Application of magnetoelectric sensors in biomedicine

V S Leontiev, V N Lobekin, A F Saplev, E A Zueva, E E Ivasheva and M I Bichurin
Yaroslav-the-Wise Novgorod State University, Veliky Novgorod, Russian Federation
E-mail: viktorsergeevich.novsu@gmail.com

Abstract. The prospects of applying highly sensitive magnetic field sensors based on the magnetoelectric effect in biomedicine are discussed in this paper. When developing highly sensitive magnetic field sensors, it is necessary to take into account the magnitude of the equivalent magnetic noise, as well as the mass and size dimensions and ease of use of the system that the sensor is included in. One of the most relevant areas discussed in the article is the application of magnetoelectric magnetic field sensors for magnetocardiography, magnetoencephalography, etc. These methods are non-invasive, have high sensitivity and are easy to use. They also have wide opportunities in detecting weak biomagnetic signals when examining the state of the human body and providing the necessary assistance.

1. Introduction
Active research on highly sensitive magnetic field sensors for use in biomedicine has been undertaken in recent years [1-6]. The most promising areas are magnetocardiography (MCG) [7] and magnetoencephalography (MEG) [8]. This activity is primarily associated with the emergence of new materials and technologies that allow detecting weak magnetic fields [9]. The required signal value for measuring the magnetic fields of a person, for example, the heart and brain, can vary from 10 pTl to 10 fTl. The main methods of diagnosing brain activity are electroencephalography (EEG) and MEG. The main reason for the extensive study of MEG is the addition of the picture of brain activity together with the EEG, i.e. these methods are independent. They register different information about brain activity from each other. The combined use of EEG and MEG makes it possible to see a more complete picture of brain activity. To date, the most common method of measuring weak magnetic fields is Superconducting Quantum Interference Device (SQUID) magnetometers. However, the use of SQUID magnetometers is limited by their cost and complexity of use (special conditions for the procedure are required).

In the modern world, there is a tendency to create small-sized, portable, mobile devices operating at room temperature, which enable to quickly and accurately measure and diagnose the necessary data. One of such mobile complexes can be devices based on the magnetoelectric (ME) effect, for example, the ME magnetocardiograph (MMCG) and the ME magnetoencephalograph (MMEG). Unlike SQUID magnetometers, systems based on the ME effect allow detecting small magnetic fields at room temperature and without special conditions necessary for making measurements.

It is well-known that the ME effect is the occurrence of electric polarization when a magnetic field is applied or magnetization when an electric field is applied. The ME interaction is observed in composite structures consisting of magnetostrictive and piezoelectric materials. In such composites, the interaction of the magnetic and electrical subsystems occurs due to mechanical deformation. This means that the ME effect is much greater at resonant frequencies, in particular, at bending resonance.
When considering the application of highly sensitive ME sensors in biomedicine, it should be borne in mind that a specialized sensor is needed for each system. This is primarily due to various tasks of the systems (measurement of blood flow velocity, monitoring of cardiac and brain activity). In each case, the sensor must have the necessary sensitivity and appropriate design.

The article discusses the use of sensors based on the magnetoelectric effect for various systems in biomedicine, magnetocardiograph, magnetoencephalograph, magnetic label and ME microwave sensors.

2. Magnetoelectric magnetoencephalograph

The MEG signals were first measured in 1968 by David Cohen [10]. The measurements were carried out without using the SQUID magnetometer. It was only in 1970 when it was possible to measure the MEG signal using the SQUID magnetometer. The difference in the data obtained was noticeable. The results obtained using the SQUID magnetometer were much more accurate and informative, similar to the signals obtained from the EEG.

When considering MEG, it is necessary to first pay attention to how electrical signals flow in the brain. The signals arise as a result of the general effect of ion currents flowing in the dendrites of neurons during synoptic transmission. According to Maxwell's equations, any electric current creates a magnetic field. To generate a detectable signal, about 50,000 active neurons are needed. Since the current dipoles must have the same orientation in order to generate magnetic fields that increase the signal, the magnetic fields of cells located perpendicular to the surface of the cortex are measured. The bundles of these neurons, which are oriented tangentially to the surface of the skull, generate measurable magnetic fields outside the cerebral cortex [11].

![Figure 1](image-url)  
**Figure 1.** The magnetic field from the brain. a) A collection of simultaneously active cortical dendrites whose summed electrical activity produces electric and magnetic fields similar to that of a current dipole. b) Equivalent dipole sources adjacent to a sulcus (fissure) in the brain oriented so that the dipole is tangential to the surface of the skull produce externally detectable magnetic fields in (c), which produce the characteristic dipolar pattern of isofield contours in (d) [11].
The magnetic field of the brain is up to 10 fTl, which is significantly lower than the level of equivalent magnetic noise in the environment, which was the main problem for the development of portable, mobile and small-sized MMEG systems. To date, the development of such systems has become possible on the basis of highly sensitive magnetic field sensors based on the ME effect [12]. The sensitive element of such a sensor is a ME structure consisting of magnetostrictive and piezoelectric layers. The most promising magnetostrictive and piezoelectric components are Metglass and Aluminum Nitride, respectively.

As a sensing element, it is proposed to use a composite structure consisting of a magnetoelectric element made in the form of a piezoelectric plate, for example, AlN 1, and plates of a magnetostrictive material, for example, Metglass 2 (Figure 2).

![Figure 2. The ME structure.](image)

The use of this composite structure will significantly increase the sensitivity of the MMEG system to the magnetic field.

![Figure 3. The structural scheme of the MMEG and MMKG devices.](image)

Figure 3 shows a structural scheme of the proposed MMEG device. The principle of operation of which is as follows: the received brain signal is detected by the ME structure, and then transmitted to a
low-noise amplifier, for example, AD745, then the received signal via wireless communication (a transmitting antenna powered by a ME energy collection device) enters a digital signal processing system, which includes a receiving antenna, a low-pass filter, an ADC, etc.

The system for measuring brain signals consists of a set of many sensors located on the human head (Figure 4). Each sensor is a complex measuring system consisting of a sensitive ME element made of an elastic piezoelectric material with a magnetostrictive material, an amplifier, and a signal transmission system. Dozens of such sensors are interconnected and attached to a PC, on which we can observe the picture of brain activity.

![Figure 4. The picture of the helmet for the MMEG system.](image)

Most importantly, the MMEG provides temporal characteristics of brain activation with an accuracy of up to a millisecond. The MMEG also provides a more accurate spatial localization of neural activity compared to the EEG.

3. Magnetolectric magnetocardiograph

The first magnetocardiogram (MCG) was recorded by Baule and McFee in 1963 [12]. Their method of measuring the magnetic field of the human heart was carried out using a pair of copper induction coils around a ferromagnetic core at room temperature in an unshielded environment [13]. The obtained MCG was significantly worse compared to the electrocardiogram (ECG) that had been used for a long time at that time due to the low sensitivity of the MCG to the magnetic field [14].

The biomagnetic signals of the human body provide a lot of useful information about the heart. MCG signals arise as a result of the flow of electric currents in the active nerve cells of the heart. The adult heart signal is the largest of the biological magnetic signals with a maximum value of about 25 Pt [15]. Figure 5 shows the expansion of the electromagnetic field of the human heart.

![Figure 5. The electromagnetic field of the heart.](image)
The most common way to record MCG is to measure the magnetic field of the heart at points evenly distributed on the anterior surface of the chest or in the frontal plane in close proximity to this surface, sometimes in the frontal plane tangent to the surface of the back. In these areas, the magnetic field of the heart is sufficient to be measured using appropriate equipment.

To get the most complete picture of the magnetic field of the heart, it is necessary to measure three orthogonal components of the magnetic induction vector at each point. However, more often, only the component normal to the surface of the chest or to the frontal plane is measured. This component depends less on the internal inhomogeneities of the body than the components tangential to the surface of the body.

Figure 6 shows a rectangular grid of measurement points in the frontal plane, tied to anatomical landmarks, i.e. adapted to the size of the chest of each individual person. This "anatomical normalization" allows for effective statistical processing of the measured data [16].

![Figure 6](image)

**Figure 6.** Standard grid of measuring positions for magnetocardiography: a) anterior chest surface, b) posterior surface of the chest. Light circles with crosses show the positions of the chest electrodes V1-V4 of the generally accepted system of electrocardiographic leads, darkened rectangles - a simplified 6-position grid, TH XI - spinous process of the eleventh vertebra.

The MGC has some differences before ECG: (i) non-invasiveness; (ii) accuracy of measurement of weak magnetic fields created by currents flowing through the myocardial fibers during cardiac activity [13]. The main goal of the MCG is to obtain as accurate clinical information about the human heart as possible.

![Figure 7](image)

**Figure 7.** The ECG and the MCG of the human heart.
Figure 7 shows the ECG and the MCG of the human heart. It can be seen that the MCG and ECG provide different information about the human heart. Therefore, electro- and magnetocardiography are not competing, but complementary research methods. MCG allows you to identify such components of the magnetic field of the heart that would otherwise remain "silent". It is the combination of the MCG and the ECG that provides the most complete information about the studied processes of human cardiac activity [17, 18].

Reermann et al. proved that thin-film ME sensors can be used to measure the magnetic fields of the heart. They successfully measured the signals of the R wave from the heart of a volunteer in a shielded room. The sensor was located at a distance of about 10 mm over the skin. The measurement results are shown in Figure 8. After averaging the collected data, a certain peak corresponding to the R wave of the human heart is observed [19].

![Figure 8. Averaged results of the R-wave measurement.](image)

It is possible to determine the necessary limits of the detectable strength and frequency of the magnetic field for each source of a biomagnetic signal. Today, SQUID magnetometers are used to study such low-frequency biological magnetic signals, but they are expensive, large-sized and require low temperatures. The solution to these problems can be the application of systems based on ME magnetic field sensors operating at room temperature and having high sensitivity, about 5 PT, low cost, a wide frequency range and ease of manufacture. A magnetic field sensor based on the ME effect can be a sensitive element in a portable, mobile ME magnetocardiograph.

The principle of operation of the MMCG with a ME sensor as a sensitive element is similar to the principle of operation of the MMEG. The structural scheme of the system is shown in Figure 3. The received signal of the magnetic component of the heart is detected by the ME structure, then transmitted to a low-noise amplifier, for example, AD745, AD7195, or OPA627, and then the signal via wireless communication (a transmitting antenna powered by a ME harvester) enters a digital signal processing system, which includes a receiving antenna, a low-pass filter, an ADC, etc. with further image acquisition in the Lab View interface.

4. "Magnetic label" - the electronic system for thrombosis examination and prevention
The blood system is one of the most sensitive systems of the human body to magnetic radiation. It is established that the body's reaction to the electromagnetic field is similar to radiation exposure, and the state of the irradiated body is usually assessed by changes in the blood [20, 21]. Numerous studies have shown that the effect of a magnetic field on blood reduces its rheological properties, leads to hypocoagulation of red blood cells, increases the rate of erythrocyte sedimentation, due to changes in
the conductivity of cell membranes and an increase in the electrical resistance and capacity of red blood cells.

Electromagnetic radiation affects many processes in the human body: starting from the nanoscale (atoms, molecules [22]), the microlevel (cell) [23, 24], to the macrolevel - the systems of the human body [25, 26] and the entire body [27, 28]. Depending on the parameters of radiation, the effect on the human body can be positive, stimulating or negative.

It is known that the hemoglobin molecule has a magnetic moment due to the content of iron atoms in it. Collecting in the red blood cell, hemoglobin molecules are ordered and adjusted to each other, and form the magnetic moment of the red blood cell.

Using this property of red blood cells, it is possible to determine the speed of blood flow, blockage of blood vessels (thrombosis, atherosclerotic plaques), the level of blood supply to the brain and other organs, and the state of blood viscosity [29].

![Figure 9. The structural scheme of a device for blood flow velocity measurement.](image)

Figure 9 shows a structural scheme of the device, the principle of operation of which is as follows: a starting impulse is formed from a magnetic marker generator using an impulse generator. In the form of a rectangular impulse, it enters the trigger, and emits a magnetic impulse, which affects the spatial orientation of red blood cells. The created "Magnetic label" in the blood composition moves towards the ME sensor and by the time of its registration it is possible to evaluate the blood flow velocity in the vessel.

The received signal is increased by an amplifier, then the bandpass filter selects the main informative component from it, after that a rectangular impulse is created from the received signal by the impulse generator, which is sent to reset the trigger. At the output of the trigger, we get an impulse, the duration of which is proportional to the speed of the time delay of the appearance on the ME sensor and is inversely proportional to the movement of the blood mass.

Measuring the blood flow velocity is a necessary task to fulfill. Sensory indicators and possible indicators of abnormal dynamics depend on the choice of the installation location. To determine these parameters, it is necessary to choose the most favorable part of the body for this: to have a laminar flow of blood; to have a blood flow velocity that is sufficient for being measured by an ME sensor; to have a relatively large diameter; to be a vessel in which neoplasms appear. Arteries, veins and capillaries are the three main types of vessels in the human body. The popliteal artery fully meets the criteria listed above.

The popliteal artery (Figure 10) is a continuation of the femoral artery. It begins at the level of the lower opening of the adductor canal, is located under the semipereminous muscle and goes along the bottom of the popliteal fossa, first adjacent to the popliteal surface of the femur and then to the articular capsule of the knee joint, and in its lower part – to the popliteal muscle.
Taking into account the position of the popliteal artery, it is possible to suggest the following location of the “Magnetic Label” generator and the ME.

![Popliteal artery](image)

**Figure 10.** Popliteal artery.

The "Magnetic label" generator should be located in the upper part of the leg closer to the groin area, and the ME sensor below the knee. Both elements are made on an elastic piezoelectric substrate with a magnetostrictive material applied. Then the whole structure is connected to each other and attached to a PC, where the obtained changes in the blood flow velocity can be observed.

There are a large number of typical, well-known situations for doctors, in which the venous blood flow is simultaneously disrupted and the coagulation system is activated. For example, during any surgical operation, a large amount of tissue thromboplastin, a substance that stimulates blood clotting, enters the bloodstream from the tissues. The harder and more extensive the operation the greater the release of this substance. The same happens with any injury. This mechanism was formed in ancient times, and without it, humanity as a biological species simply would not have survived. Otherwise, any injury to our distant ancestors, and to us, would have ended in death from bleeding. The body as a whole system does not care what caused the wound – the claws of a saber-toothed tiger or a surgeon's scalpel. In any case, there is a rapid activation of the blood clotting potential. But this protective mechanism can often play a negative role, since it creates prerequisites for the formation of blood clots in the venous system in operated patients. In the first day after the operation, it is difficult for the patient to get up, move and walk. This means that the work of the muscle-venous pump is turned off and the venous blood flow slows down. In case of injuries, in addition, it is necessary to apply plaster bandages, skeletal traction, connect bone fragments with metal pins, which sharply limits the physical activity of the patient and contributes to the occurrence of thrombosis. Its frequency after surgical operations on the abdominal organs can reach 25-40 percent. With hip fractures, prosthetics of the knee and hip joints, thrombosis in the deep veins of the legs develops in 60-70 percent of patients.

Venous thromboembolic complications during pregnancy is the most serious problem. The fact is that the woman's body itself is preparing in advance for childbirth, and therefore for blood loss. Already from the early stages of pregnancy, the blood clotting system is activated. The inferior vena cava and iliac veins are compressed by the growing uterus. Consequently, the risk of thrombosis increases.
In this case, a blood clot without any warning can break away from the vein wall in a few seconds, turn into an embolus—a blood clot that migrates through the vessels, and cause severe pulmonary embolism with an unpredictable outcome. According to experts, about 100,000 people die from pulmonary embolism in the Russian Federation every year. Thus, this disease claims more lives than car accidents, regional conflicts and criminal incidents all together.

5. Discussion
The need for outpatient monitoring of cardiac activity has been rapidly growing these days, but medical equipment in most cases is expensive and oversized. The use of low-frequency magnetic field sensors with high sensitivity, about 5 Pt, enables the development of new systems, such as the MMCG, the MMEG, etc. The exploration of the application possibilities of ME microwave sensors and ME devices for biomedical and bioengineering applications is also relevant today.

Doppler measurements of cardiac activity for monitoring vital signs is one of such applications of the ME microwave sensors. At the moment, the use of Holter monitors for daily ECG monitoring is more preferable for portable cardiac monitoring. The use of ME microwave sensors for Doppler measurements of cardiac activity makes it possible to complete the picture of cardiac activity and identify certain types of heart failure, such as fibrillation and akinesia.

The design of the Doppler ME microwave sensor can include a microwave generator, a microstrip transformer, a ME microstrip patch antenna, a mixer, a low-pass filter, a low-power microcontroller for signal processing and wireless signal transmission. The use of ME microwave sensors based on split-ring resonators is also relevant at present, as it allows conducting studies of living human tissues. The principle of operation is to transmit a signal for the extension of microwave radiation on the human body through various biological tissues to measure their thickness. The results obtained using this research method can be widely required in various medical systems.

6. Conclusion
The prospects for the application of highly sensitive ME magnetic field sensors in biomedicine are discussed in this paper. The capabilities of the ME magnetoencephalograph and magnetocardiograph, as well as the “Magnetic label” designed to measure the blood flow velocity in order to prevent thrombosis, are described in detail. The perspective of using microwave magnetic field sensors is considered. These methods are non-invasive, have high sensitivity, are easy to implement and have extensive capabilities in detecting weak biomagnetic signals for studying the human condition and providing the necessary assistance.

To date, the SQUID magnetometers remain the most common in the field of detecting weak human biomagnetic fields for magnetocardiography, magnetoencephalography, etc., having a high sensitivity tending to fTl. However, the use of SQUID magnetometers requires certain conditions, such as: low operating temperature, fully shielded room. Such conditions in modern biomedicine make it difficult to use the SQUID magnetometers in practice. The challenges facing modern biomedicine are portable mobile systems with a sensitivity comparable to the SQUID magnetometer.

Highly sensitive magnetic field sensors based on the ME effect are the most promising candidates for replacing the SQUID magnetometers among the known magnetic field sensors. The sensitivity of such devices has already reached a sensitivity equal to pTl and continues to develop towards fTl. At the same time, biomedical systems based on ME sensors operate at room temperature, have small overall dimensions and the possibility of wireless data transmission.

Acknowledgments
The reported study was funded by RFBR projects No. 19-07-00391 and No. 20-07-00168.

References
[1] Jahns R, Knöchel R, Greve H, Woltermann E, Lage E and Quandt E 2011 Magnetolectric sensors for biomagnetic measurements 2011 IEEE International Symposium on Medical
Measurements and Applications 107–10 DOI: 10.1109/MeMeA.2011.5966676

[2] Reermann Jens, Durdaut Philip, Salzer Sebastian, Demming Thomas, Piorra André, Quandt Eckhard, Frey Norbert, Höft Michael and Schmidt Gerhard 2018 Evaluation of magnetoelectric sensor systems for cardiological applications Measurement 116 230–38 DOI: 10.1016/j.measurement.2017.09.047

[3] Reermann J, Elzenheimer E and Schmidt G 2019 Real-time biomagnetic signal processing for uncooled magnetometers in cardiology in IEEE Sensors Journal 19 (11) 4237–49 DOI: 10.1109/JSEN.2019.2893236

[4] Zuo S et al 2020 Ultrasensitive magnetoelectric sensing system for Pico-Tesla Magnetomyography, in IEEE Transactions on Biomedical Circuits and Systems 14 (5) 971–84, DOI: 10.1109/TBICAS.2020.2998290

[5] Wu Hanzhou, Tatarenko Alexander, Bichurin M I and Wang Yaojin 2021 A multiferroic module for biomechanical energy harvesting Nano Energy 83 105777 DOI: 10.1016/j.nanoen.2021.105777

[6] Yang Nana, Wu Hanzhou, Wang Shidong, Yuan Guoliang, Zhang Ji, Sokolov Oleg, Bichurin M I, Wang Ke and Wang Yaojin 2021 Ultrasensitive flexible magnetoelectric sensor, APL Materials 9 021123 DOI: 10.1063/5.0039089

[7] Cohen D and Givler E 1972 Magnetomyography: Magnetic fields around the human body produced by skeletal muscles Appl. Phys. Lett. 21 (3) 114–16

[8] Merletti R and Parker P A 2004 Electromyography: physiology, engineering, and non-invasive applications Vol 11 (John Wiley & Sons)

[9] Wang Y, Gray D, Berry D, Gao J, Li M, Li J and Viehland D 2011 An extremely low equivalent magnetic noise magnetoelectric sensor Adv. Mater. 23 4111–14

[10] Cohen D 1968 Magnetoencephalography: Evidence of magnetic fields produced by arrhythm currents Science 161 (3843) 784–6 DOI: 10.1126/science.161.3843.784

[11] Baule G and Mcfee R 1963 detection of the magnetic field of the heart. Am Heart J. 66 (1) 95–96 DOI: 10.1016/0002-8703(63)90075-9

[12] Lobekin V N, Petrov R V, Bichurin M I, Rebinok AV and Sulimanov R A 2018 Magnetoelectric sensor for measuring weak magnetic biological fields IOP Conf. Ser.: Mater. Sci. Eng. 441 012035

[13] Tavarozzi I, Comani S, Del Gratta C, Romani GL, Di Luzio S, Brisinda D, Gallina S, Zimarrino M, Fenici R and De Caterina R 2002 Magnetocardiography: current status and perspectives. Part I: Physical principles and instrumentation. Ital Heart J. 3 (2) 75–85

[14] Kwong J S, Leithäuser B, Park J W and Yu C M 2013 Diagnostic value of magnetocardiography in coronary artery disease and cardiac arrhythmias: a review of clinical data Int J Cardiol. 167 (5) 1835–42 DOI: 10.1016/j.ijcard.2012.12.056

[15] Mapps D J 2003 Remote magnetic sensing of people Sensors and Actuators A: Physical 106 (1–3) 321–5 DOI: 10.1016/S0924-4247(03)00193-6

[16] Kneippo P and Titomir L I 1989 Biomagnetic measurements (Moscow: Energoatomizdat) p 288

[17] Polyakova I P 2011 Magnetocardiography: history, current status and prospects of clinical application Creative cardiology 2 103–33

[18] Lobekin V N, Petrov R V, Bichurin M I, Rebinok A V and Sulimanov R A 2018 Study of capabilities of making detection device for cerebral ischemic state Medical Research and Innovations 2 (4) 5

[19] Reermann J, Durdaut P, Salzer S, Demming T, Piorra A, Quandt E, Frey N, Höft M and Schmidt G 2018 Evaluation of magnetoelectric sensor systems for cardiological applications Measurement 116 230–38

[20] Lud G V and Bazenko N P 1977 The reaction of peripheral blood to the local effect of a magnetic field Adaptive and compensatory mechanisms in biology and medicine (Grodno) pp 60–1

[21] Belousova O I, Gorizontov P D and Fedotova M I 1979 Radiation and the blood system
(Moscow: Atomizdat) p 126
[22] Magneto-Science 2006 ed M Yamaguchi and Y Tanimoto (Tokyo: Kodansha/Springer)
[23] Iakovleva M I 1973 Physiological mechanisms of action of electromagnetic fields (Leningrad: Medicine) p 176
[24] Chizhevskii A L 1973 Electrical and magnetic properties of red blood cells (Kiev: Naukova dumka) p 93
[25] Sorokina E I 1989 Physical methods of treatment in cardiology (Moscow: Medicine)
[26] Lednev V V 1996 Bioeffects of weak combined constant and variable magnetic fields Biophysics 41 (1) 224–31
[27] Nakhil'nitskaia Z N et al 1978 Magnetic field and vital activity of organisms: (Problems of Space Biology) (Moscow: Nauka) Vol 37 p 268
[28] Reactions of biological systems to magnetic fields 1978 ed Yu A Kholodov (Moscow: Nauka) p 216
[29] Lobekin V N, Leontiev V S, Petrov R V, Bichurin M I, Rebinok A V and Sulimanov R A 2019 Measuring blood flow velocity with a magnetic label, IOP Conf. Series: Journal of Physics: Conf. Series 1352 012031