https://buxdu.uz

E-ISSN 2181-1466
9 772181 146004

ISSN 2181-6875
9 772181 687004

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Научный вестник Бухарского государственного университета
Scientific reports of Bukhara State University

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SCIENTIFIC REPORTS OF BUKHARA STATE UNIVERSITY
НАУЧНЫЙ ВЕСТНИК БУХАРСКОГО ГОСУДАРСТВЕННОГО УНИВЕРСИТЕТА

Ilmiy-nazariy jurnal
2023, № 6, iyul

Jurnal 2003-yildan boshlab **filologiya** fanlari bo‘yicha, 2015-yildan boshlab **fizika-matematika** fanlari bo‘yicha, 2018-yildan boshlab **siyosiy** fanlar bo‘yicha O‘zbekiston Respublikasi Vazirlar Mahkamasi huzuridagi Oliy attestatsiya komissiyasining dissertatsiya ishlari natijalari yuzasidan ilmiy maqolalar chop etilishi lozim bo‘lgan zaruruiy nashrlar ro‘yxatiga kiritilgan.

Jurnal 2000-yilda tashkil etilgan.
Jurnal 1 yilda 12 marta chiqadi.

Jurnal O‘zbekiston matbuot va axborot agentligi Buxoro viloyat matbuot va axborot boshqarmasi tomonidan 2020-yil 24-avgust № 1103-sonli guvohnoma bilan ro‘yxatga olingan.

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UDK: 538.945.91

APPLICATION OF SUPERCONDUCTOR MATERIALS IN MEDICINE

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Abstract: *Superconductivity is playing an increasingly important role in advanced medical technologies. Compact superconducting cyclotrons are emerging as powerful tools for external beam therapy with protons and carbon ions, and offer advantages of cost and size reduction in isotope production as well. Superconducting magnets in isocentric gantries reduce their size and weight to practical proportions. In diagnostic imaging, superconducting magnets have been crucial for the successful clinical implementation of magnetic resonance imaging. In this article, the principle of operation of some medical devices and describes the role which superconductivity is playing in them.*

Keywords: *magnetic Resonance Imaging (MRI), biomagnetic fields, magnetoencephalography (MEG), magnetocardiography (MCG), Positron emission tomography* ***(****PET).*

ПРИМЕНЕНИЕ СВЕРХПРОВОДЯЩИХ МАТЕРИАЛОВ В МЕДИЦИНЕ

Аннотация: *Сверхпроводимость играет всё более важную роль в передовых медицинских технологиях. Компактные сверхпроводящие циклотроны становятся мощными инструментами для внешней лучевой терапии протонами и ионами углерода, а также предлагают преимущества снижения стоимости и размеров при производстве изотопов. Сверхпроводящие магниты в изоцентрических гентри уменьшают их размер и вес до практических размеров. В диагностической визуализации сверхпроводящие магниты сыграли решающую роль в успешном клиническом применении магнитно-резонансной томографии. В этой статье рассматривается принцип работы некоторых медицинских устройств, и описана роль, которую играет в них сверхпроводимость.*

Ключевые слова: *магнитно-резонансная томография (МРТ), биомагнитные поля, магнитоэнцефалография (МЭГ), магнитокардиография (МКГ), позитронно-эмиссионная томография (ПЭТ).*

TIBBIYOTDA SUPER O‘TKAZISH MATERIALLARNING QO‘LLANISHI

Annotatsiya. *Supero'tkazuvchanlik ilg'or tibbiy texnologiyalarda tobora muhim rol o'ynamoqda. Yilni o'ta o'tkazuvchan siklotronlar protonlar va uglerod ionlari bilan tashqi nur terapiyasi uchun kuchli vosita sifatida paydo bo'ladi va izotop ishlab chiqarishda xarajatlar va o'lchamlarni kamaytirish afzalliklarini taklif qiladi. Izosentrik gantriyalardagi supero'tkazuvchi magnitlar ularning o'lchamlari va og'irligini amaliy nisbatlarga qisqartiradi. Diagnostik tasvirlashda supero'tkazuvchi magnitlar magnit-rezonans tomografiyaning muvaffaqiyatli klinik amalga oshirilishi uchun juda muhim bo'lgan. Ushbu maqolada ba'zi tibbiy asboblarning ishlash prinsipi va ularda o'ta o'tkazuvchanlik qanday rol o'ynashi tasvirlangan.*

Kalit so‘zlar: *magnit-rezonans tomografiya (MRT), biomagnit maydonlar, magnetoensefalografiya (MEG), magnitokardiografiya (MKG), pozitron emissiya tomografiyasi (PET).*

Introduction. The two dominant applications of superconductivity in medicine are: (1) the Magnetic Resonance Imaging (MRI) in strong magnetic fields, where 1.5 to 3T (7T for research) high-field-homogeneity superconducting magnets are employed, and (2) the passive, non-invasive measurement, mapping and evaluation of extremely weak biomagnetic fields, which originate from various organs in humans and animals. Such fields can be best measured using highly sensitive SQUIDs (Superconducting Quantum Interference Devices) as detectors [3]. This seminar is dedicated to the second area of research and diagnostic applications. The status of methods such as magnetoencephalography (MEG), magnetocardiography (MCG) and liver susceptometry will be described with some emphasis on early detection and imaging of cardiac ailments, which are the number 1 killer in highly-developed Western societies. The promising low-field MRI using SQUID detectors will be also briefly mentioned and speaker's subjective outlook towards the future presented.

Magnetic Resonance Imaging - MRI

The introduction of MRI into the healthcare system has resulted in substantial benefits. MRI provides an enormous increase in diagnostic ability, clearly showing soft tissue features not visible using X-ray imaging or ultrasound. At the same time, MRI can often eliminate the need for harmful X-ray examinations. These advantages have greatly reduced the need for exploratory surgery. The availability of very precise diagnostic and location information is contributing to the reduction in the level of intervention that is required, reducing the length of hospital stays and the degree of discomfort suffered by patients [8].

The basic science of resonance imaging has been understood for many years. The nucleus of most atoms behaves like a small spinning magnet. When subjected to a magnetic field, the nuclear spin tries to align, but the spin means that instead it rotates around the field direction with a characteristic frequency proportional to the field strength. When a pulse of exactly the right radio frequency is applied, some of the energy of the pulse is absorbed by the nucleus, which can be measured as a signal that decays typically within several milliseconds [8]. The timing of this signal decay, or relaxation, was discovered to depend critically on the chemical environment of the atom, and in particular was found to be different between healthy and diseased tissue in the human body. By rapidly switching on and off magnetic field gradients superimposed on the main field, it is possible to determine very accurate position information from these signals. The signals are processed by a computer to produce the now-familiar images from within the human body. Since the first crude MRI images were made in the 1970s, the industry has grown to a turnover of approximately $4B/year in new equipment sales. There are now well over 30,000 MRI systems installed worldwide, and the number is growing by 10% annually.

Advantages of Superconductivity:

The heart of the MRI system is a magnet. The typical field values required for the latest generation of MRI cannot be achieved using conventional magnets. Just as importantly, high homogeneity and stability of the magnetic field are essential to achieve the resolution, precision and speed required for economical clinical imaging. The use of superconducting magnets provides a unique solution to these requirements. This trend will continue as field strength continues to progress from the current mainstream 1.5 T (Tesla) and 3 T systems to ever higher strengths in order to improve the clarity of the signal generated and increase the speed of image acquisition.

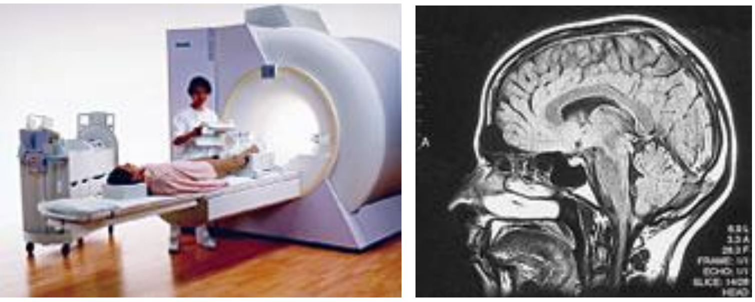

Figure. 1 Magnetic resonance imaging device and the image obtained in it

Magnetoencephalography (MEG) and Magnetic Source Imaging (MSI)

The same extreme sensitivity of SQUIDs that enables ULF-MRI has already enabled the development and use of Magnetoencephalography (MEG), sometimes referred to as magnetic source imaging (MSI). In these systems, which are available commercially, an array of SQUID sensors detects magnetic signals from the brain in a totally non-invasive manner. Major successes include:

- Pre-surgical mapping of brain tumors. By applying external stimuli (visual, audio, tactile), one can map out the function of the brain (which can be highly distorted by the presence of the tumor) prior to surgical removal of the tumor. With the aid of an MRI, this enables one to construct a 3D model of the brain and tumor.
- Showing the least invasive way of performing the surgery. This technique has been successful in reducing the incidence of collateral damage to the brain resulting from the surgical removal of the tumor.

- Location and pre-surgical mapping of the source of focal epilepsy. The focus is located using MSI. Pre-surgical mapping is conducted as for tumor surgery.
- Monitoring recovery from stroke or brain trauma (e.g. severe blow to the head as in football players, motorcycle accidents). MSI is used to monitor the response of the brain to standardized external stimuli (visual, audio, tactile) over a period of time to quantify the rate of recovery.

The use of MEG has been also extended to studies of unborn fetuses (fMEG). This technique has the potential to provide assessment of fetal neurological status and to assist physicians during high-risk pregnancies and diagnostics associated with infections, toxic insult, hypoxia, ischemia and hemorrhage. There are presently no other techniques for noninvasive assessment of fetal brain status.

The major challenge for the wider deployment of MEG systems is the initial cost of the system and the large database required to demonstrate excellent correlation of MSI with subsequent surgery. This effort involves system installation and data collection at research hospitals, an activity that is currently sparsely supported. The current initial diagnostic technique is low cost, Electroencephalography (EEG). The major advantage of MEG over EEG is that the former does not require any contact with the patient's skin. In EEG, since electric currents travel the path of least resistance, moisture on the patient's scalp and variations in skull thickness can distort the mapping of the epilepsy source.

Conversely, the magnetic field detected in MEG passes undistorted from the source to the SQUID detectors in the helmet worn by the patient. Since the interpretation of MSI inevitably requires an MR image, the combination of ULF-MRI with MSI into a single system would both reduce the cost of the combined procedures and improve their co-registration accuracy.

Magnetocardiography (MCG)

Sensitive SQUIDs are also the basis of functional imaging of the heart in magnetocardiography (MCG or MFI- heart magnetic field imaging) systems. MCG systems detect, non-invasively and with unprecedented accuracy, the net flows of cardiac electric currents that drive the muscles in the heart. In many clinical locations around the world, both scientists and physicians are independently validating the benefits of utilizing MCG for the detection and diagnosis of many forms of heart disease, especially cardiac ischemia and coronary artery disease. Sensitivity for the detection of ischemia has been reported as high as 100% in recent studies, and with such diagnostic accuracy it is not unreasonable to predict that MCG systems will find a home not only in hospitals, and especially emergency departments, but also in outpatient imaging centers and cardiology clinics, where the rapid evaluation of patients with suspicion of a life-threatening heart attack is absolutely critical to save lives. Significant economic benefits can also be projected. Compared with electrocardiography (EKG), MCG has a number of distinct advantages:

- completely non-invasive, requiring no electrode contact with the skin;
- provides wide-ranging information about the electrophysiological activity of the heart, including the detection of coronary artery disease; and
- signal strength depends on the distance between the heart and the detector, enabling the accurate measurement of the MCG of a fetus without saturating the detector with the signal from the mother's heart (fetal-MCG or fMCG).

While commercial systems do exist, the challenge for MCG, as in the case for MEG, is the development of a large enough database of clinical diagnostic correlations to convince insurers, such as Medicare, of the economic and healthcare benefits of MCG. Because it is radiation-free and risk-free, MCG can be used often during routine follow-up after an operation or during cardiac rehabilitation. The efficacy of a drug regimen can be tracked with MCG or even the recurrence of blockages after invasive treatment of a coronary artery. With the safety of a blood pressure reading and being equivalent to the diagnostic power of a magnetic resonance imaging procedure, MCG should be poised to revolutionize cardiac care.

Positron emission tomography

PET also relies on detection of photons, but in this case the photons are 511 keV back-to-back gamma rays emitted when a positron annihilates with an electron. The positrons are emitted by a radioactive nucleus disintegrating inside the subject; these positrons slow down and encounter an electron typically within a 1-2mm distance from the parent nucleus. The annihilation gammas are given off almost perfectly aligned, so detecting the two photons allows one to draw a line defining the path along which the decaying nucleus will be located. By observing many such coincident pairs, a density map of the radioactivity can be generated [1].

The radioactive material is attached to a substance that is selectively absorbed in the tissue being imaged, so the PET spectrum will identify these tissues. As discussed in Subsec. 2.5, a common system is to attach 18F to deoxyglucose, which is absorbed from the blood to fuel metabolic activity. PET can be used for studies of activity in the brain, or inversely areas of the brain that have been inactivated by disease such as

Alzheimer's. Identification of metastatic lesions, also characterized by higher metabolic activity, makes PET of extreme value for locating targets for therapy. Figure 2 shows a whole-body PET scan, identifying locations of metastatic disease, secondary tumors located far from the primary mass [1]. We have seen in Subsec. 2.5 that the production of the short-lived positron emitters is a major application for small accelerators. Desirable half-lives for these isotopes should be short enough to render insignificant the dose of radiation to the patient following the procedure, and so are less than an hour or two. Consequently, isotopes that are not available from a "generator" should be produced very close to the use point to minimize the loss of activity due to long delivery times. Large PET centers tend to have their own cyclotrons, with automated chemistry to transport and process the target material directly into the pharmaceutical to be used for the procedure.

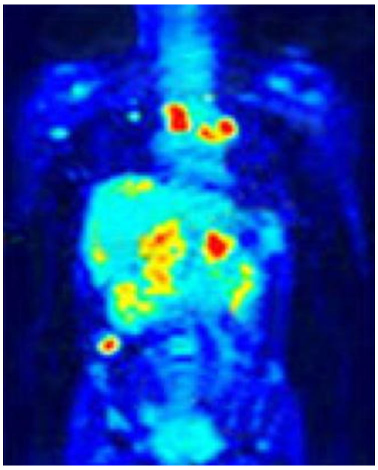

Figure. 2. Whole-body PET scan showing metastatic tumors, identified by high metabolic activity and the uptake of FDG (18F-deoxyglucose). (Courtesy of Blanchard Valley Health System, http://www.bvhealthsystem.org.)

As stated previously, this places great emphasis on development of accelerator and chemistry systems that are compact, reliable and inexpensive.

Conclusion. In conclusion, most modern medical devices manufactured and invented in recent years use superconducting materials. It is widely used in diagnostic devices. This is because the electrical resistance of the superconducting material is very small. This increases the level of accuracy of the obtained analysis results. In addition, these devices are energy-efficient, since the electrical resistance of their conductors is almost r=0, heat energy is released very little, and it is possible to obtain a strong magnetic field in a small size using a superconductor. In the article, we have given an overview of a few devices, in the following articles we will provide more extensive and detailed information about all devices that work on the basis of superconductors in medicine.

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