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Short review of devices for detection of human breath sounds and heart tones

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Abstract
The article reviews currently available acoustic sensors used to detect breath sounds and heart sounds on the surface of the human body. The review covers acoustic mechanoelectrical devices, dynamic, piezoelectric and electrostatic microphones as well as microelectromechanical systems (MEMS) currently used to obtain biological acoustical signals. In addition, the review part of the article ends with the authors' conclusions on the use of certain acoustic sensors to detect acoustic noises of the human bronchopulmonary and cardiovascular systems.

Keywords: Biological signals; acoustic sensor; heart sounds; bronchopulmonary system; auscultation.

Auscultation in medicine is a physical examination method that allows drawing conclusions on patients' state of health based on sounds produced by internal organs [1].

The key drawback of this method is the subjectivity of physicians' assessment of acoustic data. It is connected with the fact that diagnostic decisions depend on many hard-to-record and subjective factors. It is noteworthy that frequency characteristics of the stethoscope weaken signals with the frequency of over 120 Hz [2-4] and the human ear is characterized with low sensibility to low frequencies. In this connection, physicians' assessment of the bronchopulmonary and cardiovascular systems by means of auscultation is subjective. Subjective perception can be explained in the following way. Up to 80% of adults have an ear for music, but only 12-15% of them have musical memory. An ear for music implies an ability to detect both individual musical elements and quality of musical sounds (pitch, volume, and structure) as well as functional relations between them in a piece of music (tonal memory, sense of rhythm). It has been found out that the range of frequencies detected by the female ear is significantly wider than that for the male ear. Females more clearly perceive high sounds and better distinguish tones and intonations. The acuity of female hearing remains high up to 38-40 years old, while males' sense of hearing starts going down at the age of 32-35 years. Hearing acuity of males and females becomes comparable at the age of 63-65 years, and it becomes approximately 2-2.5 times lower as compared to the level of 25 years of age. However, people maintain an ability to perceive high-frequency timbre components. The hearing acuity becomes approximately three times lower by the age of 65 years, people stop hearing sounds with the frequency of over 10-12 kHz. The changes indicated are connected with sclerotic processes in the internal ear and general reduction of the sensitivity of cortical representations of the analyzers in the brain [5].

Unfortunately, the height of physicians' professional strength and optimal combination of experience, knowledge, and professional skills fall on the age of 35-40 years – the period of time, when human sensory organs start losing their acuity. The use of up-to-date electronic achievements can compensate for age-related changes in the sensory organs to a certain extent. As opposed to standard stethoscopes, electronic stethoscopes allow not only recording acoustic signals produced by the human cardiovascular and bronchopulmonary systems but also conducting a mathematic analysis of these sounds in order to compose an objective conclusion on patients' state of health. It has restored interest in research on the human body's acoustic phenomena and led to the emergence of many scientific papers directed at the development of effective and sage methods for automated analysis of acoustic data of the human bronchopulmonary and cardiovascular systems and introduction of these methods into medical practice [3].

Acoustic sensors are used in medical equipment primarily to detect and record human bronchopulmonary sounds and heart sounds. At the same time, the type of acoustic detectors used to detect certain signals (heart sounds, pulmonary sounds) depends on the area of application of specific medical equipment.

Devices for electronic auscultation use practically all types of acoustic mechano-electrical devices that transform acoustic vibrations into electrical signals. The most popular devices are various microphones, including piezoelectric sensors and acceleration sensors (accelerometers).

Dynamic microphones are one of the most common types of detectors. It is a light membrane based on a flexible hanger with attached copper wire coil. The coil is placed in a constant magnetic field. Sound vibrations detected by the mobile membrane are transferred to the wire coil. It produces synchronized magnetic vibrations that cause electromagnetic induction. The quality of generated signals significantly depends on the mechanical properties of the mobile system, uniformity of the magnetic field and other features of the system [6].

Dynamic microphones have good acoustic and electric characteristics: sensitivity from 1 mV/Pa, frequency range from 50-100 Hz to 10-15 kHz. Acoustic sensors based specifically on this type of microphones were used in the first experiments for registration of breath sounds [7]. An undisputable benefit of this type of microphones is a very low level of noises primarily determined by heat noises of the wire used and noises produced by galvanic couples in the junction point.

However, dynamic microphones have several drawbacks: difficult and massive construction, relatively low sensitivity, difficulties with forming directional responses, etc. Therefore, nowadays acoustic sensors based on condenser (electrostatic) microphones are used significantly more widely. It consists of a thin metallized polymer film that plays a role of mobile condenser armature and massive immobile armature located at a close range (0.1-0.15 mm). The condenser carries constant voltage that is transformed into low-frequency signals, when the mobile armature vibrates under the influence of sounds. An alternative option of condenser microphones is an electret microphone. In this case, the immobile armature is a plate of polarized serum. Such a microphone does not require external power supply, since an electrostatic charge is formed on it during the process of production [6].

A wide range of detected frequencies, stable parameters, and high sensitivity can be attributed to the benefits of sensors based on electrostatic microphones. The sensitivity of up-to-date electrostatic microphones is from 1.5 mV/Pa for electret microphones and from 5 mV/Pa for microphones with phantom power supply (the higher this indicator, the higher the sensibility). The signal/noise proportion for the best models of electret microphones is −62 dB. As for microphones with external power supply, it is −110 dB. However, these microphones are characterized with high output resistance (dozen and hundred megaohms) and should be used with a low-ohm microphone cable. This problem can be solved by means of a buffer amplifier based on a field transistor or small electric lamp. This solution also has certain drawbacks: increased value of noises in the range of up to 100 Hz, if the field transistor is used [6].

Piezoelectric microphones are a bit less popular in phonography. The core of this microphone is a piezoelectric element impacted with sound waves (directly or through a membrane). As a result, it generates potentials that change together with changes in the sound pressure. It leads to generation of alternating electric signals on the opposite parts of the piezoelectric element. It is characterized with a simple structure, rather good frequency characteristics in the sphere of low frequencies; however, it is quite sensitive to temperature and moist.

Piezoelectric microphones used in medicine have a membrane structure. These microphones consist of a diffuser made of paper or a thin aluminum foil connected with the piezoelectric element. The sound pressure impacts the diffuser and, through it, the piezoelectric element. Such microphones are characterized with extremely high sensitivity (up to 50 mV/Pa).

As for the drawbacks of piezoelectric sensors, these are a need for hard and high-quality contact with the patient's skin (it is achieved by means of special pastes and gels) and low mechanical durability. The latter is conditional to the fact that thin ceramic films are used in highly sensitive acoustic sensors. They can be of 100 μm in thickness and less.

Some authors say about an increased level of noises of piezoelectric films. However, it can be reduced significantly, if advanced nanotechnologies are used to produce piezoelectric ceramic components.

At the beginning of the 1980s of the past century, the development of submicro- and nanotechnologies has made it possible to produce sensors based on the MEMS technology, including microphones. It is possible to single out the following benefits of MEMS microphones: MEMS microphones can be smaller than most compact microphones; they are less liable to vibration, temperature fluctuations and electromagnetic interference and more resistant to noises due to the absence of wires and installation of circuits close to the MEMS crystal.

Besides MEMS microphones, inexpensive, precise, and compact MEMS accelerometers can be used to detect acoustic signals. These devices became popular in the middle of the nineties of the past century. They contain one-, two-, or three-axis microsensors that can measure acceleration simultaneously on one or several coordination axes [8].

MEMS elements usually contain an electronic signal converter circuit that significantly simplifies the use of these devices. The converter of up-to-date MEMS accelerometers contain an electrometric amplifiers, 12- or 16-digit digital-to-analog converter and digital interface that usually uses the I2C serial data communication protocol. The ADXL103 MEMS accelerometer is widely used in smartphones and tablets. It costs six dollars and has the resolution of 1 mcg and operating range of frequencies from 5 Hz to 2.5 kHz. Its dimensions are $5 \times 3 \times 2$ mm, and its weight is less than 2 g [8].

There are data on successful experiments on the use of up-to-date MEMS accelerometers to record breath sounds. The 12M1 MEMS accelerometer was used in adult volunteers. It successfully registered not only pulse fluctuations of the front chest wall but also breath sounds. Placing an accelerometer sensor on the front wall of the trachea allowed recording its vibrations within the range of 4.5 kHz in smokers whose length of smoking was over 5 yrs. The sounds recorded matched with pathologic side tones accompanying chronic bronchitis [9].

Based on the research findings and recommendations presented in Table 1 [2], the

Table 1: CORSA recommendations for characteristics of sensors that detect human pulmonary sounds.

Parameters	Values
Frequency range	100 Hz-5 kHz
Frequency response function (FRF) form	Flat in the audio range of frequencies, irregularity no more than 6 dB
Dynamic range	>60 dB
Sensitivity	It should not change depending on the frequency of signals, direction of sounds or pressure applied onto the sensor
Signal/noise ratio (SNR)	>60 dB
Direction diagram	Omnidirectional
Sensor attachment	Condenser microphone – elastic belt, glue
	Piezoelectric microphone, accelerometer – glue
Protection against noises and interference	Acoustic sounds: protection against vibration, covering with sound-absorbing filling. Electromagnetic interference: twister pair cable or shielded microphone cable.
Frequency response function of the amplifier	Constant and flat in the audio range of frequencies under study
Dynamic range of the amplifier	>60 dB

authors chose the following types of acoustic sensors for the initial research stage: electret, piezoelectric, and MEMS microphones. As opposed to other representatives of this group, the level of sensitivity of compact dynamic microphones did not allow recording weak acoustic signals.

During the experiments, it was revealed that sensors based on MEMS microphones recorded the highest-quality bronchopulmonary sounds. The microphones were installed into a sound-detecting head of the binaural stethoscope. Signals detected by the sensor were transmitted to a notebook's microphone input, where they were digitized by a sound AD converter (16 bit, 44.1 kHz) and recorded on a PC hard drive in the form of WAVE files without any loss of quality.

Figure 1 demonstrates a graphic representation of breath sounds obtained by means of the acoustic sensor based on the MEMS microphone.

As it is seen from Figure 1 that demonstrates the graphic representation of breath sounds produced by the bronchopulmonary system, the acoustic sensor based on the MEMS microphone allows recording high-quality acoustic signals of the human bronchopulmonary system. Signals contain a maximum volume of useful information and minimum volume of noises hindering the diagnosis making process in case of auscultation. In this case, the acoustic sensor was placed in the area of the right second intercostal space. The frequency range of the signal recorded was 60-140 Hz [10].

Bronchopulmonary signals recorded by means of the sensor designed by the authors can be used for further mathematic processing. It will allow singling out signal fragments corresponding to patients' inspiratory/expiratory sections. They can be analyzed further to automatically diagnose patients' disease.

Unlike the noises of the human bronchopulmonary system, most sound vibrations reasoned by heart sounds and noises are beyond the limits of sound perception. Therefore, during the registration of phonocardiograms an acoustic sensor should register sound vibrations beyond perception by ear. It is possible to make up the complete picture of heart noises by analyzing phonocardiograms obtained in each frequency range. As for the diverse filtration schemes, the Maass and Weber scale (Table 2) used in the modern phonocardiographs has the greatest practical importance nowadays.

In order to perform the long-term monitoring of cardiac activity (in both adults and fetuses during their intrauterine growth), it is more preferable to record phonocardiograms within a low-frequency band (40-90 Hz), which allows avoiding the overlapping of breath sounds with heart sounds down to the limit. Thus, on the basis of the required frequency characteristics and the analysis of the modern market of heart noise and tone registration devices, the authors have chosen a piezoelectric converter [4,11]. The required coherence of resistances was provided by the electronic part of the sensor designed by the authors. The sensor was fastened with an elastic band at the standard points of hearts auscultation. The signal was recorded by analogy with the recording of bronchopulmonary noises. The sensor has allowed obtaining the recording of the human cardiovascular system tones (Figure 2) with a certain number of extraneous

Figure 1: Breath sounds of the human bronchopulmonary system recorded by means of the MEMS microphone.

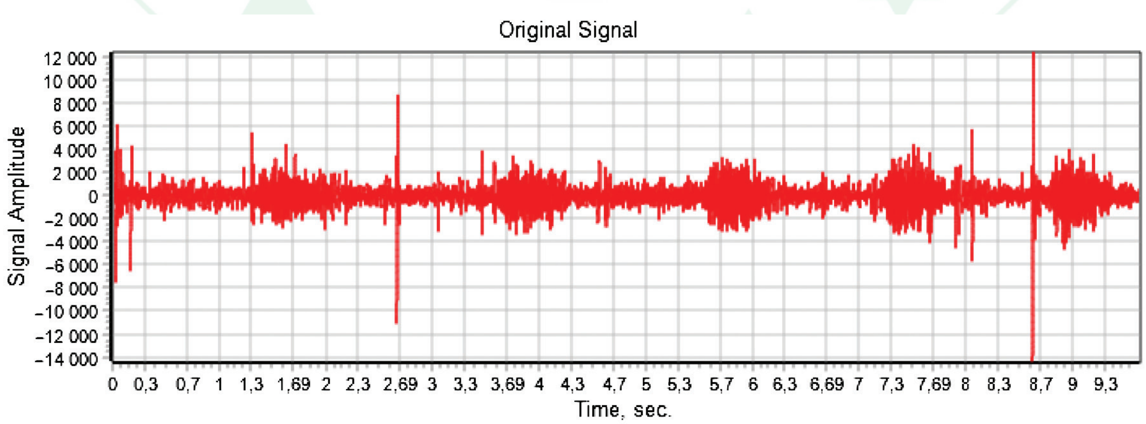
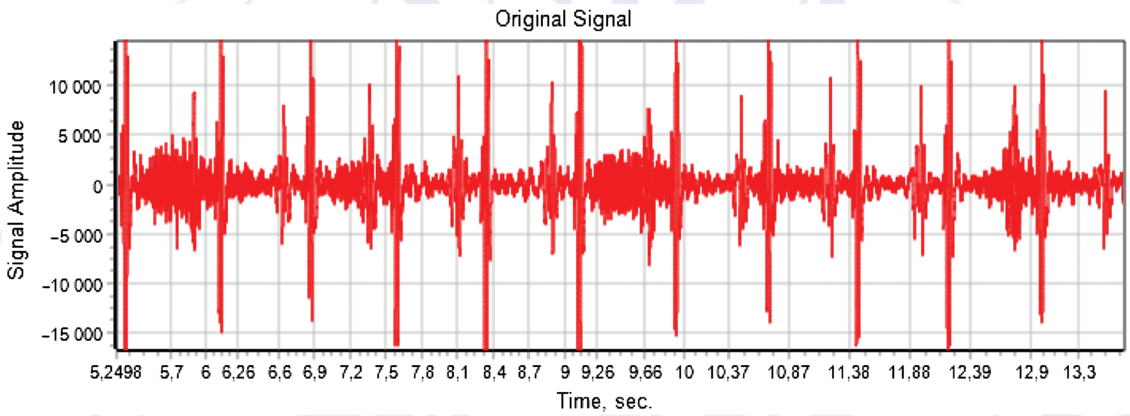


Table 2: Maass and Weber scale.

Notation	Rated frequency (Hz)	Pass-band (Hz)
H	35	Up to 70
C_1	70	40-180
C_2	140	140-400
B_1	250	250-650
B_2	400	400-1000
A	140	100-400

Figure 2: Results of human heart tone registration with a piezoelectric sensor.

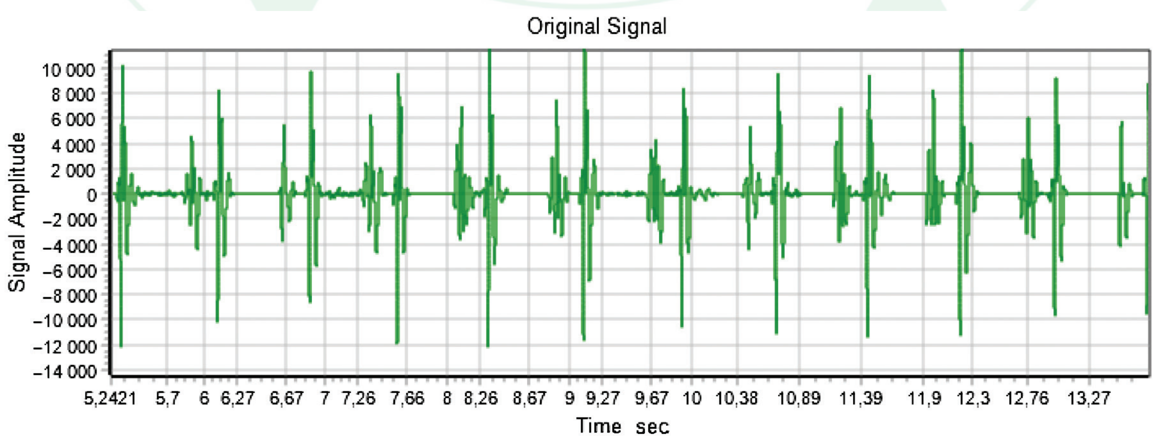


noises concerned with the activity of the human respiratory system (its low-frequency constituents) and ambient noises.

The structure used provides the quality of the signal in the required frequency band that is sufficient for the future discrimination of heart sounds. The sensor of such a type can be successfully used to register heart sounds in adults and fetuses (during their intrauterine growth). However, such peculiarities of fetus heartbeat registration as low amplitude, source movement, and a significantly noisy signal determine the need to modernize the sensor and its loading, so that it can be used for fetus heartbeat registration in the future.

In order to eliminate noises from the acoustic signal obtained, the authors used the designed and software-based Type 1 Cherbyshev low-frequency filter, and its performance result is presented in Figure 3.

Figure 3: Results of detecting human heart sounds by means of the piezoelectric sensor following noise removal.



The further mathematic treatment of the human heart sounds obtained will allow calculating the heart rate (both in real time and in a delayed mode) and performing the noninvasive diagnostics of the patient's cardiovascular system by analyzing the first and second heart sounds derived.

When performing the work, the authors modeled and tested different types of sensors used to register respiratory sounds and heart sounds on the basis of various sensing devices. In addition, they analyzed the properties of acoustic sensors and their suitability for recording the acoustic signals of the human bronchopulmonary and cardiovascular systems.

The analysis of the data obtained allows making the following conclusions and providing further recommendations.

It is preferable to detect breath sounds by means of MEMS microphones and highly sensitive electret microphones. At the same time, it is necessary to take into account the following aspects:

1) For high-quality perception of breath sounds, microphones should have a phonendoscope-resembling design: it implies the presence of a funnel with a sound-amplifying membrane. The funnel cavity should be necessarily connected with external space by means of a small tunnel. The quality of recorded sounds significantly depends on the diameter and length of this tunnel.
2) A microphone installed in the focus of the sound funnel should have a vibration- and sound-proof attachment. This requirement is also relevant to an electric cable attached to the microphone.
3) For high-quality detection of signals, an amplifier of the condenser or analog MEMS microphone should have a low level of noises, no more than 4-6 nV/√Hz.
4) The analysis of digital MEMS microphones connected to a microcontroller by means of the I2S protocol demonstrated good results. However, this scheme necessarily requires software for active noise cancellation.

It is preferable to detect heart sounds by means of piezoelectric contact microphones and accelerometers. It is connected with the fact that the first heart sound has the frequency of 16-18 Hz, which lies outside of the frequency range of electret microphones. Piezoelectric sensors and accelerometers register such vibrations without any problems. The use of piezoelectric contact sensors also has its own peculiarities:

1) Input resistance of the piezoelectric sensor's amplifier should amounts to few megaohms. Input current should be at the level of nanoamperes. It makes provisions for the use of amplifiers with field transistors.
2) Noise characteristics of amplifiers with field transistors are marked by a high level of low-frequency flicker noises prevailing in the operating range. Therefore, acceptable results can be obtained by means of JFET transistors with the level of noise of no more than 1 dB, e.g., 2SK170, 2SK209, 2SK2394, or 2SK3557, and chosen couples for formation of bipolar circuits (2SK2145 or 2SK3320). Speaking about low-noise operating amplifiers, it is advisable to use ADA4004-1 and AD8671.
3) The construction of acoustic sensors implies hard contact with patients' skin; therefore, it is necessary to use medical stainless steel under the 18/10 brand or analogues as a metal membrane the piezoceramic element is attached to.
4) Hard contact between the sensor and patient's skin significantly lowers down requirements to the sensor's acoustic design. The only condition is a need for relatively strong attachment of the piezoelement's membrane to its body. On the one hand, it creates additional conditions supporting high-quality contact with the skin. On the other hand, it reduces the level of external noises and interference.

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