстрації нормального стану органу слуху. У кожному експерименті вимірювання були розподілені між 6 діапазонами частот (2 кГц, 4 кГц, 6 кГц, 8 кГц, 10 кГц, 12 кГц) – по 16 вимірювань у кожному. Далі було розраховано середнє значення сигналу отоакустичної емісії та стандартну помилку в кожній смузі для кожного експерименту. Отримані значення були використані в представленому методі для пошуку відмінностей між ними. Пізніше був реалізований статистичний аналіз для перевірки надійності методу. При статистичному аналізі було враховано нормальність розподілу результатів у групах і в залежності від цього використано параметричний або непараметричний тест. Надійність зазначених методів перевіряли також шляхом використання критерію Соколова.

Результати. Імплементація запропонованого методу показала, що для кожного діапазону частот результати були розділені на дві великі групи – нормальна група (містить експеримент №1 у своєму складі) і відмінна група. Відмінності між двома групами наступні – нормальна група має вищі середні значення, менші стандартні помилки експериментів у ній і результати менш кучно розподілені на графіку. Надійність запропонованого методу перевіряли за допомогою трьох різних тестів – наявність статистично значущих відмінностей між середніми значеннями експериментів у нормальній групі та групі із відмінностями, наявність статистично значущих відмінностей між даними експерименту № 1 та кожного експерименту в групі з відмінностями та кореляція результатів методу із результатами використання критерію Соколова. Випробування підтвердили надійність запропонованого методу і показали, що він навіть має переваги перед уже використовуваними методами – будь то більша чутливість або простота його реалізації.

Висновок: тестування нового методу показало його надійність за результатами проведених серій тестів для кожного діапазону частот. Крім простоти реалізації та збільшення швидкості аналізу результатів, запропонований метод також має більш високу чутливість, ніж деякі вже існуючі методи аналізу результатів аналізу стану органу слуху в біологічному об'єкті.

Ключові слова — отоакустична емісія; продукт спотворення; біологічний об'єкт; об'єктивна аудіологія; машинне навчання.