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Magnetoelectric sensor for measuring weak magnetic biological fields

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Abstract. The paper is devoted to the sensors used for measuring biological magnetic field. The possibilities and sensitivities of magnetoelectric sensors for determining weak magnetic fields were investigated. The importance of human biological magnetic fields measurement for disease diagnosis and treatment was discussed. Recommendations on the use of magnetoelectric sensors for studying the weak biological magnetic fields of living organisms were given.

1. Introduction

To date, high-sensitivity magnetic field sensors are widely used in various areas of human activity, for example, in the automotive industry, space vehicles, archaeological research, robotics, measurement technology, and medical diagnostics. Classical old methods are constantly being improved, mainly with the use of new materials and technologies, such as miniaturization. These new sensors bring revolutionary changes in technology and, in some cases, demonstrate new opportunities. Very promising are hybrids of various effects, for example, magneto-optical, magnetoacoustic or magnetoelectric (ME) effect. In the ME effect, the magnetization can be caused by an electric field or the reverse electric polarization can be caused by a magnetic field.

To measure weak magnetic fields generated by living organisms, high sensitivity is necessary. Generation of weak magnetic fields can be caused by constant currents or magnetic particles that are very effectively used in biomedicine, therapy and diagnostics of a number of serious diseases such as coronary heart disease, cerebral ischemia, brain tumor, epilepsy, gastrointestinal tract diseases that makes measurement and diagnostics of biological magnetic fields very relevant for this study.

Another topic for discussion is about the methods for spatial matching of magnetic localization data (which, naturally, is carried out with respect to the measurement system) with anatomical structures of the heart. The advantages and disadvantages of various methods of topographic mapping, applied at present, are analyzed in detail. These are magnetic resonance imaging (MRI), computed tomography, X-ray tomography and echocardiography. It is concluded that, despite the high cost of the equipment, it is more appropriate to still use MRI and, possibly, a CT scan. Other methods do not provide enough detailed information, but it is hoped that the use of modern software that allows 3D reconstruction of echocardiography data will make this cheaper mapping method sufficiently accurate [1].



The aim of this work is to study the influence of weak biological magnetic fields on living organisms, in particular humans, and to review and compare the characteristics of magnetic field sensors.

2. Human magnetic fields and their importance for the human life

Studies of the biological effects of permanent magnetic fields are concentrated on large fields of field level in MRI devices (magnetic resonance imaging), usually several Tesla (several tens of thousands of Gauss). Unfortunately, studies of the effect of fields typical for magnetic therapy products, most of which are limited to a few hundred Gauss even on the surface of a magnet, are very few. Nevertheless, the main mechanisms of the influence of magnetic fields on biological organisms that allow developing magnetic therapy are already known. These mechanisms include: 1) increased blood flow as a result of increased oxygen content (both of which are the basis of the body's ability to self-repair); 2) a change in the rate of migration of calcium ions, as a result of which, on the one hand, calcium enters the broken bone faster and it fuses faster, and on the other hand, calcium is washed out of the affected with arthritis joint more quickly; 3) change in the acid-base balance (pH) of various fluids in the human body and animals (imbalance is often a consequence of the disease); 4) a change in the production of hormones by the endocrine glands; 5) change in enzyme activity and rates of various biochemical processes, 6) change in blood viscosity.

Magnetic fields of a living organism are caused by three causes. 1) Ionic points arising from the electrical activity of cell membranes (mainly muscle and nerve cells). 2) The smallest ferromagnetic particles, trapped or specially introduced into the body. These two sources create their own magnetic fields. 3) When an external magnetic field is applied, the inhomogeneities of the magnetic susceptibility of various organs appear and distort the superimposed external field [2].

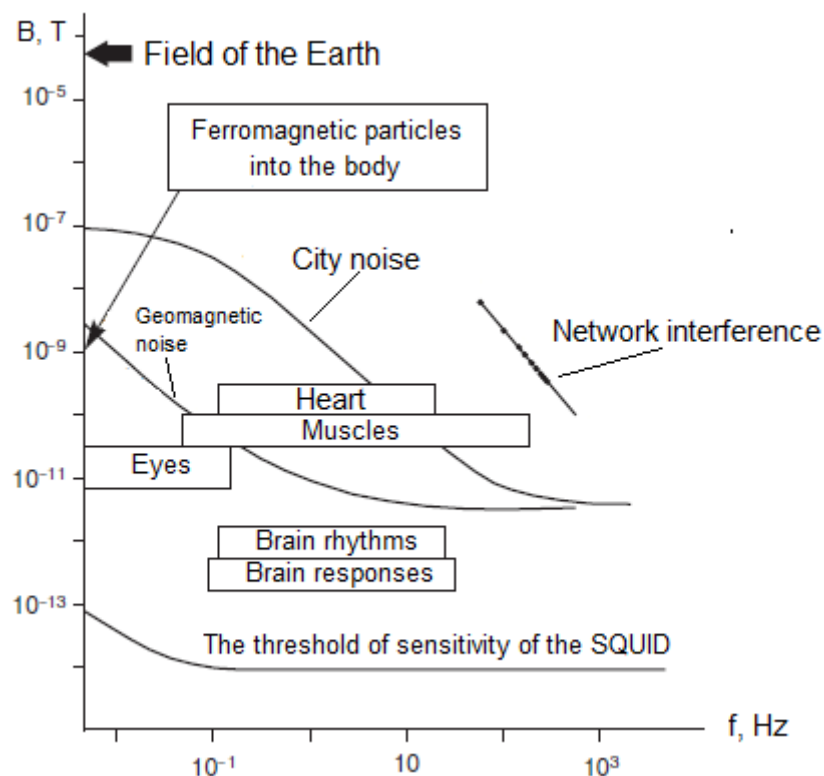


Figure 1. Place of human biomagnetic signals in the magnetic field scale. Specific interference levels and frequency ranges of signals are indicated [1].

Registration of these potentials is used in research and clinical practice: electrocardiography, electroencephalography, and the like. Also there are magnetic analogues, i.e. magnetocardiography and magnetic-encephalography, recording the changes in time of the magnetic component of the same electrical processes in the body.

Magnetography is used to study the heart, fetus, skeletal muscles, eye, retina, brain, magnetic contamination of the lungs, permanent currents in human skin, etc.

Magnetic fields are rapidly weakened when removed from the source of activity, since they are a consequence of relatively strong currents in the operating body, while surface potentials are determined by weaker and "smeared" currents in the skin. Therefore, magnetography is more convenient for the precise determination (localization) of the site of bioelectric activity [3].

It is possible to single out the main directions in the clinical application of the MCG:

- MCG of healthy volunteers;
- MCG conduction system of the heart;
- localization of additional ways of conducting irritable foci and evaluating the effectiveness of their radiofrequency ablation;
- Diagnosis of cardiac hypertrophy;
- Myocardial ischemia and its viability (especially in patients with a small or unchanged ECG, evaluation of the effectiveness of antianginal therapy, etc.);
- diagnosis of cicatricial changes;
- study of repolarization (prolongation and dispersion of QT), stratification of the risk of arrhythmias and evaluation of the effectiveness of antiarrhythmic therapy;
- monitoring of rejection after cardiac transplantation.

To identify patients with a high risk of sudden cardiac death, there is no single diagnostic method [4]. As effective diagnostic markers of the approaching structural adjustment of the electrophysiological properties of the myocardium, it is possible to use the characteristics of low-amplitude oscillations of the detected parameters, which, when approaching the points of loss of structural stability, begin to change earlier than it appears in the value of the average values of the parameters recorded. That is, the sensitivity of the MCG to local currents, the possibility of detecting small changes should allow us to evaluate the electrical homogeneity of the myocardium and to separate the pathological zones of the myocardium with fast and slow conductivity.

The advantage of magnetocardiography remains in its absolute non-invasiveness (passivity), that is, the absence of any energy that is induced on the body of the subject. However, recently there are publications that the successes related to the solution of the inverse problem of electrocardiology in terms of epicardial potentials and modern methods of ECG analysis on the basis of appropriate biophysical models allow us to approach a sufficiently high accuracy in the diagnosis of myocardial ischemia. Here the registration of multiple surface ECGs is supplemented with geometric information about the surfaces of the heart and the body and their mutual arrangement, obtained by computed tomography. But in magnetocardiography, the same task of anatomical binding arises in the solution of the inverse problem of magnetocardiography [5].

2.1 Importance of the magnetic field

Reducing the level of the external magnetic field leads to a violation of the magnetic field in the circulatory system, as a result of which blood circulation is disturbed, oxygen and nutrients are transported to organs and tissues, which can eventually lead to the development of the disease. Thus, the insufficient level of external magnetic effect in terms of the degree of harm caused to the body can fully compete with the deficiency of minerals and vitamins.

Under the influence of magnetic fields there is an increase in the permeability of blood vessels and epithelial tissues, so that it is possible to accelerate the absorption of edemas and the dissolution of medicinal substances. This effect is the basis of magnetotherapy and is widely used for various types of injuries, injuries and their consequences.

2.2 Effect of magnetic field on various systems of the body

Weak magnetic fields of technogenic and natural origin affect the circadian rhythms and physiological functions of a person, which ultimately affects the general state. In natural conditions, a person is exposed only to natural electromagnetic fields, which he tuned throughout the entire evolution process on planet Earth. When artificial sources of magnetic, electric and electromagnetic fields intervene in this process of interaction, a synchronization violation occurs. On the average, the Earth's magnetic field varies with an average frequency of 8 Hz, although this value can fluctuate significantly. Our body is already tuned to perceive this frequency and considers it a natural background. Our cells are thus sensitive to a given frequency of magnetic field exposure.

Various scientific studies have shown that a low-frequency (2-8 Hz) electromagnetic field affects the rate at which a person responds to an optical signal. The magnetic field in the range of 5-10 Hz changes the time of the human brain reaction to many other external influences.

Studies have shown that when a short-term alternating magnetic field with a frequency of 0.01-5 Hz is applied to the human body, the character of the human brain's electroencephalogram changes abruptly. Under the influence of weak variable magnetic fields, the person's pulse rate increases, the head starts to hurt, the state of health worsens and weakness in the entire body is felt. In this case, there is a strong change in brain electrical activity [6].

3. Magnetic field sensors used in medicine

Various converters of non-electrical quantities in electrical have firmly taken their place in many areas of human knowledge, and even more so in medicine. It is difficult to imagine a modern doctor dealing with the diagnosis of various diseases and their treatment, not based on a huge number of achievements of such sciences as radio electronics, microelectronics, metrology, materials science. And although the sensors are one of the slowest growing areas of medical electronics, and indeed of all electronics in general, the vast majority of diagnostic and therapeutic devices and systems directly or indirectly contain a variety of different transducers and electrodes, without which, sometimes the operation of this system is unthinkable.

To measure weak constant and slowly changing magnetic fields, magnetoresistive transducers, nuclear magnetic resonance converters, SQUIDS and ferroprobe converters are currently used. Due to the compactness, low cost, wide operating temperature range, low noise level, the possibility of measuring the direction of the magnetic field, the flux-gate transducers and magnetometers based on them are the most preferable.

Magnetic fields are usually divided into superstrong (over 100 T), strong (from 4 to 100 T), medium (from 0.05 to 4 T), and weak (less than 0.05 T). In medical diagnostic systems, high sensitivity is required, since many living organisms generate weak but measurable magnetic fields of $B \leq 10$ nT. Modern medicine practices numerous passive (for example, bone replacement) and active implants (apparatuses for auxiliary circulation, artificial heart, various stimulants, etc.). Non-invasive testing of functional characteristics, resources and other properties is possible using high-sensitivity magnetic field sensors.

The magnetic field sensor is the main element of any magnetometer and is designed to convert the magnetic induction B into an electrical signal, most often into a voltage U . When creating magnetic field sensors, various physical effects are used, for example, Hall, Gauss, Suhl effect, and others.

The main characteristics of magnetic field sensors can be identified as follows: 1) measuring range, 2) linearity, 3) hysteresis, 4) inaccuracy in the conversion of magnetic induction (including temperature dependence), 5) displacement, 6) long-term stability, 7) noise, 8) directional pattern, 9) sensitivity to the transverse field; 10) frequency range of measurements, 11) geometric dimensions of the sensor, 12) power consumption; 13) heat generation, 14) operating temperature range.

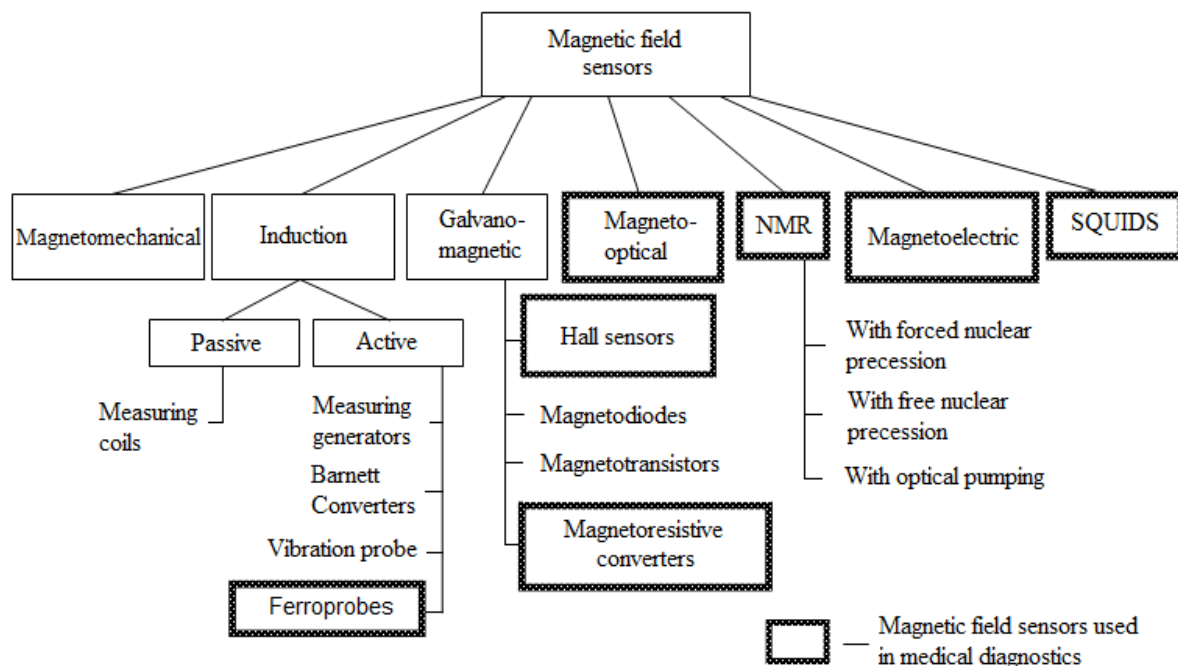


Figure 2. Types of magnetic field sensors.

To measure weak magnetic fields over a wide temperature range, magnetoresistive sensors are most widely used. The principle of operation of magnetoresistive sensors is based on the effect of changing the electrical resistance of a material in a magnetic field. Magnetoresistive sensors can be manufactured using integrated technologies, which significantly reduces their size and cost.

The temperature response of the magnetoresistors depends on the material of the doping impurities. As a rule, with increasing temperature, the resistance decreases, and after applying the magnetic field, the decrease occurs faster. Magnetoresistors have low noise, are not affected by surface effects and is characterized by very small aging.

Depending on the physical effect and the material, the following magnetoresistive sensors are distinguished:

- magnetoresistors based on the Gauss effect;
- anisotropic magnetoresistive sensors (AMP);
- giant magnetoresistive sensors (GMR);
- Spin-tunnel magnetoresistive sensors (STMS). [7]

SQUID (Superconducting Quantum Interference Device) is a supersensitive magnetometer used to measure very weak magnetic fields. SQUID magnetometers have a record high sensitivity, reaching $5 \times 10^{-33} \text{ J / Hz}$ (sensitivity to the magnetic field - 10^{-13} T). For long-term measurements of averaged values over several days, sensitivity values of $5 \times 10^{-18} \text{ T}$ can be achieved [8].

The Hall sensor (position sensor) is a magnetic field sensor. The operation of the device is based on the Hall effect. This effect is based on the following principle: if a certain conductor is placed with a direct current in a magnetic field, then a transverse potential difference (Hall voltage) appears in such a conductor.

Nuclear magnetic resonance (NMR) tomography, better known as magnetic resonance imaging (MRI), is an important medical diagnostic tool used to study the functions and structure of the human body. It allows obtaining detailed images of any organ, especially soft tissue, in all possible planes. It is used in areas of cardiovascular, neurological, musculoskeletal and oncologic imaging.

Table 1. Types of sensors for quasistationary magnetic fields.

Sensor type	Hall Effect	AMC, GMC	Ferroprobe	SQUID	ME sensors
Current/Field	Field	Field	Current	Current	Field
Max sensitivity	1000 nT	0,5 nT	100 pT	5 fT	5pT
Frequency range	30 kHz	100 MHz	10 kHz	10 MHz	10 MHz
Strengths	Low cost, linearity of characteristics, dynamic range of measurements ≤ 70 dB	Low cost, sensitivity, dynamic range of measurements ≤ 100 dB	High sensitivity, dynamic range of measurements ≤ 70 dB	Very high sensitivity, wide range of frequencies, dynamic range of measurements ≥ 120 dB	High sensitivity, small size, dynamic range of measurements ≤ 70 dB
Weaknesses	Low sensitivity	Low dynamic range, 1/f noise	Large size	Low operating temperature (4 K), fragile, high cost	Complexity of technology and calculations

Researches of the influence of a strong static magnetic field on human blood were carried out numerous times using methods such as nuclear magnetic resonance (NMR), magnetic tomography (MRI). As early as 1936, the scientists Powling and Koryel reported the diamagnetic susceptibility of oxyhemoglobin (ie, oxygen-enriched blood) and the paramagnetic susceptibility of deoxyhemoglobin (ie, oxygen-poor blood). In the course of these studies it was possible to estimate, in particular, the magnitude of the effective magnetic moments of the complex $\text{Fe} + 2$, which is part of the hemoglobin of human blood. 10 years ago (1993) Higashi and co-authors studied the orientation of normal red blood cells in a strong permanent magnetic field with a maximum value of up to 8 Tesla. It was found that the red blood cells are oriented in such a way that the plane of their disc is parallel to the direction of the applied field. Finally, in 1997, American researchers Hike and Chen from the University of Florida studied various aspects of the effect of strong permanent magnetic fields on human blood, namely: on magnetic susceptibility, magnetomotive force and viscosity [9].

The magnetic susceptibility of blood was measured using a SQUID magnetometer. It was found that the blood behaves as a diamagnetic liquid when it is enriched in oxygen (in the arteries) and as a paramagnetic material when it is deoxygenated (in the veins). Figures 3 and 4 show the results of measuring the magnetization of blood in the arteries (1) and veins.

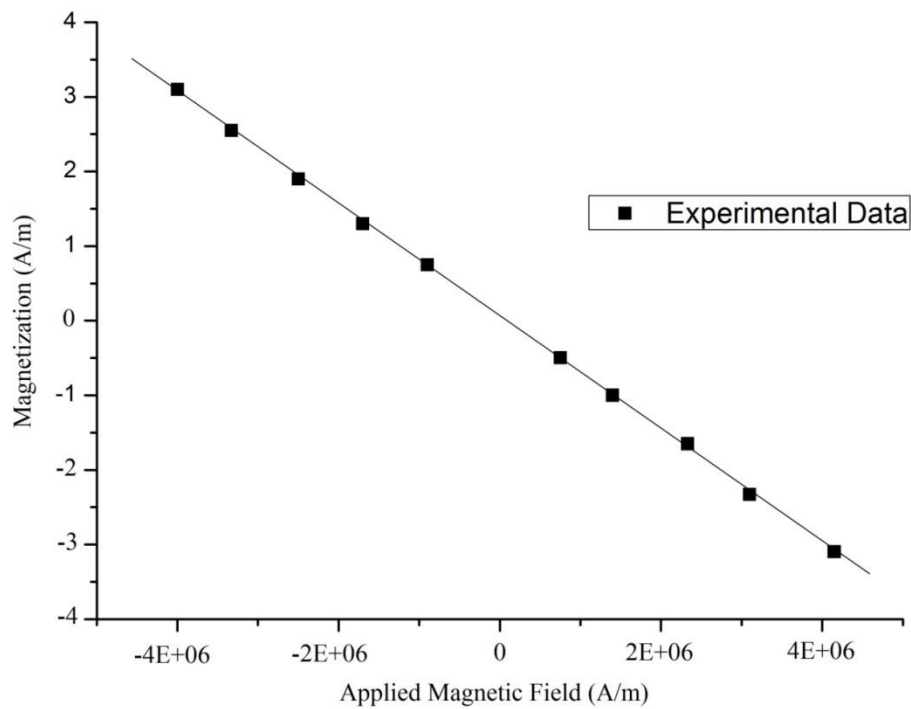


Figure 3. Oxygen-enriched blood magnetization.

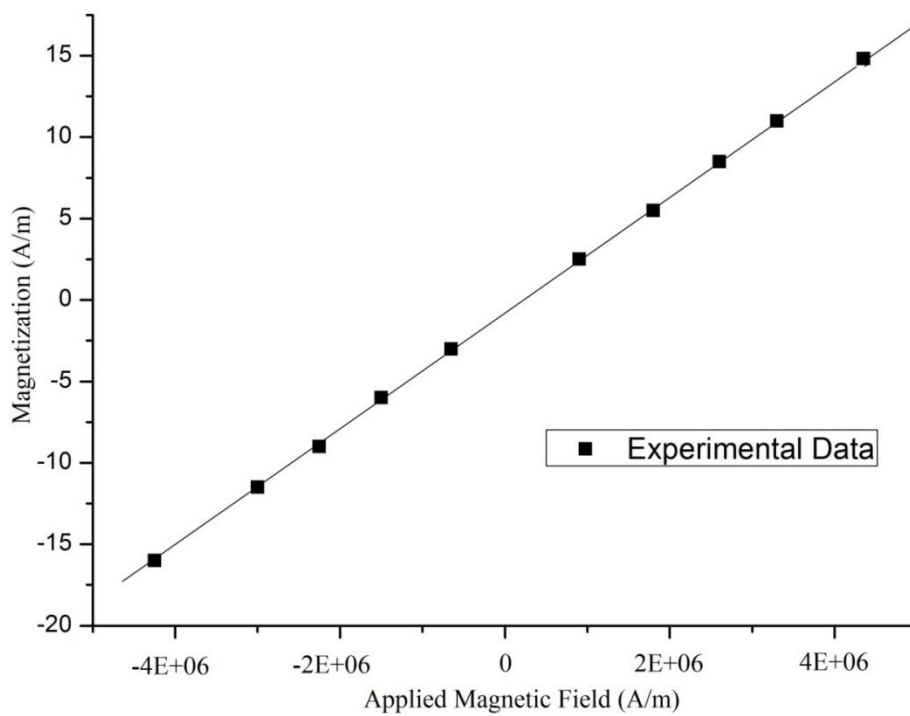


Figure 4. Oxygen-poor blood magnetization.

4. ME sensors, comparison

Sensors on ME materials are designed for operation in DC and AC circuits and fix the presence of both an alternating electromagnetic field and a constant magnetic field. Analogues of ME sensors have been widely used: Hall sensors, induction coils, including double induction coils (Helmholtz coils), SQUID sensors, ferroprobes, magnetotransistors, magnetodiodes, magnetoresistors, magneto-optical and fiber optic systems, etc. In turn, ME sensors can be widely used in medical technology as measuring devices for human magnetic fields and living beings, for measuring magnetobiological reactions, for electrical signals of the heart, for searching for ferromagnetic inclusions signals of skeletal muscle, eye, background and evoked brain activity, eye tissue, may also be used for magnetic sensors in ME tomography. In security systems, ME sensors can be used as motion detectors, in metal detectors; for the automotive industry - in ABS systems, engine management systems; in robotics – in control of angular and linear movements; in measuring equipment for the production of magnetometers, instruments for measuring the characteristics of the magnetic field and the magnetic properties of materials. Depending on the value being determined, it is possible to use field strengths (oerstedmeters), field directions (inclinators and deklinators), field gradients (gradiometers), magnetic induction (teslameters), magnetic flux (webmeters, or fluxometers), coercivity (coercimeters), magnetic permeability (mu-meters), magnetic susceptibility (kappa-meters), magnetic moment; in devices of automation and electronics as non-contact current sensors. Other possible applications are in such areas as geology, mineral search; archeology, during archaeological excavations; in astrophysics, in the study of the orbits of planets; in navigation on the sea, space and aviation; in seismology [10, 11, 12].

To measure weak constant and slowly changing magnetic fields, magnetoresistive transducers, nuclear magnetic resonance converters, SQUIDS and ferroprobe converters are currently used. Due to the small size, low cost, wide operating temperature range, low noise level, the possibility of measuring the direction of the magnetic field, the flux-gate transducers and magnetometers based on them are the most preferable.

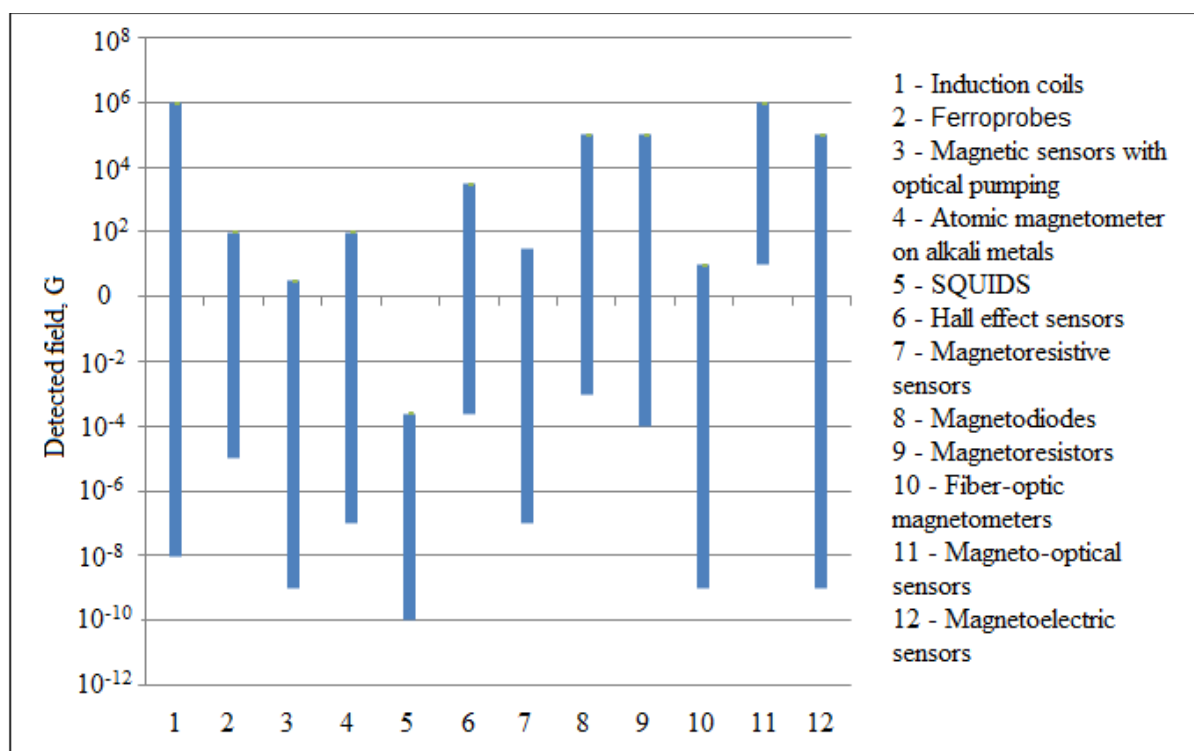


Figure 5. Magnetic sensor comparison.

As noted, the ME effect is the induction of the electric field by the magnetic field, or the inducing of the magnetization by the electric field, i.e. is a cross-effect that allows simultaneous use of dual control of magnetic and electric fields, which leads to a number of advantages over sensors operating according to other principles [12]. The study of the ME effect, materials and sensor construction has paid much attention to the work of foreign authors, which proves their relevance and demand. ME sensors have great prospects for measuring weak magnetic fields, since they have high sensitivity, low cost, and also small dimensions, for ease of use.

5. Conclusion

In this paper an overview of magnetic field sensors is presented, comparative characteristics are given, and the advantages of ME sensors are indicated. The current application of magnetic field sensors in various fields of human activity is indicated, especially for recording biological signals caused by electric fields or magnetic particles in medical diagnostics. The influence of weak magnetic fields on living organisms, their importance for human health and the influence of biological fields on various body systems are also considered. Recommendations are given on the use of ME sensors for studying the weak magnetic biological fields of living organisms.

6. Acknowledgements

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