

MAGNETOENCEPHALOGRAPHY IMEGL

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MAGNETOENCEPHALOGRAPHY (MEG)

Primary Disciplinary Field(s): Cognitive Neuroscience, Clinical Neurology, Biomedical Engineering

1. Core Definition and Function

Magnetoencephalography (MEG) is a sophisticated, non-invasive neurophysiological technique used to measure the magnetic fields produced by electrical currents occurring naturally in the brain. As a functional neuroimaging method, MEG provides unparalleled insight into the real-time dynamics of neural activity, distinguishing it from structural imaging techniques like MRI or CT scans. The fundamental principle driving MEG measurement is that synchronized electrical activity within populations of neurons generates extremely weak magnetic fields that pass through the skull and scalp unimpeded. By measuring these external magnetic fields, researchers and clinicians can infer the location, magnitude, and temporal evolution of the underlying neuronal currents. This diagnostic capability allows for the precise mapping of brain function with millisecond resolution, a crucial advantage when studying rapid cognitive processes or pathological electrical discharges.

The source of these detectable magnetic fields lies in the intracellular electrical currents generated primarily by postsynaptic potentials in cortical pyramidal neurons. When tens of thousands of these neurons fire simultaneously and are oriented perpendicularly to the scalp surface--such as those lining the walls of cortical sulci--the resulting current flow creates a measurable magnetic field according to the principles of electromagnetism, specifically the Biot-Savart Law. These magnetic signals are minute, typically in the range of femtoTesla (fT, 10^{-15} Tesla), which is roughly one billionth the strength of the Earth's magnetic field. Therefore, MEG requires extremely sensitive detection apparatus and specialized magnetic shielding to isolate the neural signals from environmental noise, ensuring the acquisition of clean, high-fidelity data suitable for accurate source localization and analysis.

While often utilized alongside electroencephalography (EEG), which measures the corresponding electrical potentials on the scalp surface, MEG offers distinct advantages due to the nature of magnetic fields. Crucially, magnetic fields are not distorted or smeared by tissues of differing conductivity, such as the skull and meninges, which severely affect EEG signals. This characteristic allows MEG to achieve significantly better spatial resolution for current sources oriented tangentially to the scalp compared to EEG, particularly when attempting to localize activity deep within the cortical folds. The robust combination of high temporal fidelity and relatively precise spatial mapping makes MEG an invaluable tool for understanding both normal brain function, such as sensory processing and language, and pathological conditions like epilepsy.

2. Historical Development and Etymology

The possibility of measuring the brain's magnetic fields was purely theoretical until 1968 when physicist **David Cohen** at the Massachusetts Institute of Technology (MIT) successfully recorded the first reliable MEG signal. Cohen utilized a simple copper induction coil placed in a magnetically shielded room to detect the magnetic activity emanating from the human alpha rhythm. While this initial demonstration proved the feasibility of the concept, the sensitivity of the instruments available at the time was insufficient for widespread clinical or research application, requiring prolonged averaging and limiting the depth of measurable activity. The term **Magnetoencephalography** itself is descriptive, combining 'magneto' (pertaining to magnetic fields), 'encephalo' (pertaining to the brain), and 'graphy' (the process of recording).

The technological breakthrough that transformed MEG from a laboratory curiosity into a practical neuroimaging tool was the development of the **Superconducting Quantum Interference Device (SQUID)**. Invented in the 1960s, SQUIDs are incredibly sensitive magnetometers capable of detecting magnetic flux changes far below the noise floor of standard electronic devices. Cohen, working with a SQUID system in the early 1970s, demonstrated that these devices could capture brain activity with much greater precision than earlier coils, opening the door for multi-channel systems. The requirement for SQUIDs meant that MEG instrumentation had to be maintained at cryogenic temperatures using liquid helium, a significant logistical constraint that continues to characterize current high-fidelity systems, although newer technologies are attempting to mitigate this requirement.

The maturation of MEG technology occurred primarily in the 1980s and 1990s with the introduction of commercial whole-head systems. Initial devices only covered small regions of the head, but engineering advancements allowed researchers to pack hundreds of SQUID sensors into helmet-like arrays, enabling simultaneous measurement across the entire cortex. This development coincided with parallel advancements in computational methods, particularly in **source localization algorithms** (such as Minimum Norm Estimates or Multiple Dipole Models), which are essential for mathematically solving the inverse problem--determining where in the brain the measured magnetic fields originated. This synergistic evolution cemented MEG's status as a distinct and powerful tool in the neuroscientific arsenal.

3. The Physics of MEG: Signal Generation and Measurement

The detectable magnetic field originates specifically from the primary intracellular currents flowing along the dendrites of neurons, particularly the large, elongated pyramidal cells of the cortex. When these neurons receive synaptic input, causing a net flow of charge (the primary current), a magnetic field is generated perpendicular to the direction of current flow. This relationship is codified by the Biot-Savart Law. It is crucial to understand that MEG is preferentially sensitive to

currents flowing parallel to the scalp surface--known as tangential sources. These sources are typically found deep within the sulcal walls. Conversely, currents that flow radially (perpendicular to the scalp), such as those located at the gyral crowns, produce magnetic fields that are largely undetectable outside the head because the magnetic field lines tend to loop back on themselves and cancel out upon reaching the surface.

This sensitivity profile results in a fundamental difference between MEG and its electrical counterpart, EEG. While EEG measures voltage differences resulting from both tangential and radial sources, the magnetic field measurement of MEG inherently filters out radial sources, which simplifies the interpretation of the measured signal, though it also represents a limitation. The magnetic fields are not distorted by intervening tissues because biological materials are essentially magnetically transparent at these frequencies and strengths. This lack of signal blurring allows for cleaner data acquisition compared to EEG, where the highly resistive nature of the skull significantly smears and reduces the electrical potential reaching the scalp surface, complicating the crucial step of source localization.

To successfully record these minute femtotesla signals, two primary engineering solutions are required. First, the detection apparatus must employ SQUID sensors, which are coupled to specialized flux transformers (gradiometers or magnetometers) designed to pick up the weak magnetic signals while simultaneously suppressing distant interference. Second, the entire MEG system must be housed within a highly effective **Magnetically Shielded Room (MSR)**. These rooms are constructed from multiple layers of high-permeability metals (like mu-metal) and conductive materials, creating a passive shielding environment that attenuates external magnetic noise by factors of hundreds or thousands, making it possible to resolve the extremely weak neuromagnetic activity generated by the brain.

4. Instrumentation and Technology

The core technology enabling MEG is the array of **Superconducting Quantum Interference Devices (SQUIDs)**. A SQUID is a sophisticated magnetometer capable of detecting magnetic flux at levels approaching the theoretical quantum limit, making it the most sensitive magnetic field detector currently available. Modern commercial MEG systems utilize helmet-shaped arrays containing anywhere from 150 to over 300 SQUID sensors, strategically positioned to cover the entirety of the subject's head. Since SQUIDs must operate at temperatures near absolute zero (around 4 Kelvin), they are contained within a Dewar--a specialized, vacuum-insulated container filled with liquid helium--which isolates the sensors from the patient's head while maintaining the necessary cryogenic conditions for superconductivity.

Each SQUID is coupled to a pickup coil, which captures the magnetic flux. These coils are typically configured as either **magnetometers** or **gradiometers**. Magnetometers measure the absolute

magnetic field at a single point, making them highly sensitive to both brain activity and distant environmental noise. Gradiometers, conversely, measure the spatial difference in the magnetic field across two or more nearby points. Since environmental noise (which originates from far away) tends to be uniform across the short distance separating the coils, the subtraction inherent in the gradiometer configuration effectively cancels out external noise while preserving the magnetic signal originating from the localized brain source. Most modern MEG systems employ a combination of radial and planar gradiometers to optimize noise cancellation and signal capture.

The secondary, but equally essential, technological component is the **Magnetically Shielded Room (MSR)**. The MSR typically comprises several layers of passive shielding materials. The outer layers are often made of aluminum or copper to shield against high-frequency electromagnetic interference, while inner layers consist of highly permeable materials like mu-metal, which effectively divert low-frequency static or slowly changing magnetic fields (such as those from traffic or subway lines) away from the sensors. Although MSRs are highly effective, advanced MEG systems also incorporate active shielding systems. These use real-time measurements of residual magnetic interference coupled with feedback coils to dynamically generate opposing magnetic fields, further reducing environmental noise and enhancing the signal-to-noise ratio of the delicate brain measurements.

5. Key Characteristics and Advantages over Other Neuroimaging Modalities

One of the most defining characteristics of MEG is its superior **temporal resolution**. Since the magnetic fields are a direct, instantaneous result of neuronal depolarization, MEG can track changes in brain activity on a millisecond timescale. This feature is critical for understanding rapid cognitive processes, such as the initial stages of visual recognition, auditory processing, or the precise timing of motor commands, phenomena that are impossible to resolve using hemodynamic techniques like functional Magnetic Resonance Imaging (fMRI), which operates on a timescale of seconds due to the slow nature of the blood-oxygen-level dependent (BOLD) response. MEG provides a window into the actual neural computations occurring in real-time, rather than the metabolic correlates of those computations.

Another significant advantage of MEG, particularly over EEG, is the aforementioned lack of signal distortion by the skull and scalp. Unlike electrical signals, magnetic fields pass through biological tissues without significant attenuation or dispersion. This transparency greatly simplifies the crucial step of **source localization**, the mathematical process used to infer the neural sources responsible for the recorded signals. While both EEG and MEG rely on solving the ill-posed "inverse problem," the cleaner magnetic data of MEG generally yields more accurate and reliable estimates of source location, especially for tangential currents in the cortex. This high-fidelity spatial information complements its excellent temporal resolution, offering a powerful combination for functional brain mapping.

Furthermore, MEG is a completely **non-invasive** technique, requiring no ionizing radiation (unlike PET or SPECT) or injection of radioactive tracers. The procedure simply involves the subject sitting or lying down with their head placed inside the sensor helmet, making it safe for repeated measurements, including longitudinal studies and use in pediatric populations. The derived data, often integrated with structural MRI scans to provide anatomical context, produces highly sophisticated functional maps. When co-registered with MRI, the combined technique, often referred to as Magnetic Source Imaging (MSI), allows researchers and clinicians to visualize brain activity superimposed directly onto the patient's individual brain anatomy, enhancing the practical utility of the results.

6. Clinical Applications

MEG has become an indispensable clinical tool, particularly in the fields of epileptology and neurosurgery, where precise localization of pathological or eloquent cortex is essential. The primary clinical application is the pre-surgical evaluation of patients with medically intractable **epilepsy**. MEG can accurately locate the **epileptogenic zone**--the small region of the brain responsible for initiating seizures. By mapping the interictal (between-seizure) spike discharges, MEG provides neurosurgeons with crucial information that guides the resection plan, minimizing the amount of healthy tissue removed while maximizing the chance of a seizure-free outcome. This information often supplements or confirms data gathered from intracranial EEG (iEEG).

Another vital clinical use is **pre-surgical mapping of eloquent cortex**, specifically in patients undergoing tumor resection or treatment for vascular malformations. The eloquent cortex refers to functionally critical areas, such as the primary motor, sensory, and language centers (Wernicke's and Broca's areas). By identifying the precise location of these functions using standardized cognitive tasks (e.g., finger tapping for motor cortex, listening for auditory cortex), MEG generates functional maps. Surgeons use these maps to plan surgical approaches that spare these critical areas, thereby significantly reducing the risk of post-operative neurological deficits, such as paralysis or aphasia. This functional mapping capability is often superior to fMRI in certain high-risk surgical cases due to MEG's higher spatial precision in cortical mapping.

Beyond pre-surgical planning, MEG is gaining traction in diagnosing and monitoring various neurological and psychiatric disorders. In research settings, it has been used to investigate biomarkers for conditions such as **Alzheimer's disease**, **Parkinson's disease**, **Autism Spectrum Disorder (ASD)**, and **Schizophrenia**. For instance, studies using MEG have identified abnormalities in oscillatory brain activity--such as altered power in alpha or gamma bands--in patients with these disorders, offering potential objective measures for diagnosis and tracking disease progression. While many of these applications remain primarily in the research domain, the clinical utility is rapidly expanding as MEG data interpretation becomes more standardized.

7. Limitations and Challenges

Despite its powerful capabilities, MEG faces significant limitations, primarily concerning cost and accessibility. The instrumentation required--the SQUID array, the liquid helium cryogenics, and the construction of a dedicated Magnetically Shielded Room (MSR)--makes the initial investment exceptionally high. Furthermore, the operational costs are substantial due to the ongoing need for liquid helium replenishment (for conventional low-temperature SQUIDs) and specialized maintenance of the MSR and sensor electronics. This high economic barrier limits the availability of MEG centers, confining them largely to major academic medical institutions and specialized research facilities.

A technical limitation intrinsic to the physics of MEG is its relative insensitivity to brain activity originating from **radial sources** (currents flowing perpendicular to the scalp) and deep subcortical structures. As discussed, the magnetic fields generated by radial sources cancel out rapidly outside the head, meaning MEG primarily maps tangential cortical activity. While this simplifies the inverse problem, it means that deep brain structures, such as the thalamus, basal ganglia, and cerebellum--which play critical roles in many neurological disorders--are difficult or impossible to localize directly using MEG alone. Researchers often employ multimodal integration, combining MEG data with deep-source-sensitive techniques like fMRI or deep EEG electrodes, to compensate for this depth limitation.

Finally, the process of **source localization**, while generally more accurate than EEG, remains a complex mathematical challenge known as the inverse problem. Since an infinite number of current distributions could theoretically produce the measured magnetic field pattern on the surface, the solution relies heavily on complex computational algorithms and assumptions (priors) about the sources. Accurate localization also requires precise coregistration of the MEG coordinate system with the patient's structural MRI, requiring painstaking effort to track the subject's head position relative to the sensor array. Head movement during the scan, even slight movement, can significantly degrade the quality of the data and introduce localization errors, requiring sophisticated real-time head tracking and compensation techniques.

8. Further Reading

[Magnetoencephalography \(Wikipedia\)](#)

[Superconducting Quantum Interference Device \(SQUID\)](#)

[Biot-Savart Law](#)

[Epilepsy \(World Health Organization\)](#)