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Source Imaging: A Report from the ACR  
Commission on Neuroradiology**

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This information is current as  
of April 17, 2024.

*AJNR Am J Neuroradiol* published online 1 December 2022  
<http://www.ajnr.org/content/early/2022/12/01/ajnr.A7714>

# ACR White Paper on Magnetoencephalography and Magnetic Source Imaging: A Report from the ACR Commission on Neuroradiology

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## ABSTRACT

**SUMMARY:** Magnetoencephalography, the extracranial detection of tiny magnetic fields emanating from intracranial electrical activity of neurons, and its source modeling relation, magnetic source imaging, represent a powerful functional neuroimaging technique, able to detect and localize both spontaneous and evoked activity of the brain in health and disease. Recent years have seen an increased utilization of this technique for both clinical practice and research, in the United States and worldwide. This report summarizes current thinking, presents recommendations for clinical implementation, and offers an outlook for emerging new clinical indications.

**ABBREVIATIONS:** ACR = American College of Radiology; AD = Alzheimer disease; ASD = autism spectrum disorder; CMS = Centers for Medicare and Medicaid Services; CPT = Current Procedural Terminology; ECD = equivalent current dipole; iEEG = intracranial electroencephalography; MEG = magnetoencephalography; MSI = magnetic source imaging

Magnetoencephalography (MEG) is a noninvasive method of detecting neural activity in the brain with millisecond time resolution. The current clinically approved indications for MEG are localization of epileptic foci and localization of eloquent cortices for presurgical planning. The goal of the MEG community at large is to advance current clinical practices and to develop new clinical indications for MEG. Multiple groups have researched the use of MEG in a variety of clinical disorders including concussion, Alzheimer's disease, autism, and others. Additionally, MEG can be used as an adjunct to other therapies, such as neuromodulation. Multispecialty collaboration

is necessary for the successful development of a comprehensive clinical MEG program. The team includes clinicians, MEG scientists, and technologists, often with complementary and/or overlapping skill sets. MEG centers across the United States operate in various clinical departments. Close collaboration with Radiology, Neurology, and Neurosurgery has been instrumental in advancing MEG for clinical use. While there are several publications outlining good clinical practice for acquiring and analyzing clinical MEG data, at the current time, implementation varies across sites. In this report, we describe the current clinical landscape for MEG and emerging applications, as well as provide recommendations for the composition and training of multidisciplinary teams involved in the performance and interpretation of clinical MEG studies, including the roles of the physician, MEG scientist, and MEG technologist in performance of current and future clinically approved MEG studies. We advocate that clinical reporting should be performed after consultation with the entire team, including technologists, MEG scientists, and physicians.

## Prior American College of Radiology Involvement in MEG

In 2001, with the joint support of the American College of Radiology (ACR), American Society of Neuroradiology, and American Academy of Neurology, 2 neuroradiologists (Roland Lee, Steven Stufflebeam) and 1 neurologist (Michael Funke) testified at the Centers for Medicare and Medicaid Services (CMS) in support of 3 new Current Procedural Terminology (CPT) codes for MEG:

95965 (MEG recording and analysis of spontaneous brain activity)

Received September 30, 2022; accepted after revision October 4.

From the Advanced Neuroscience Imaging Research Laboratory (J.A.M., E.M.D., A.L.P.), MEG Center of Excellence (J.A.M., E.M.D., A.L.P.), and Department of Radiology (J.A.M., E.M.D., A.L.P.), University of Texas Southwestern Medical Center, Dallas, Texas; Department of Neuroradiology (R.L.), University of California San Diego, San Diego, California; ACR Commission on Neuroradiology (J.J.), American College of Radiology, Reston, Virginia; Stanford University School of Medicine (J.J.), Stanford, California; Department of Neuroradiology (M.W.), University of Texas MD Anderson Center, Houston, Texas; Athinoula A. Martinos Center for Biomedical Imaging (S.S.), Department of Radiology, Massachusetts General Hospital, Charlestown, Massachusetts; Department of Radiology and Imaging Sciences (J.A.), University of Utah School of Medicine, Salt Lake City, Utah; Department of Radiology and Biomedical Imaging (P.M., S.S.N.), University of California, San Francisco, San Francisco, California; Pediatric Neurosciences (P.F.), Helen DeVos Children's Hospital, Grand Rapids, Michigan; Department of Pediatrics and Human Development (P.F.), College of Human Medicine, Michigan State University, Grand Rapids, Michigan; and Department of Radiology (W.G., E.S., T.P.L.R.), Children's Hospital of Philadelphia, Perelman School of Medicine at the University of Pennsylvania, Philadelphia, Pennsylvania.

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<http://dx.doi.org/10.3174/ajnr.A7714>

95966 (MEG recording and analysis of evoked magnetic fields, single technique)

95967 (MEG recording and analysis of evoked magnetic fields, each additional technique, after invoking 95966 once).

The Relative Value Scale Update Committee reviewed these codes at the April 2001 meeting, and CMS implemented the codes and payment rates in 2002, with subsequent scheduled reviews and revisions of the payment rates.

### **fMRI versus MEG**

fMRI has been in clinical use for over 2 decades, slightly predating the clinical adoption of MEG. Clinical indications for fMRI involve presurgical mapping of eloquent cortex. While fMRI provides complementary information to MEG, the underlying neurophysiologic basis of the signal is quite different. Functional MR imaging relies on changes in blood flow associated with neuronal activity, making it an indirect measure of brain function, whereas MEG provides a more direct measure. Both modalities can provide accurate delineation of eloquent cortex. However, MEG is uniquely suited to identification of epileptogenic activity. Mapping of eloquent cortices can be performed at the same time as the epilepsy study with MEG. Clinical MR imaging scans are obtained separately from fMRI and MEG studies, with distinct CPT codes, and provide anatomic reference for functional maps. For both fMRI and MEG, robust paradigms exist for motor, sensory, and language mapping. For both modalities, areas of activation are mapped onto a structural MR imaging study as part of the presurgical evaluation.

### **Current Indications for MEG and Magnetic Source Imaging**

**Presurgical Mapping of Epileptogenic Zones.** MEG is clinically approved for preoperative planning in patients with intractable, or drug-resistant, epilepsy. The millisecond time resolution of MEG is ideally suited to capture bursts of abnormal neuroelectrical activity, as seen in epilepsy, and the spatial precision of magnetic source imaging (MSI) allows the accurate localization of the epileptogenic zone(s) (ie, seizure-generating tissue).<sup>1</sup> The onset of each interictal epileptiform discharge is projected to source space (ie, brain space) as an equivalent current dipole (ECD) to visualize the location of potential seizure onset zone(s). In this way, MEG and MSI can provide unique information for presurgical planning in intractable epilepsy. MEG is optimally beneficial during presurgical planning for cases in which common noninvasive modalities result in an inconclusive hypothesis regarding epileptogenic zone location, MR imaging–negative (ie, nonlesional) cases, cases in which MR imaging identifies multiple lesions (eg, tuberous sclerosis), and patients with large lesions, anatomical malformations, and/or prior resection.<sup>1-3</sup>

Empirical investigations have found that MEG and MSI contribute added clinical value during presurgical planning in patients with intractable epilepsy, as surgical resection of the epileptogenic zone(s) can eliminate or reduce seizures.<sup>4-6</sup> Presurgical planning often involves the acquisition of multiple neuroimaging modalities (eg, MR imaging, FDG-PET, ictal-SPECT, single-photon emission CT). These data are used to plan intracranial electroencephalography (iEEG), in which a grid of subdural electrodes and/or depth electrodes is implanted directly into the brain to confirm

epileptogenic zone localization. Recent studies have revealed good concordance between MEG and iEEG in localizing epileptogenic activity, bolstering MEG's potential as an alternative, noninvasive tool for preoperative planning.<sup>7</sup>

Inclusion of MEG in the presurgical neuroimaging battery bestows better clinical outcomes and correlates with postoperative seizure freedom.<sup>8,9</sup> Specifically, resection patients in whom the MEG dipole cluster was completely sampled by iEEG had a strikingly higher chance of seizure freedom relative to patients with incomplete/no iEEG sampling. A similar finding was observed for patients in whom the MEG dipole cluster was completely resected relative to those with partial/no resection of the MEG cluster.<sup>9</sup> Finally, patients with a single tight dipole cluster, those with a cluster that had stable orientation perpendicular to the closest major sulcus, and those with agreement between MEG and iEEG localization were more likely to be seizure-free postresection.

**Presurgical Mapping of Eloquent Cortices.** MEG is used to non-invasively map the eloquent cortex in patients before they undergo epilepsy or brain tumor surgery. The goals are to minimize deleterious postoperative functional outcomes and/or identify whether functional reorganization has occurred. Specifically, localization of somatosensory, motor, auditory, and/or visual cortices, as well as localization and lateralization of language cortices may be performed to predict postsurgical outcomes and optimize the preservation of these functions postoperatively.<sup>10</sup>

Eloquent cortex mapping requires the application of specific tasks during MEG recording that are designed to elicit the functions of interest. These tasks generate magnetic evoked fields, and MSI is employed to localize stereotyped deflections in, or components of, the evoked magnetic field. The ability to capture different neurophysiological responses within 1 recording is a distinct advantage of MEG relative to fMRI, and MEG may be superior for functional mapping in patients who have cerebrovascular malformations or tumors near the functional cortex. However, MEG and fMRI often serve complementary roles in eloquent cortex mapping, and their amalgamation can enhance the reliability of functional localization.<sup>11,12</sup>

With respect to each function, somatosensory responses reliably map to the posterior bank of the central sulcus contralateral to the side of stimulation in a manner that follows expected somatotopic organization. In a similar fashion, motor responses localize to the primary motor cortex contralateral to the side of movement. Both contralateral and ipsilateral auditory responses may be localized and map to Heschl's gyri. Visual responses localize to the primary visual cortex contralateral to the stimulated visual hemifield near the calcarine fissure.<sup>13,14</sup> Importantly, prior research has found that such MEG-based localizations have high concordance with intraoperative cortical mapping. Finally, a distributed network of bilateral cortical regions often underlies language processing. Receptive language responses often localize to the posterior superior temporal gyrus (ie, Wernicke's area), supramarginal gyrus, and angular gyrus, while expressive language responses often map to the pars triangularis and pars opercularis in the inferior frontal cortex (ie, Broca's area). A laterality index is computed to determine hemispheric dominance of

language function. Multiple studies have demonstrated high concordance between MEG-based language mapping and invasive procedures (eg, intracarotid amobarbital procedure or Wada), favoring MEG as a noninvasive option for language mapping and lateralization.<sup>10,15-18</sup>

A key transformative step is the integration of source-modeled MEG data with MR imaging to yield MSI, either by the overlay of single equivalent dipole sources or by statistical mapping of either spontaneous or event-related changes.<sup>19,20</sup> This renders MEG data directly interpretable by the neuroradiologist in a fashion very analogous to fMRI, but combining both mapping of functional, eloquent cortex, as well as the sources of interictal spontaneous discharges (dysfunctional MR imaging).

## CLINICAL MEG RECOMMENDATIONS

### **Roles, Training, and Certification/Accreditation**

**Qualifications of Physicians Interpreting Clinical MEG Studies.** Physicians interpreting and reporting clinical MEG studies should have appropriate medical licensure and proper training for the clinical application. For radiologists, this may include specialized clinical knowledge of neurophysiology, neuroanatomy, brain mapping, neuropsychology, and image acquisition and interpretation such as required through the American Board of Radiology Subspecialty Certification in Neuroradiology. In addition, MEG-specific training is recommended to include supervised learning or clinical practice of at least 50 MEG studies for the specific indication being reported. Alternatively, a minimum of 2 years of experience interpreting clinical fMRI or MEG brain mapping studies is recommended.

**Qualifications of MEG Scientists Involved in Clinical MEG Studies.** MEG scientists involved in clinical MEG studies should be well-versed in signal processing, source analysis, neurophysiology, cognitive neuroscience, image processing, physics, and other scientific aspects of MEG and its application to patient care. In addition, MEG-specific training is recommended to include supervised learning or clinical practice of at least 50 MEG studies for the specific indication being reported, which can also be fulfilled through a minimum of 2 years of experience in the source modeling of MEG studies by a postdoctoral fellowship with a clinical MEG component, or through rotations at clinical MEG facilities.

**Qualifications of MEG Technologists.** The MEG technologist should have a background in either EEG or imaging (eg, MR imaging) or related disciplines. Supervised learning or clinical practice of at least 50 MEG studies, including a review of the principles of MEG technology, technical aspects of the MEG systems, patient preparation, data acquisition, operational routines, tuning procedures, testing procedures, troubleshooting, artifact identification, prevention, and elimination, data storage, and basic source localization procedures. Alternatively, a minimum of 6 months of supervised clinical experience in an active MEG center is recommended.

### **Procedure/Workflow of Clinical MEG Examination, Analysis, and Reporting**

MEG-guided localization of epileptogenic zones involves several key steps. Before recording, surface EEG electrodes and head

position indicator coils are affixed to manufacturer-specified locations on the patient's head. These coils generate a specific frequency during MEG recording to allow for head localization. The patient's head shape and location of head position indicator coils is digitized for subsequent co-registration of MEG and structural MR imaging data. Simultaneous MEG and scalp EEG data are recorded. Typically, 40–120 minutes of spontaneous (ie, resting-state) data are collected. Due to the limited duration of recordings and the movement-related artifact introduced by seizures, ictal discharges are rarely captured. Rather, MEG recordings primarily capture interictal epileptiform discharges.<sup>8</sup> To increase the yield of interictal epileptiform discharges during the scan, patients are asked to come sleep-deprived and sleep in the scanner.<sup>21</sup> These data are preprocessed to remove noise and co-register the MEG data with a structural MR imaging (typically a 3D T1). Preprocessing algorithms and steps vary depending on the manufacturer. A professional with specialized training (eg, epileptologist, neurophysiologist, etc) reads the time-series EEG and MEG data and identifies epileptic discharges. The identified discharges are localized to source space via the ECD model, referred to as modeling in this article.<sup>22</sup> Modeling can be completed by anyone with specialized training in the neuroscience, physics, and mathematical concepts behind the dipole model (eg, scientist, physician, technologist). Dipoles that meet statistical cutoff criteria (eg, goodness of fit, volume of confidence) are displayed on a structural MR imaging scan, which can be exported to PACS.

Dipoles may form clusters within a specific region. The clustering of 5 or more dipoles within a region is considered a reliable indicator of an epileptogenic zone.<sup>23</sup> Both the tightness and orientation of the dipoles within a cluster have clinical relevance.<sup>1,9</sup> The location of these dipoles and characteristics of any clusters formed are reported by a physician. A suggested template for reporting is located in the Appendix.

In contrast to presurgical mapping of epileptogenic zones, which relies on resting-state recordings, eloquent cortex mapping relies on task-based recordings. The patient should be awake and alert. During a task, identical or similar stimuli are repetitively delivered to the patient, and a corresponding trigger (eg, number) is time-stamped into the data. Offline, the data are epoched into meaningful windows of time surrounding each stimulus, baseline-normalized, and averaged together to enhance the signal-to-noise ratio. This distinguishes the magnetic evoked field generated by the stimuli, and components of the field are modeled to localize the functional cortex. The time and location of each component modeled are reported by a physician.

Somatosensory cortex mapping most often employs brief electrical stimulations to the median nerve. However, stimulation of the posterior tibial nerve and/or mechanical stimulation of the hand, foot, or other body regions may also be performed. To map the motor cortex, the patient is asked to perform a simple movement such as pressing a button, tapping a finger, or moving a foot at either a self-paced or visually- or auditorily-cued time interval. For auditory cortex mapping, often 1000-Hz tones are briefly presented through inserted ear tubes at 60 dB above the patient's hearing threshold, either monaurally or binaurally.<sup>10,13</sup> To map the visual cortex, stimuli, often checkerboards, are presented on a projector screen to the full visual field, each hemifield,



or each quadrant. Language cortex mapping may utilize auditory and/or visual stimuli and can be grouped into 2 categories: receptive or expressive. Receptive language tasks include passively listening to words or silently reading words presented on the projector screen. Expressive language tasks include covert verb generation and picture naming.<sup>10,14,24</sup>

Many of the patients undergoing MEG have epilepsy that is poorly controlled by medications. It is important that safeguards be put in place for responding to medical emergencies. This includes the availability of emergency personnel and supplies depending on the setting.

### **Billing and Reimbursement**

As noted in the Background, since 2002, the CMS has authorized and implemented 3 CPT codes and their payment rates for MEG: 95965, 95966, 95967. Using these 3 codes, clinical MEG is a well-established reimbursable procedure and is accepted as the standard of care in evaluation of patients with epilepsy and in the presurgical mapping of eloquent cortices.

### **Quality Improvement and Quality Control**

A critical component of establishing and maintaining a high-quality clinical MEG program is to invest in the training and education of all team members. Most manufacturers offer training programs for new sites. The American Board of Registration of Electroencephalographic and Evoked Potential Technologists offers a MEG technologist certification program. Both the American Clinical MEG Society and the American Society for Functional Neuroradiology offer clinical guidelines, continuing education at annual meetings, and clinical MEG fellowship training programs for neurologists and neuroradiologists, respectively. Other relevant conferences include the biannual meeting of the International Society for the Advancement of Clinical MEG and the biannual International Conference on Biomagnetism. A number of excellent publications are available, including the *MEG-EEG Primer* textbook, *Clinical Magnetoencephalography and Magnetic Source Imaging* textbook, the November 2020 issue of the *Journal of Clinical Neurophysiology*, and clinical MEG guideline articles published by the International Federation of Clinical Neurophysiology and American Clinical MEG Society.<sup>13,24,25</sup>

A clear protocol for assessing the technical quality of the data is vital. Noise measurements and empty room recordings are often collected daily or before recording each patient to monitor changes in the environment and identify issues with equipment. During data acquisition, the position of the patient's head within the MEG helmet is monitored for proper placement, observations of artifact and noise are documented, and averages of events during evoked testing may be computed online to visually inspect for the presence of the expected magnetic evoked fields. Routine (eg, monthly) quality-assurance testing of the digitization equipment, MEG system, and software is often conducted by utilizing a phantom for recordings. Collaborative interdepartmental conferences should also be held regularly to compare MEG results with clinical outcomes (eg, stereoelectroencephalography data).

## **EMERGING INDICATIONS**

### **Concussion**

Many articles in the peer-reviewed literature show that MEG can objectively diagnose concussions (mild traumatic brain injury) with significantly more sensitivity (about 85% sensitivity) than the relatively insensitive standard neuroimaging techniques such as CT or MR imaging.<sup>26-33</sup> EEG has long demonstrated that low-frequency activity in the delta-band (1–4 Hz) is abnormal in awake, alert adults. Studies in animal models confirm that deafferentation of neurons due to traumatic injury to axons or blockage of cholinergic transmission will generate these slow/delta-waves.<sup>31,34</sup> Resting-state MEG more sensitively detects delta waves than EEG, with about 85% sensitivity in diagnosing concussions compared with normal controls, even in single subjects when using an automated voxelwise algorithm, which also localizes the areas of abnormal slow-waves.<sup>26</sup>

Another MEG finding in patients with concussion is excessive synchronous resting-state high-frequency gamma-band activity (30–80 Hz) in certain frontal and other brain regions, which may be due to selective vulnerability of inhibitory GABAergic interneurons due to head trauma.<sup>29</sup>

Resting-state functional connectivity studies with MEG reveal various patterns of aberrant functional connectivity in patients with mild traumatic brain injury, likely reflecting differing mechanisms of injury, including disruption of networks, and injury to inhibitory GABAergic interneurons.<sup>32,33</sup>

### **Post-Traumatic Stress Disorder**

Post-traumatic stress disorder affects about 7% of American adults during their lifetime and is especially prevalent in combat veterans. Compared with normal controls, MEG in patients with post-traumatic stress disorder shows differences in resting-state neurocircuitry, including hyperactivity in the amygdala, hippocampus, posterolateral orbitofrontal cortex, dorsomedial prefrontal cortex, and insular cortex in high-frequency (beta and gamma) bands; hypoactivity from the ventromedial prefrontal cortex, frontal pole, dorsolateral prefrontal cortex in high-frequency bands; and hypoactivity in the precuneus, dorsolateral prefrontal cortex, temporal and frontal poles, and sensorimotor cortex in alpha and low-frequency bands.<sup>35</sup>

### **Autism Spectrum Disorder**

The physical properties of MEG offer sensitivity not only to spatial localization of detected signals but also characterization in terms of the time course and spectral content of such brain activity. As such, it may allow description of not just functional centers but also “when” the brain activity is occurring and, indeed, “what” is the nature of such activity. This opens up considerable promise for application to psychiatric disorders, commonly with no MR imaging-visible structural anomaly. One promising target disorder is autism spectrum disorder (ASD), a highly prevalent (~2%) neurodevelopmental disorder. Although there is indeed an ultimate possibility (and current exploration) of identifying early electrophysiologic predictors of ASD in infants and young children, an alternative promising role for MEG lies in the stratification, or subtyping, of the remarkably heterogeneous ASD population. Such stratification may have value in terms of

potential enrichment of clinical trials for behavioral/pharmaceutical therapies as well as potentially providing early “brain-level” indices of drug “target-engagement” as a predictor of ultimate efficacy. Considerable promise is shown in the *latency* of simple sensory evoked responses (eg, the auditory cortex 50-ms [M50] and 100-ms [M100] components, which tend to be delayed in children with ASD, perhaps triggering a cascade of delayed neural communication, with ultimate behavioral sequelae).<sup>36-38</sup>

## Dementia

Dementia is a neurodegenerative condition that usually affects people aged older than 65 years that causes major cognitive dysfunction, loss of independence, and reduced quality of life. The ever-increasing proportion of aged people in modern societies is leading to a substantial increase in the number of people affected by dementia and Alzheimer’s disease (AD) in particular, which is the most common cause for dementia. Several resting-state MEG studies have shown frequency-specific alterations in local and long-range neural synchrony in various dementias, even at the earliest prodromal stages of AD manifestation.<sup>39</sup> Increased synchrony delta-theta bands and decreased alpha or beta bands are consistently reported not only in patients with the AD neuropathological spectrum including those who are asymptomatic but carry higher risk of AD, as well as in clinically symptomatic individuals with positive AD biomarkers,<sup>40-46</sup> but also in patients with variants of primary progressive aphasia, a form of dementia that impacts language function.<sup>47</sup> Disruption of information flow quantified by MEG source imaging may also underlie clinical symptoms in AD.<sup>48</sup> Studies have also reported task-induced MEG activity changes in AD with mismatch paradigms that highlight the translational potential for neurophysiological “signatures” of dementia, to understand disease mechanisms in humans and facilitate experimental medicine studies.<sup>49</sup>

## CONCLUSIONS

MEG and MSI provide a powerful tool for characterizing brain activity in health and disease. Clinical applications as of this date are in the localization of spontaneous epileptiform activity as part of surgical work-up of patients with seizure disorders as well as presurgical mapping of eloquent cortex for patients undergoing resective surgery of tumors, AVMs, etc. However, there are many emerging applications being researched currently.

A neuroradiologist can be a key member of the team conducting and interpreting MEG studies. Promising future areas of MEG/MSI application will also likely capitalize on the neuroradiologist’s ability to work in a multidisciplinary team, integrating anatomic, physiologic, functional, and clinical information.

Disclosure forms provided by the authors are available with the full text and PDF of this article at [www.ajnr.org](http://www.ajnr.org).

## REFERENCES

- Burgess RC. **MEG for greater sensitivity and more precise localization in epilepsy.** *Neuroimaging Clin N Am* 2020;30:145–58 [CrossRef Medline](#)
- Bagić AI, Burgess RC. **Utilization of MEG among the US epilepsy centers: a survey-based appraisal.** *J Clin Neurophysiol* 2020;37:599–605 [CrossRef Medline](#)
- Jung J, Bouet R, Delpuech C, et al. **The value of magnetoencephalography for seizure-onset zone localization in magnetic resonance imaging-negative partial epilepsy.** *Brain* 2013;136:3176–86 [CrossRef Medline](#)
- De Tiège X, Carrette E, Legros B, et al. **Clinical added value of magnetic source imaging in the presurgical evaluation of refractory focal epilepsy.** *J Neurol Neurosurg Psychiatry* 2012;83:417–23 [CrossRef Medline](#)
- Mohamed IS, Toffa DH, Robert M, et al. **Utility of magnetic source imaging in nonlesional focal epilepsy: a prospective study.** *Neurosurg Focus* 2020;48:E16 [CrossRef Medline](#)
- Englot DJ, Nagarajan SS, Imber BS, et al. **Epileptogenic zone localization using magnetoencephalography predicts seizure freedom in epilepsy surgery.** *Epilepsia* 2015;56:949–58 [CrossRef Medline](#)
- Knowlton RC. **The role of FDG-PET, ictal SPECT, and MEG in the epilepsy surgery evaluation.** *Epilepsy Behav* 2006;8:91–101 [CrossRef Medline](#)
- Supek S, Aine CJ. *Magnetoencephalography: From Signals to Dynamic Cortical Networks.* Springer; 2019
- Murakami H, Wang ZI, Marshly A, et al. **Correlating magnetoencephalography to stereo-electroencephalography in patients undergoing epilepsy surgery.** *Brain* 2016;139:2935–47 [CrossRef Medline](#)
- Bowyer SM, Pang EW, Huang M, et al. **Presurgical functional mapping with magnetoencephalography.** *Neuroimaging Clin N Am* 2020;30:159–74 [CrossRef Medline](#)
- Stufflebeam SM. **Clinical magnetoencephalography for neurosurgery.** *Neurosurg Clin N Am* 2011;22:153–67 [CrossRef Medline](#)
- Grummich P, Nimsky C, Pauli E, et al. **Combining fMRI and MEG increases the reliability of presurgical language localization: a clinical study on the difference between and congruence of both modalities.** *Neuroimage* 2006;32:1793–1803 [CrossRef Medline](#)
- Hari R, Baillet S, Barnes G, et al. **IFCN-endorsed practical guidelines for clinical magnetoencephalography (MEG).** *Clin Neurophysiol* 2018;129:1720–47 [CrossRef Medline](#)
- Zillgitt A, Barkley GL, Bowyer SM. **Visual mapping with magnetoencephalography: an update on the current state of clinical research and practice with considerations for clinical practice guidelines.** *J Clin Neurophysiol* 2020;37:585–91 [CrossRef Medline](#)
- Kreidenhuber R, De Tiège X, Rampp S. **Presurgical functional cortical mapping using electromagnetic source imaging.** *Front Neurol* 2019;10:628 [CrossRef Medline](#)
- Hirata M, Kato A, Taniguchi M, et al. **Determination of language dominance with synthetic aperture magnetometry: comparison with the Wada test.** *Neuroimage* 2004;23:46–53 [CrossRef Medline](#)
- Hirata M, Goto T, Barnes G, et al. **Language dominance and mapping based on neuromagnetic oscillatory changes: comparison with invasive procedures.** *J Neurosurg* 2010;112:528–38 [CrossRef Medline](#)
- Findlay AM, Ambrose JB, Cahn-Weiner DA, et al. **Dynamics of hemispheric dominance for language assessed by magnetoencephalographic imaging.** *Ann Neurol* 2012;71:668–86 [CrossRef Medline](#)
- Gofshteyn JS, Le T, Kessler S, et al. **Synthetic aperture magnetometry and excess kurtosis mapping of magnetoencephalography (MEG) is predictive of epilepsy surgical outcome in a large pediatric cohort.** *Epilepsy Res* 2019;155:106151 [CrossRef Medline](#)
- Hillebrand A, Barnes GR. **Beamformer analysis of MEG data.** *Int Rev Neurobiol* 2005;68:149–71 [CrossRef Medline](#)
- King MA, Newton MR, Jackson GD, et al. **Epileptology of the first-seizure presentation: a clinical, electroencephalographic, and magnetic resonance imaging study of 300 consecutive patients.** *Lancet* 1998;352:1007–11 [CrossRef Medline](#)
- Sarvas J. **Basic mathematical and electromagnetic concepts of the biomagnetic inverse problem.** *Phys Med Biol* 1987;32:11–22 [CrossRef Medline](#)
- Burgess RC. In: Levin KH, Chauvel KH, eds. *Handbook of Clinical Neurology: Clinical Neurophysiology: Basis and Technical Aspects.* Vol 160, Chapter 13. Elsevier; 2019:203–14
- Burgess RC, Funke ME, Bowyer SM, et al; ACMEGS Clinical Practice Guideline (CPG) Committee. **American Clinical Magnetoencephalography Society Clinical Practice Guideline 2: presurgical**

- functional brain mapping using magnetic evoked fields. *J Clin Neurophysiol* 2011;28:355–56 [CrossRef Medline](#)
25. Bagic AI, Knowlton RC, Rose DF, et al; ACMEGS Clinical Practice Guideline (CPG) Committee. **American Clinical Magnetoencephalography Society clinical practice guideline I: recording and analysis of spontaneous cerebral activity.** *J Clin Neurophysiol* 2011;28:348–54 [CrossRef Medline](#)
  26. Huang MX, Nichols S, Baker DG, et al. **Single-subject-based whole-brain MEG slow-wave imaging approach for detecting abnormality in patients with mild traumatic brain injury.** *Neuroimage Clin* 2014;5:109–19 [CrossRef Medline](#)
  27. Huang MX, Nichols S, Robb A, et al. **An automatic MEG low-frequency source imaging approach for detecting injuries in mild and moderate TBI patients with blast and non-blast causes.** *Neuroimage* 2012;61:1067–82 [CrossRef Medline](#)
  28. Huang MX, Theilmann RJ, Robb A, et al. **Integrated imaging approach with MEG and DTI to detect mild traumatic brain injury in military and civilian patients.** *J Neurotrauma* 2009;26:1213–26 [CrossRef Medline](#)
  29. Huang MX, Huang CW, Harrington DL, et al. **Marked increases in resting-state MEG gamma-band activity in combat-related mild traumatic brain injury.** *Cereb Cortex* 2020;30:283–95 [CrossRef Medline](#)
  30. Lewine JD, Davis JT, Bigler ED, et al. **Objective documentation of traumatic brain injury subsequent to mild head trauma: multimodal brain imaging with MEG, SPECT, and MRI.** *J Head Trauma Rehabil* 2007;22:141–55 [CrossRef Medline](#)
  31. Gloor P, Ball G, Schaul N. **Brain lesions that produce delta waves in the EEG.** *Neurology* 1977;27:326–33 [CrossRef Medline](#)
  32. Huang MX, Harrington DL, Robb Swan A, et al. **Resting-state magnetoencephalography reveals different patterns of aberrant functional connectivity in combat-related mild traumatic brain injury.** *J Neurotrauma* 2017;34:1412–26 [CrossRef Medline](#)
  33. Tarapore PE, Findlay AM, Lahue SC, et al. **Resting state magnetoencephalography functional connectivity in traumatic brain injury.** *J Neurosurg* 2013;118:1306–16 [CrossRef Medline](#)
  34. Ball GJ, Gloor P, Schaul N. **The cortical electromicrophysiology of pathological delta waves in the electroencephalogram of cats.** *Electroencephalogr Clin Neurophysiol* 1977;43:346–61 [CrossRef Medline](#)
  35. Huang M, Risling M, Baker DG. **The role of biomarkers and MEG-based imaging markers in the diagnosis of post-traumatic stress disorder and blast-induced mild traumatic brain injury.** *Psychoneuroendocrinology* 2016;63:398–409 [CrossRef Medline](#)
  36. Roberts TPL, Khan SY, Rey M, et al. **MEG detection of delayed auditory evoked responses in autism spectrum disorders: towards an imaging biomarker for autism.** *Autism Res* 2010;3:8–18 [CrossRef Medline](#)
  37. Roberts TP, Cannon KM, Tavabi K, et al. **Auditory magnetic mismatch field latency: a biomarker for language impairment in autism.** *Biol Psychiatry* 2011;70:263–69 [CrossRef Medline](#)
  38. Matsuzaki J, Kuschner ES, Blaskey L, et al. **Abnormal auditory mismatch fields are associated with communication impairment in both verbal and minimally verbal/nonverbal children who have autism spectrum disorder.** *Autism Res* 2019;12:1225–35 [CrossRef Medline](#)
  39. López-Sanz D, Serrano N, Maestú F. **The role of magnetoencephalography in the early stages of Alzheimer's disease.** *Front Neurosci* 2018;12:572 [CrossRef Medline](#)
  40. Nakamura A, Cuesta P, Fernández A, et al. **Electromagnetic signatures of the preclinical and prodromal stages of Alzheimer's disease.** *Brain* 2018;141:1470–85 [CrossRef Medline](#)
  41. Pusil S, López ME, Cuesta P, et al. **Hypersynchronization in mild cognitive impairment: the 'X' model.** *Brain* 2019;142:3936–50 [CrossRef Medline](#)
  42. Canuet L, Pusil S, López ME, et al. **Network disruption and cerebrospinal fluid amyloid-beta and phospho-tau levels in mild cognitive impairment.** *J Neurosci* 2015;35:10325–30 [CrossRef Medline](#)
  43. Ranasinghe KG, Cha J, Iaccarino L, et al. **Neurophysiological signatures in Alzheimer's disease are distinctly associated with TAU, amyloid-beta accumulation, and cognitive decline.** *Sci Transl Med* 2020;12:eaaz4069 [CrossRef Medline](#)
  44. Ranasinghe KG, Hinkley LB, Beagle AJ, et al. **Regional functional connectivity predicts distinct cognitive impairments in Alzheimer's disease spectrum.** *Neuroimage Clin* 2014;5:385–95 [CrossRef Medline](#)
  45. Sami S, Williams N, Hughes LE, et al. **Neurophysiological signatures of Alzheimer's disease and frontotemporal lobar degeneration: pathology versus phenotype.** *Brain* 2018;141:2500–10 [CrossRef Medline](#)
  46. Cuesta P, Barabash A, Aurtentetxe S, et al. **Source analysis of spontaneous magnetoencephalographic activity in healthy aging and mild cognitive impairment: influence of apolipoprotein E polymorphism.** *J Alzheimers Dis* 2015;43:259–73 [CrossRef Medline](#)
  47. Ranasinghe KG, Hinkley LB, Beagle AJ, et al. **Distinct spatiotemporal patterns of neuronal functional connectivity in primary progressive aphasia variants.** *Brain* 2017;140:2737–51 [CrossRef Medline](#)
  48. Engels MM, Yu M, Stam CJ, et al. **Directional information flow in patients with Alzheimer's disease. a source-space resting-state MEG study.** *Neuroimage Clin* 2017;15:673–81 [CrossRef Medline](#)
  49. Kocagoncu E, Quinn A, Firouzian A, et al; Deep and Frequent Phenotyping Study Team. **Tau pathology in early Alzheimer's disease is linked to selective disruptions in neurophysiological network dynamics.** *Neurobiol Aging* 2020;92:141–52 [CrossRef Medline](#)

## APPENDIX

### Sample MEG Report

**Patient:**

**Date of Birth:**

**MRN:**

**Acc#:**

### EXAM: MAGNETOENCEPHALOGRAPHY (MEG)

#### DATE OF EXAM:

#### History and reason for Study:

\*Copy from Tech report\*

MEG is performed as part of presurgical planning.

#### Technique:

The Magnetoencephalography (MEG) scan was performed at \*\*. There were [] minutes of spontaneous magnetoencephalography (MEG) with electroencephalograph (EEG) data acquired with a \*\* MEG system and individual/cap EEG electrodes. The patient was asked to be sleep-deprived before the appointment.

**Somatosensory:** Somatosensory functioning was assessed by using electrical stimulation of the right and left median nerves, each median nerve was tested twice for waveform reproduction. 200 stimuli were delivered at 800- to 1100-ms intervals. 200 trials of 300 ms were averaged with a prestimulus baseline of 100 ms and a 200-ms poststimulus time.

**Language:** Receptive language fields were obtained by binaural presentation of 180 audio words. The subject was tested twice, once in a passive listening mode, and again with the task to overtly repeat 5 target words, when presented. At least 120 trials were averaged for each test with a 500 seconds prestimulus baseline and 1000 ms poststimulus time.

**Motor:** The patient was instructed to press a button pad with index finger of their right and left hand. There were 2 trials run for waveform reproduction. The rate of tapping was deliberately varied but averaged about one tap every 2–3 seconds. Each epoch was 2 seconds capturing 100 button press stimuli.

**Auditory:** 1000 Hz tones were generated and delivered monaurally without masking at 60-dB hearing loss to ear inserts. The tone burst consisted of a 250-ms duration tone with a 15-ms rise/fall time. The tone burst was repeated 100 times, delivered once every 2 seconds. One hundred trials were averaged with a 200-ms prestimulus baseline and 1800 ms poststimulus time.

**Visual:** Pattern reversal stimuli were projected into the shielded room, reflected via one mirror onto an opaque white screen, and then reflected directly into the patient's eyes. The patient [did/did not] require vision correction glasses [rx L/rx R]. The checkerboard had a 50° radius and size of the projected checkerboard squares were approximately 5°, which were alternated with a refresh rate of 0.4 Hz. Six hundred epochs of hemifield stimulation were recorded for each hemifield with a 100-ms prestimulus baseline and 3000-ms poststimulus time following each pattern shift. The patient was asked to fixate on a single spot located just to the left or right of the pattern checkerboard image for hemifield studies.

All recorded data were analyzed utilizing \*\* software. MEG activity was superimposed on the patient's 3D-volumetric brain images obtained on the MR imaging performed on [].

Artifacts:

\*delete if none\*

Comparisons:

\* include MR imaging, fMRI, PET, SPECT \*

#### FINDINGS:

##### Interictal Findings:

The patient was awake, drowsy, and sleeping during the recording. Epileptiform discharges [were/were not] observed during spontaneous MEG recordings. [] selected epileptiform discharges in the MEG were mapped by using a single equivalent current dipole (ECD) model. A single dipole was selected to represent each epileptiform discharge. The dipole selection criteria included a goodness of fit of 80% or better, and a confidence volume less than 1 cm<sup>3</sup>. Dipole locations were calculated and projected onto the patient's MR imaging where they appear as yellow triangles for interictal spikes.

##### Interictal Epileptiform Discharge Source Modeling Showed Dipoles From:

Tight/Loose/Scattered cluster in the left/right \*\*\* with stable/variable perpendicular/oblique/parallel orientation.

##### Ictal Findings:

No seizures were captured.

##### Somatosensory Findings:

All runs produced robust responses with consistent mapping of corresponding peaks for each run.

For stimulation of the left thumb, the latency of N20m response was \*\*\* msec.

For stimulation of the left thumb, the latency of N30m response was \*\*\* msec.

For stimulation of the right thumb, the latency of N20m response was \*\*\* msec.

For stimulation of the right thumb, the latency of N30m response was \*\*\* msec.

##### Somatosensory Response Source Modeling:

Localized to expected locations.

##### Language Findings:

ECD models were calculated every millisecond from 250- to 750-ms poststimulus onset independently for each sensor's hemisphere corresponding to left and right evoked fields. All ECD estimates meeting the statistical thresholds and localizing to temporal cortical areas were entered into laterality quantification.

##### Language Response Source Modeling:

Receptive language with active word recall task localized to the left/right temporal lobe with a laterality index of +/- X.XX, concentrated in the Wernicke area.

Receptive language with passive listening localized.



**Motor Findings:**

Movement of the left second digit generated a good response. The motor response was seen with a latency of \*\*\* ms following the activation of the button.

Movement of the right second digit generated a good response. The motor response was seen with a latency of \*\*\* ms following the activation of the button.

**Motor Response Source Modeling:**

Localized to expected locations.

**Auditory Findings:**

Trials for each ear were performed. The N100m response was a sustained response. The best fields picked to represent the contralateral responses had a latency of \*\*\* ms for the left ear stimulation and \*\*\* ms for the right ear stimulation. The best fields picked to represent the ipsilateral responses had latency of \*\*\* ms for the left ear stimulation and \*\*\* ms for the right ear stimulation.

**Auditory Response Source Modeling:**

Localized to expected locations in the primary auditory cortex.

**Visual Findings:**

All runs produced robust responses with consistent mapping of corresponding peaks for each run.

For right visual hemifield mapping, the N75m, P100m, and N145m responses were easily identified and had typical latencies, waveform morphology, topographic field maps, and dipole moments.

For left visual hemifield mapping, the N75m, P100m, and N145m had typical latencies, waveform morphology, topographic field maps, and dipole moments.

**Visual Response Source Modeling:**

Localized appropriately to the primary visual cortex (V1).

**IMPRESSION:**

-attending, MD.