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Pure-tone audiometer

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Abstract. The research focuses on a pure-tone audiometer designing. The relevance of the study is proved by high incidence of an auditory analyser in older people and children. At first, the article provides information about subjective and objective audiometry methods. Secondly, we offer block-diagram and basic-circuit arrangement of device. We decided to base on STM32F407VG microcontroller and use digital pot in the function of attenuator. Third, we implemented microcontroller and PC connection. C programming language is used for microcontroller's program and PC's interface. Fourthly, we created the pure-tone audiometer prototype. In the future, we will implement the objective method ASSR in addition to pure-tone audiometry.

1. Introduction

Audiometry is the science of measuring hearing acuity and variations in a sound. It is well-known that all sounds can vary according to loudness (intensity) and the speed of sound wave vibrations (tone). Audiometry is performed using an audiometer, a special electro-acoustic device. The relevance of the study is proved by high incidence of the auditory analyzer in older people and children. According to the website of the Russian Federal Service of State Statistics in the period from 2000 to 2014, the average number of new cases of disability caused by diseases of the ear and mastoid process is about 9.5 thousand people per year. Thus, diagnosis is the first and the most important stage of the recovery process, since the therapy is more successful at the early stages of the disease. Nowadays, audiometry is widely used for evaluation of a hearing status in clinics. There are several methods for determining hearing thresholds [1, 2].

1.1 Pure-tone audiometry

Pure-tone audiometry is used to determine the hearing thresholds at different frequencies. As a rule, a frequency range of the hearing test varies within 125 – 8000 Hz. This range corresponds to the speech frequencies, so it is of prime importance in hearing research. During air conduction audiometry, the patient gets a pure tone of one frequency through headphones. Generally, the research begins with a frequency of 1000 Hz. The initial intensity of the sound should be easy for identification for a patient [3].

Gradually, the tone level of intensity is reduced at 10 dB to the disappearance of its perception. Then the stimulus intensity increases up in increments of 5 dB to the emergence of auditory sensations. For a more precise definition of thresholds, these operations are repeated.

During the bone conduction audiometry, the test signal is reproduced using the bone oscillator located on the mastoid bone or the frontal bone.

The values of the thresholds are inserted into the audiogram blank sheet. The tone frequency expressed in hertz is recorded on the horizontal axis, while the vertical axis shows the tone intensity expressed in decibels referred to the average normal hearing thresholds. Air conduction curves are shown as a continuous line, while the bone conduction curves are presented as a dotted line. The information for the right ear thresholds is marked with points while those for the left ear are marked with crosses.

The audiogram gives a fundamental description of auditory sensitivity. According to the international classification of hearing loss, to calculate the degree of hearing lesions, it is necessary to summarize the four values, i.e. the lowest audible sound intensity using the frequencies of 500, 1000, 2000 and 4000 Hz, and then to divide the sum by 4 to get the arithmetic average using the following formula:

$$I = \frac{I(500) + I(1000) + I(2000) + I(4000)}{4}. \tag{1}$$

The choice of these frequencies is based on the fact that they are the main speech frequencies. According to the calculated average value, the degree of hearing loss is determined as shown in Table 1. The audiogram helps to determine not only the degree of hearing loss, but also the type of pathology: sensorineural, conductive or mixed.

Table 1. Degrees of hearing loss.

Degree	Hearing loss range (dB)
I	26–40
II	41–55
III	56–70
IV	71–90
Deafness zone	> 91

1.2. Speech audiometry

It is well known that patients may have a different perception of speech with a completely identical threshold audiogram. Therefore, there is a method of speech audiometry. The method is as follows: a speech or a few words written by a high-quality recording equipment is further transmitted to the headphones; the groups of words are selected so that they are phonetically uniform and follow a verbal, rhythmic, and dynamic structure of the language. During the recording, all the words are pronounced with the same loudness, which is controlled with a voltmeter. Each record contains 50 words; the attenuator adjusts the sound level at which the recorded words are passed to the test subject.

Speech audiometry is performed to obtain the curve characterizing intelligibility. To build it, one needs to define at least three points. Abnormalities of the conductive apparatus show the intelligibility curve which is almost parallel to the normal one, with the intelligibility thresholds usually exceeding normal thresholds by no more than 40-50 dB. In the case of sensorineural hearing loss intelligibility, the curve is not parallel to the normal curve.

1.3. Suprathreshold audiometry

Patients with different degrees of hearing loss in both ears can experience loudness growth enhancement, which is known as recruitment. The essence of the phenomenon is that the impaired ear perceives sound stimuli louder than the healthy ear perceives them. This phenomenon is observed in some hearing disorders, such as lesions of the organ of Corti cells. Recruitment detection tests are called the suprathreshold audiometry.

The most common test of this type of audiometry is Short Increment Sensitivity Index (SISI-test). The essence of the SISI-test is as follows: the sound intensity exceeds the threshold by 20 dB, while a sudden short (200 ms) amplification by 1 dB occurs once per 3-5 seconds. The patient presses a button when hearing loudness growth. The normal human ear is capable of detecting the increase in 20 or 30% of all cases.

In other words, the healthy ear cannot distinguish a short-term access of the tone by 1 dB. The more correct answers the patient gives, the higher the likelihood of hearing damage is, since this is the case when the sensitivity to the short-term access of the tone increases. The SISI-test is used to determine the ear receptor destruction and hearing loss [4].

The suprathreshold audiometry has a diagnostic value. The presence of recruitment helps to distinguish the sensory hearing loss (loss of the inner ear) and the neural hearing loss (damaged nerve VIII).

1.4. Objective audiometry

Recording of auditory evoked potentials (ABR) is the most effective method of differentiation of the sensory hearing loss from neural hearing loss. The key difference of ABR from all above-mentioned methods is its objectivity; in this case, we do not even need to receive a response directly from the patient.

During testing, series of acoustic stimulation pulses (clicks) pass through headphones with the frequency of 11 to 21 pulses per second. The stimulus may be a tone sequence, as well as a chirp-signal. The positive electrode is placed on the forehead or on the vertex, the negative - on the ipsilateral mastoid or earlobe. A third electrode, which is grounding, is located on the forehead near the bridge of the nose or on the opposite mastoid.

When a patient receives an acoustic stimulus, the brain produces evoked potentials. The line obtained on the encephalograph screen has several peaks. The magnitude of peak 5 characterizes the work of the auditory analyzer.

During this procedure, the electrodes record not only the ABR, but also various types of the electrical potential caused by the work of the brain, muscle activity, etc. The amplitude of these potentials exceeds hundreds and thousands of times the ABR amplitude. To highlight ABR among these noises, all recorded periods of activity are added together and then averaged by a computer processor. The weak point of the ABR method seems to be a long duration of the procedure, when using tone bursts; however, they are used to construct the threshold audiogram.

The thresholds of detecting peak V (ABR threshold) expressed in dB correlate well with subjective audiometric thresholds. To construct the estimated audiogram, we should apply a modification of minus 10-15 dB [5].

In addition to the ABR, there is another objective method, namely Auditory Steady-State Response (ASSR). Installation of electrodes for recording the auditory steady-state potential is the same as the ABR record. Unlike the previous methods, the offered method places special emphasis on the modulated signal supplied to the patient and relies heavily on three types of modulation: frequency, amplitude, and hybrid modulation. ASSR uses a mathematical algorithm for the detection of hearing thresholds: Fourier analysis is based on the stimulus modulation frequency to obtain information about the amplitude and phase response [6]. Hearing is considered normal if the ABR or ASSR is recorded at the level of the input stimulus of 35 dB. The absence of the ABR or ASSR to this stimulus is the basis for a diagnostic test [7].

ASSR has the advantage compared to the ABR since it allows one to examine patients with residual hearing, as the stimulus can be produced at levels up to 120 dB [8].

As a result of the reviewed procedures, we focused on implementation of pure-tone audiometry and ASSR.

2. Research methods

This research focuses on various designs of audiometers which were examined to find out the current level of implementation of these instruments.

The first audiometers were the instruments, using which it was possible to carry out pure-tone audiometry and speech audiometry. Since these techniques are basic, the audiometers of this type are still in use. Today there are audiometers that have touch screens and comfortable control tools (knobs and buttons). Knobs can be rotated to control frequency and amplitude; buttons can be pushed to present the stimulus [9].

It is important to note that many companies producing medical electronics seek for ways to reduce the weight and dimensions of the devices, making them portable like the audiometers produced by MedRx (USA). In addition, recently automated audiometry has become a research field of great importance, since it saves the patient's time and does not require additional devices [10].

There are very interesting developments of Neurosoft Company (Russia) which are used all over the world. Neuro-Audio is a state-of-the-art instrument having a full set of objective and subjective methods for diagnosing the level of destruction of the auditory and vestibular analyzers: ABR, ASSR, multi-ASSR, medium and long latency auditory evoked potentials, otoacoustic tests, electrocochleography, vestibular myogenic evoked potentials, cognitive evoked potentials (P300, MMN), pure-tone audiometry. All of these functions are implemented in a compact enclosure.

We offer the following block diagram of the audiometer (Figure 1).

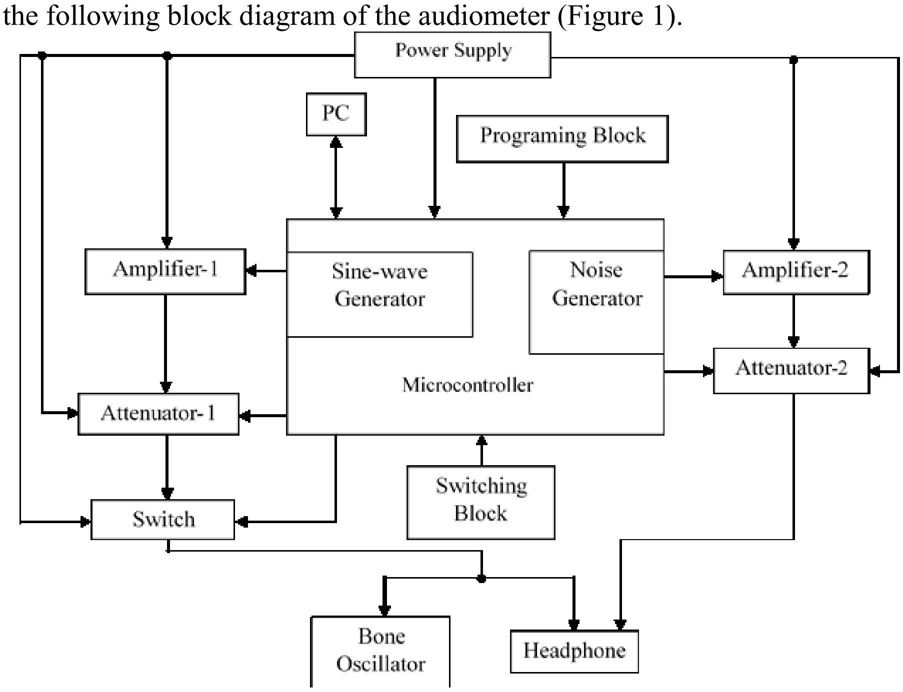


Figure 1. Block diagram of pure-tone audiometer.

A sine-wave generator outputs a voltage of the one of the following octave frequencies: 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz (pure tones). A microcontroller controls the generator. The signal passes through amplifier-1 and attenuator-1. Then it passes through a switch, which directs it to a headphone, or to a bone oscillator. The masking noise produced by a noise generator is also amplified and regulated, but enters only the headphones. The microcontroller controls attenuators implemented on digital resistors. In addition, the device has a connection with the computer to visually simulate the audiogram. There is a block of microcontroller programming and the patient button in the device. The supply voltage is supplied to the generators, amplifiers and power supply from the microcontroller.

To realize the objective audiometric techniques, we must use a bioamplifier. The polarization galvanic electromotive force is generated at the skin-electrode. The only way to reduce the influence of sources of EMF galvanic polarization is to increase the input impedance of the amplifier and its balancing. Due to the high level of common mode noise and sufficiently low input signal values of biopotentials, the solution is the use of a instrumentation amplifier built with three operational amplifiers. In addition to the circuits with discrete components, integrated circuits are widely used. E.g., AD620 has been designed specifically for measuring biopotentials [11]. In general, the use of integrated circuits makes it possible to enhance the efficiency and reliability of the device.

3. Audiometric headphones

When conducting audiometric studies it is necessary to use special earphones having a uniform frequency response over a wide frequency range. Basic headphones parameters are operating frequency range, impedance, and sensitivity.

The frequency range covers the frequencies which can be reproduced by the device. A human hears the range 20 Hz - 20 kHz. Headphones with the frequencies that exceed this range have a higher sound quality than the headphones with a narrow range. To perform audiometry (especially high audiometry) it is important to perform measurement at all the frequencies. Therefore, the frequency range should exceed the audible range. Moreover, it will provide less distortion when playing back the boundary frequencies of the audible range.

Impedance is an important feature, because the volume of playback and the level of energy consumption are dependent on the impedance of the headphones. The higher the impedance, the lower the volume of the headphones (at the same sensitivity), and the smaller the power consumption. In addition, high impedance improves playback quality by improving the signal-to-noise ratio.

Total harmonic distortion (THD) determines the sound fidelity. Its value depends on internal parasitic resonances, reflections and other distortion factors. The value of <1% is acceptable (and more often indicated) but the method of measurement of THD is not standardized among manufacturers.

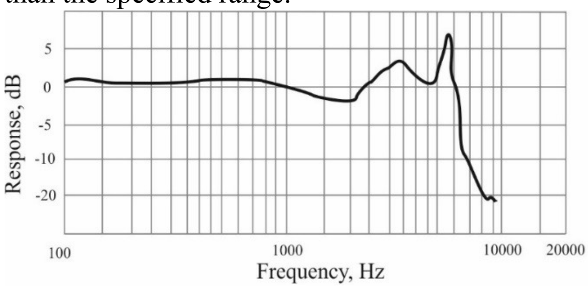
Headphone sensitivity characterizes its volume. It is usually expressed in dB/mW. Unfortunately, due to the lack of a strict standard for measuring the stand structure, the sensitivity of headphones produced by different manufacturers is not comparable.

Table 2 shows the parameters of audiometric headphones produced by Telephonics (USA) and Sennheiser (Germany) [12, 13].

Table 2. Specifications of Audiometric Headphones.

	TDH39	HDA280
Frequency band	100 – 8000 Hz	20 – 20000 Hz
Impedance	10 Ohm	37 Ohm
Sensitivity (at 1 kHz, 1 W)	108±4 dB	117 dB
THD (at 1 kHz, 100 dB)	< 1 %	< 0,7 %
Estimated cost	210 $ (200 €)	205 $ (195 €)

The objective difference in the quality of headphones can be shown when comparing the frequency response. It demonstrates the dependence of the relative transmission ratio, expressed in decibels, on the frequency. The reference level (0 dB) is usually about 1 kHz. The unique feature of professional audiometric headphones is that they have a flat frequency response at low frequencies. This is shown by the following characteristics for headphones TDH39 and HDA280 (Figure 2). As a rule, conventional earphones have a reduction of frequency response in this frequency range due to the occurrence of any air gap between the ear and the earphone. Since audiological studies are conducted at frequencies from 125 Hz to 8 kHz, the frequency response of the headphones is only slightly greater than the specified range.



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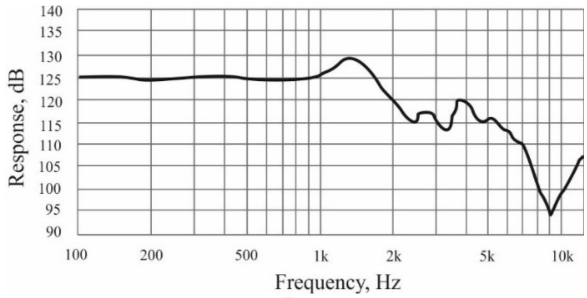

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Figure 2. Frequency response of audiometric headphones: (A) TDH-39P; (B) HDA280.

For audiometry purposes it is necessary to know advanced specifications including the environmental sound attenuation characteristics (to determine the Maximum Permissible Ambient Noise Levels: MPANLs), the linearity of the response to voltage, and the Reference Equivalent Threshold Sound Pressure Levels (RETSPL) [14].

An important technical characteristic is the shape of the headphone ear pads. “Supra-aural” means that the cushion sits on the pinna. Circum-aural cushion seals around the ear. It makes them more comfortable for the patient. Compared to a circum-aural cushion, the supra-aural cushion has many leaks and is not a good attenuator of external sounds [15].

In addition to headphones with a closed form of ear cushions (Supra-aural and Circum-aural) for audiometry we can use audiometric insert earphones, for example, ER-3A by Etymotic Research (USA). Foam pads surround the tips of these headphones. Foam eartip is compressed before being placed in the ear, and then they straighten tight sealing the ear canal. Foam eartips are designed for single-use and should be replaced with new eartips for each test session performed.

The advantage of audiometric insert earphones is that they provide a good sound separation between the ears over the entire range of frequencies of the test. This eliminates the need for masking noise in cases where the patient has a large difference in the sound perception by the left and the right ear. Besides, the use of insert earphones reduces the requirements for soundproofing of the audiological room [16]. Insert earphones are useful when testing profoundly deaf patients with “left corner audiograms”, where the response to the TDH-39 is often vibrotactile rather than auditory.

The frequency response of the currently recommended supraaural headphone (TDH-39) is not significantly different from that of the most common clinical audiometric insert earphone (ER-3A). In fact, the Etymotic Research ER-3A was purposely designed to mimic the limited real-ear frequency response of the TDH-39 so that the two transducers could be used interchangeably [17].

More than that, we researched the frequency response of headphones MDR-ZX310 by Sony. These headphones have been researched using noise-level meter Testo816 with automatically switchable measuring ranges 30-80 dB, 50-100 dB, 80-130dB. The generator that is connected to the headphones sets the frequency from 125 Hz to 18 kHz. The amplitude of the input signal is 2.5V.

Table 3. Experimental Frequency Response.

f (kHz)	0.125	0.250	0.500	1	2	3	4	6	8	10	12	14	16	18
U (dB)	79.9	89.1	92.4	100.9	102	102	102	102	102	101	99.2	90.9	81.9	46.5

The experiment shows that the researched headphones have a flat frequency response in the frequency range from 1 kHz to 10 kHz. There is a decrease in the output signal level at the lower and upper frequencies. The experimentally obtained characteristic will be used when creating a sine-wave generator. For frequency response alignment, we will make correction by increasing the input voltage.

4. Interface
The program was developed in C++ in a Visual Studio environment. The appearance of the program is shown in Figure 3.

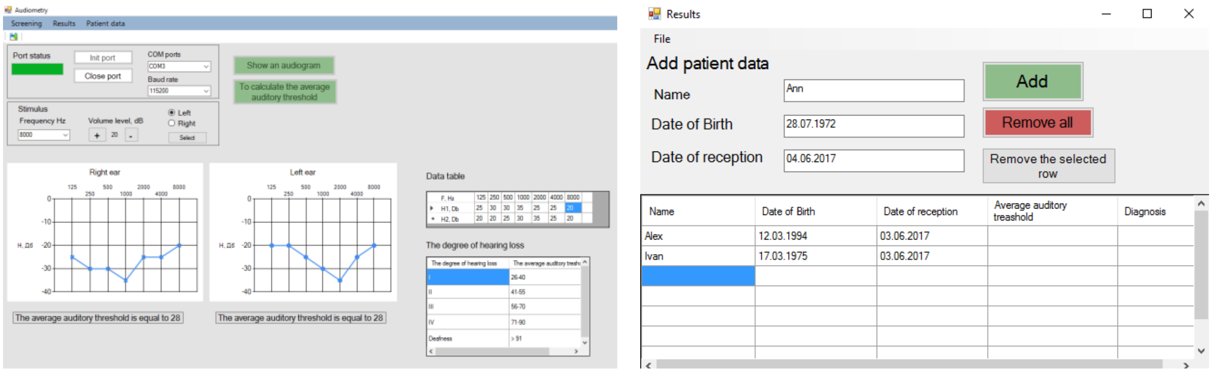

Figure 3. Appearance program for controlling the audiometer.

At the program opening only “Start test” button is available for the user in the work area. When the button is clicked, the available com-ports are searched and panels for configuring com-port and signal parameters are displayed in the working area.

The “COM ports” field is used to select the virtual com-port number. The “Baud rate” field is used to select the transmit/receive baud rate, which will be coordinated with the microcontroller. When the “Init port” button is pressed, the microcontroller is connected to the program.

After that, user should select the frequency of the signal applied to the headphones and the volume level in decibels, as well as which ear will be examined: right or left, and press the “Select” button. The “Select” button is pressed once when the ear is selected, then this button is unavailable when the frequency and level are changed.

After selecting all the parameters, the hearing study begins according to the method. When the patient hears the signal sent to the headphones, he presses the button. Each press is displayed in the program. At the same time, the program records the current level and frequency of the signal. After researching at all frequencies, the buttons “Get an audiogram”, “Calculate an audibility threshold” and buttons for examining the other ear become available to the user. The construction of an audiogram and calculation of the threshold of audibility is automatic.

The program has the ability to save or print the results. The user should go to the “Results” tab of the main menu, select “Generate”, and then a new interactive window will open. There are options to add and remove new patients in the Result window. User should save a table with patients or open existing documents to modify and view the data contained in them.

5. Conclusion
The research outcomes enabled us to consider the most common methods of audiometry, each of them having its own niche. Pure-tone threshold audiometry helps to evaluate the degree of hearing loss and to properly rectify the hearing aid under each octave frequency. Speech audiometry is used to determine the percentage of words intelligibility. Suprathreshold audiometry helps to determine the location of lesions of the auditory analyzer. In this respect, objective methods seem to be the most accurate. These methods can be applied when a patient cannot give clear answers.

In the course of our work, the following methods have been chosen for implementation: pure-tone audiometry and ASSR. A structural diagram of a pure-tone audiometer was developed, as well as software for visualizing an audiogram on a computer monitor and the ability to print survey results was developed. The layout was made using the STM32F4-Discovery board. Based on the literature review of the headphones, the device adjusts the unevenness of the headphones frequency response. In the future, the implementation of the ASSR methodology in addition to pure-tone audiometry is planned.

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