Раздел 3
АППАРАТУРНЫЕ ИССЛЕДОВАНИЯ МОЗГА И ПОВЕДЕНИЯ

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Recent Advances in Magnetoencephalography

The review of novel advances in the magnetoencephalography (MEG) technique is present, including the development of optically pumped magnetometers (OPM) which are very promising for brain-computer interfaces (BCIs). The main advantage of OPMs over conventional SQUID devices is that they do not require cryogenic cooling, that decreases their price by 2–3 times. Moreover, the OPMs can be placed within millimeters from the scalp, that approximately doubles the signal-to-noise ratio. In addition, they are not so susceptible to muscle artefacts as EEG. In addition, the location of OPMs in a field-nulling apparatus decreases the influence of artefacts caused by head movement in the ambient field. All these advantages 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 made in the past few years, OPM–MEG is so far a developing technology that needs further improvement. Due to their large size, the number of channels is relatively small and therefore they cannot cover the entire head. The min-

iaturization and universality of lightweight helmets would be an essential step towards further development of OPM wearable for BCI applications.

Keywords: magnetoencephalography (MEG), SQUID, OPM

In the early 19th century, a Danish physicist Hans Chrostian Oersed discovered that electrical currents generate magnetic fields, with the direction described by a simple right-hand rule. Later, a nuclear physicist David Cohen from Massachusetts Institute of Technology, made the first MEG measurement in 1960s, although the sensitivity was very low and the signal was very noisy. He used a magnetically shielded room (MSR) to remove the overwhelming noise of the Earth's magnetic field. The next major advance in biomagnetic technology came with the development of the point-contact *superconducting quantum interference devise* (SQUID) by Zimmerman and his colleagues. Operating at liquid He temperature of –269 degrees, the SQUID achieved an unprecedented level of sensitivity to weak magnetic signals. Using signal-averaging techniques, the SQUID made it possible to measure stimulus-evoked neuromagnetic signals. Compared with a standard clinical magnetic resonance scanner magnet strength of 1,5 Tesla, the strength of the signals detected by MEG are 10^{14} orders smaller. The smallest measurable magnetic field changes are produced by simultaneously active arrays of approximately 50 000 pyramidal cells, which in theory covers a cortical surface area of 0,9 mm diameter. SQUID can detect tiny magnetic signals, much less than one-billionth the strength of the Earth's magnetic field, and then convert these signals into electric voltages.

Rapid advances in atomic physics over the last decade have led to a new generation of magneto-encephalography operating at room temperatures, so-called *optically-pumped magnetometers* (OPMs), capable to achieve sensitivity similar to that of cryogenically cooled devices. These new sensors can be placed directly on the scalp surface giving, theoretically, a large increase in the magnitude of the measured signal. Further motivation to develop room-temperature alternatives to low-temperature SQUID magnetometers comes from high helium costs, which complicate the operation of MEG systems. Using median nerve stimulation, Boto and his colleagues [1] showed that the OPM can detect both evoked (phase-locked) and induced (non-phase-locked oscillatory) changes when placed over sensory cortex, with signals ~4 times larger than equivalent SQUID measurements. Further, source-space modelling shows that, with 13 sequential OPM measurements, source-space signal-to-noise ratio (SNR) is comparable to that from a 271-channel SQUID system. These results highlight the opportunity presented by OPMs to generate uncooled, potentially low-cost, high SNR MEG systems.

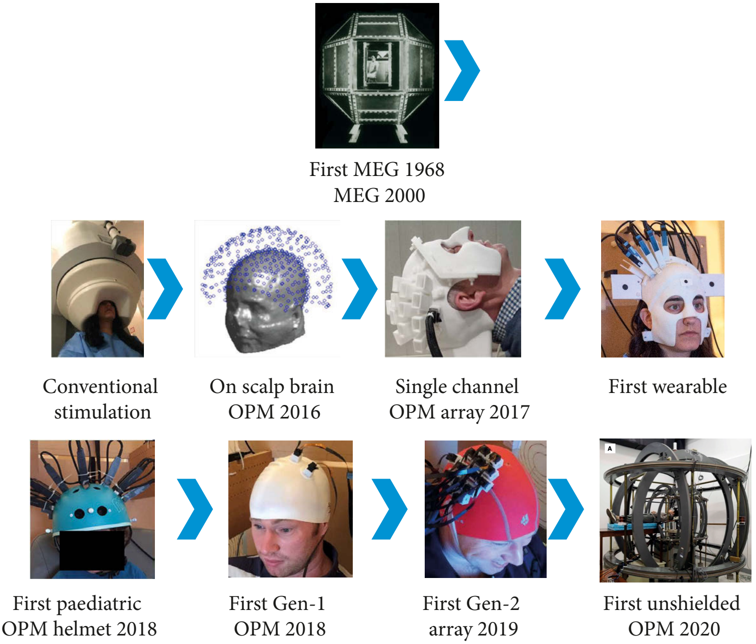
Robust and easy to use OPM sensors have recently become available commercially; these sensors are fabricated such that they have a small footprint meaning that a large number of sensors can be placed flexibly around the head and whole-head coverage is feasible. First experimental realizations of OPM–MEG involved recording neuromagnetic fields from restrained subjects, whose heads are fixed in position with respect to the sensors and surroundings. In 2019, Lin et al. [2] used OPMs to measure MEG signals in the human cerebellum that was impossible by SQUID systems. They used air-puff stimulus to the eyeball to elicit cerebellar activity. They used a 3D-printed cast to accurately inform sensor positions and orientations according to the brain anatomy. They detected evoke response in the cerebellum area. In 2020, Borna and his colleagues [3] developed a 20-channel OPM-based MEG system using OPM sensors. They conducted auditory evoked magnetic field (AEF) and somatosensory evoked magnetic field (SEF) experiments on three subjects. Because OPMs can be placed conformally to the scalp, OPM MEG systems can lead to enhanced spatial resolution as they capture finer spatial features compared to traditional SQUID-based MEG systems.

From June 2020, high-sensitive Gen-2 three-axis magnetometers are available from the *QuSpin Company* (Colorado). Meanwhile, researchers at the University of Nottingham have used the company's two-axis sensors to operate a whopping 50-channel array. *QuSpin* also makes a compact, high-sensitivity *Total-Field Magnetometer* (QTFM) which can operate in Earth's field and can resolve minute field changes for applications such as magnetic observatories and aboard small, mobile platforms.

Fast development of the MEG devices allowed their use in brain-computer interfaces (BCIs). The principal application of a BCI is as a form of neural prosthesis for people suffering from severe paralyzing conditions. The majority of BCIs are based on extracranial EEG recordings during motor imagery. In 2005, Lal et al. [4] reported the first working online

MEG-based BCI. The subjects were instructed to imagine movements of their tongue or left little finger. The choice of these two imaginations was motivated by the relatively great distance of the respective cortical areas on the motor cortex.

Fig. 2 illustrates the evolution of the MEG machines from the first MEG MSR in 1968 to the first unshielded OPM in 2020.



First MEG 1968
MEG 2000

Conventional stimulation

On scalp brain OPM 2016

Single channel OPM array 2017

First wearable

First paediatric OPM helmet 2018

First Gen-1 OPM 2018

First Gen-2 array 2019

First unshielded OPM 2020

Fig. 2. Development of MEG technique in XX and XXI centuries

Significant progress of MEG research was made in cognitive neuroscience. For example, in 2019 an interesting method of motor imagery (MI) classification was reported [5]. The method allows us to reveal differences between subjects belonging to two groups of motor imagery (MI), visual (VI) and kinesthetic (KI), distinguished by activation and inhibition of different brain areas in motor-related α- and β-frequency regions. Similar to real movement, KI implies muscular sensation when performing an imaginary moving action that leads to event-related desynchronization (ERD) of motor-associated brain rhythms. By contrast, VI refers to visualization of the corresponding action that results in event-related synchronization (ERS) of α- and β-wave (μ-band) activity. Although the brain activity corresponding to MI is usually observed in specially trained subjects or athletes, the authors have showed that it is also possible to identify particular features of MI in untrained subjects. The analysis of evoked responses was shown that in all KI subjects the activity in the frontal cortex is suppressed during MI, while in the VI subjects the frontal cortex is always active (fig. 3).

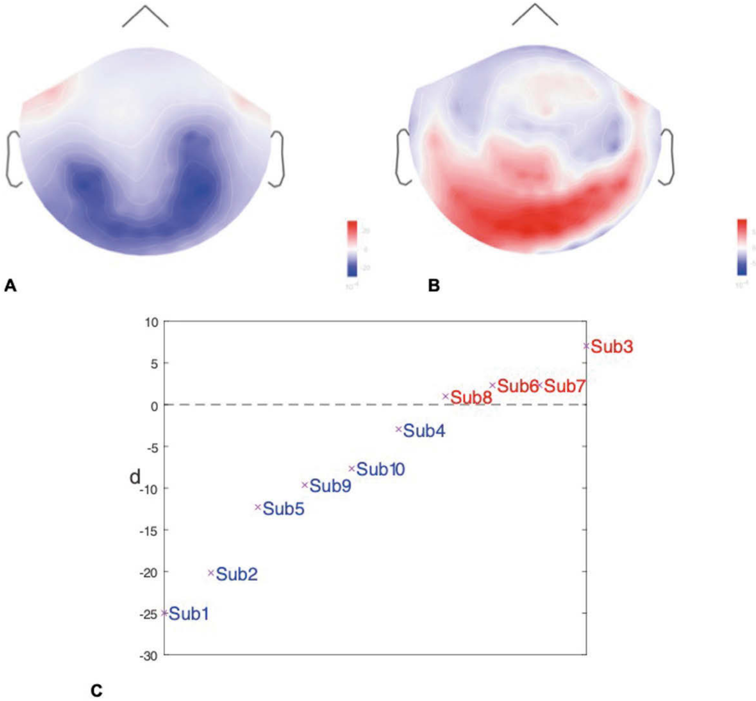


Fig. 3. MEG brain activity in subjects of (A) kinesthetic and (B) visual type of MI: A) Event-related desynchronization (ERD) in μ-band for KI subject 1; B) Event-related synchronization (ERS) in μ-band for VI subject 7; C) Averaged over all channels ERS/ERD degree d of 10 subjects

To conclude, the future of the MEG application concern three basic directions: fundamental research in neuroanatomy and neurophysiology, new diagnostic tools, and BCIs for communication and control purposes.

The development in any of the aforementioned areas may imply breakthrough within the others. Thus, there is need for coordination of further research and efforts of both clinicians and engineers toward another breakthrough thanks to the combination of MEG and fMRI to reflect brain dynamics. Not only brain cortex can be used as a source of magnetic field, but also signals from deeper brain tissues will be available for research. It is expected that new computational models for reconstitution of MEG signals will be developed. These models may help in deeper understanding of complex brain processes associated with particular functions and further understanding of individually shaped features of brain processes and signals.

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