Lurian Journal. 2021. Vol. 2, No. 3. P. 111–114.
DOI 10.15826/Lurian.2021.2.3.10
УДК 615.84

Overview of the Most Important Advances in Magnetoencephalography Technology

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Обзор наиболее важных достижений в технологии магнитоэнцефалографии

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Abstract. The overview of the latest advances in magnetoencephalography (MEG) technology, including the development of optically pumped magnetometers (OPM), is presented. The main advantage of OPM over conventional superconducting quantum interference devices (SQUID) is the absence of cryogenic cooling, which reduces the cost of equipment by 2–3 times. Moreover, the OPM can be positioned a few millimeters from the scalp, which roughly doubles the signal-to-noise ratio. In addition, they are not as susceptible to muscle artifacts as electroencephalography (EEG) signals. Moreover, placing the OPM in a nulling magnetic field reduces the effects of head movement artifacts in the surrounding field. All these advantages open up great potential for the development of a new generation of OPM-based brain-computer interfaces (BCIs) that are cheaper, more flexible and more responsive than SQUID-based BCIs, which can perform both motor and non-motor tasks. Despite the tremendous progress made over the past few years, OPM–MEG is still an evolving technology that requires further improvement. Due to the large size of the sensors, the number of channels is relatively small (less than 50), so they cannot cover the entire head. Although many BCI applications require only a few sensors, their correct placement in selected areas of the scalp is very important. The miniaturization and versatility of lightweight helmets could be an important step towards the further development of OPM for BCI and other applications.

Keywords: *magnetoencephalography (MEG); superconducting quantum interference device (SQUID); optically pumped magnetometer (OPM)*

Аннотация. Представлен обзор новейших достижений в технологии магнитоэнцефалографии (MEG), включая разработку магнитометров с оптической накачкой (OPM). Основным преимуществом OPM перед обычными сверхпроводящими квантовыми интерференционными устройствами (SQUID) является отсутствие криогенного охлаждения, что снижает стоимость оборудования в 2–3 раза. OPM можно расположить на расстоянии нескольких миллиметров от кожи головы, что примерно вдвое увеличивает соотношение сигнал/шум. Кроме того, они не так восприимчивы к мышечным артефактам, как сигналы электроэнцефалографии (ЭЭГ). Размещение OPM в обнуляющем магнитном поле снижает влияние артефактов движения головы в окружающем поле. Все эти преимущества открывают большой потенциал для разработки нового поколения интерфейсов мозг — компьютер (BCI) на основе OPM, они дешевле, гибче и чувствительнее, чем BCI на основе SQUID, которые могут выполнять как моторные, так и немоторные задачи. Несмотря на огромный прогресс, достигнутый за последние несколько лет, OPM–MEG все еще является развивающейся технологией, требующей дальнейшего совершенствования. Из-за большого размера датчиков количество каналов относительно невелико (менее 50), поэтому они не могут покрыть всю голову. Для многих приложений BCI требуется всего несколько датчиков, но при этом очень важно правильно разместить их в выбранных областях черепа. Миниатюризация и универсальность легких шлемов может стать важным шагом на пути дальнейшего развития OPM для BCI и других приложений.

Ключевые слова: *магнитоэнцефалография (MEG); сверхпроводящее квантовое интерференционное устройство (SQUID); магнитометр с оптической накачкой (OPM)*

Magnetoencephalography (MEG) is a widely used neuroimaging technique, that measures weak magnetic fields generated by neurocortical ionic currents. This is a safe noninvasive method of brain imaging that provides important information about neuronal activity in the living human brain with high temporal (about 1 ms) and spatial (about 1–2 mm) resolution. While the EEG modality benefits from the simplicity of the measurement equipment, it suffers from a relatively low (around 2 cm) spatial resolution. At the same time, MEG requires more sophisticated instrumentation and measurement methods due to extremely low magnetic fields generated by the brain tissue. Currently, there are two MEG techniques, one is based on superconductivity under low (helium) temperatures, so-called superconducting quantum interference device (SQUID), and another one, known as optically pumped magnetometers (OPM), explores quantum mechanical properties of alkai atoms under optical pumping and operates under room temperatures.

The main advantage of OPMs is that they do not require cryogenic cooling, that decreases the OPM price by 2–3 times as compared to the conventional SQIUD-based

MEG systems. Moreover, the OPMs can be placed within millimeters from the scalp, that approximately doubles the signal-to-noise ratio (SNR). In addition, they are not so susceptible to muscle artefacts as EEG (Boto et al., 2018). The location of OPMs in a field-nulling apparatus (Holmes et al., 2018) decreases the influence of artefacts caused by head movement in the ambient field. Recently, 3D-printed helmets were demonstrated (Boto et al., 2018; Lin et al., 2019; Tierney et al., 2018). All these features give potential possibilities to develop a new generation of OPM-based BCIs, cheaper, more flexible and sensitive than SQUID-based BCIs, which can serve for both motor and non-motor tasks.

Despite the enormous progress, OPM–MEG is so far a developing technology that needs improvement. Due to their large size, the number of channels is relatively small (less than 50) (Borna et al., 2020; Boto et al., 2018; Iivanainen, Zetter, Grön, Hakkarainen, & Parkkonen, 2019) and therefore they cannot cover the entire head. In addition, OPMs can only be mounted in specific areas over the brain cortex. Although for many BCI applications only several sensors are required, their correct location over selected brain areas is very important. The miniaturization and universality of lightweight helmets would be an essential step towards further development of OPM wearable for BCI applications.

Significant progress in the MEG research has been achieved in cognitive neuroscience. For example, Chholak, Maksimenko, Hramov, and Pisarchik (2020) studied how voluntary and involuntary attention affect brain dynamics. The authors performed the MEG experiment with the Necker cube, in which the pixels' intensities on two faces were modulated with different frequencies. The tags at these frequencies and their harmonics were observed in the average power spectra of the MEG data recorded from the visual cortex. The subjects were asked to voluntary interpret the cube as either left- or right-orientated. The wavelet analysis allowed identifying the currently perceived cube orientation since the spectral energy was higher at the modulation frequency of the cube face to which the subject focused attention. The results of this experiment confirmed our hypothesis that higher attention requires a larger neuronal network to process information and make decision, this in turn increases neural noise since a larger number of synapses and neurons are involved (Pisarchik et al., 2019). Finally, it was shown that stronger brain noise causes more frequent switching between perceptual states or more frequent response selection and hence shorter dominance times.

Further development of studies using MEG is likely to be directed towards combination with fMRI. Not only the cerebral cortex can be used as a source of the magnetic field, but signals from deeper brain tissues will also be available for research. It is expected that new computational models will be developed to reconstruct MEG signals to help better understand the processes associated with specific brain functions.

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Original manuscript received February 04, 2021
Revised manuscript accepted June 26, 2021
First published online October 25, 2021

To cite this article: Pisarchik, A. N. (2021). Overview of the Most Important Advances in Magnetoencephalography Technology. *Lurian Journal, 2*(3), pp. 111–114. doi: 10.15826/Lurian.2021.2.3.10