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Towards Best Practices in Clinical Magnetoencephalography: Patient Preparation and Data Acquisition

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Abstract

A magnetoencephalography (MEG) recording for clinical purposes requires a different level of attention and detail than that for research. As contrasted with a research subject, the MEG technologist must work with a patient that may not fully cooperate with instructions. The patient is on a clinical schedule, with generally no opportunity to return due an erroneous or poor acquisition. The data will generally be processed by separate MEG analysts, who require a consistent and high-quality recording in order to complete their analysis and clinical report.

To assure a quality recording, (1) MEG technologists must immediately recheck their scalp measurement data during the patient preparation, in order to catch disturbances and ensure registration accuracy of the patient fiducials, electrodes, and head position indicator (HPI) coils. During the recording, (2) the technologist must ensure that the patient remains quiet and as far in as possible in the helmet. After the recording, (3) the technologist must consistently prepare the data for subsequent clinical analysis.

This paper aims to comprehensively address these matters for practitioners of clinical MEG in a helpful and practical way. Based on the authors' experiences in recording over three thousand patients between them, presented here are a collection of techniques for implementation into daily routines that ensure good operation and high data quality. The techniques address a gap in the clinical literature addressing the multitude of potential sources of error during patient preparation and data acquisition, and how to prevent, recognize, or correct those.

Keywords

clinical MEG; simultaneous recording of MEG/EEG; best clinical practices; quality assurance and control; MEG artifacts; patient preparation; degaussing

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Introduction

No longer a “new technology,” magnetoencephalography (MEG) has transformed functional brain imaging in presurgical evaluation of patients who are candidates for epilepsy surgery. Numerous official documents, including those from professional medical societies, are testimony that MEG has transitioned into current clinical practice: AAN model coverage policy,¹ ACMEGS position statements,^{2,3} and evidence based clinical indications.⁴ The set of published clinical MEG practice guidelines^{5,6,7,8} and research guidelines^{9, 10} were designed to point in the direction of excellent standards of practice, not just minimal requirements. In addition, a pathway now exists for the formal certification of MEG technologists.¹¹

MEG measures minute magnetic fields generated by neuronal electrical activity in the form of intracellular currents, induced by inhibitory and excitatory post-synaptic potentials, with superb spatiotemporal resolution; similarly, EEG measures potential distributions over the scalp generated by the same electrical activity. Other functional brain imaging modalities have time resolution ranging from several seconds (fMRI) to tens of minutes (PET). MEG does not require injection of radioactive tracers (PET, SPECT) or contrast media (MRI), nor exposure to strong magnetic fields or loud noises (MRI, fMRI). Therefore, MEG is a minimal-risk procedure and can be repeated as often as needed in patients of all ages.

Nevertheless, recording MEG in infants and children, or patients that cannot be as cooperative as desirable, poses unique challenges compared to cooperative adult patients, mainly due to head movement within the sensor helmet. Additional issues are posed by ferromagnetic impurities like ferrous dust in the hair, certain inks used in tattoos or make-up, dental work, and a number of implanted medical devices. These materials and devices can result in significant artifacts that may be difficult or even impossible to separate from magnetic brain signals.

A collection of techniques is presented for implementation into daily routines that ensure good operation and high data quality. The quality of the obtained data determines the quality of the reported results, specifically the accuracy of localizing the sources of normal and abnormal cortical brain activity. Nevertheless, there is a gap in the clinical literature addressing the multitude of potential sources of error during patient preparation and data acquisition, and how to prevent, recognize, or correct those. This paper aims to comprehensively address these matters for practitioners of clinical MEG in a helpful and practical way.

Patient Selection and Introduction

Contrary to some beliefs, MEG can actually be recorded on most types of patients, including babies and infants.^{12,13} The primary risk is the quality of the data or to the instrument itself, not the patient. Practice has shown only two contra-indicated conditions for which the patient should be declined. The first are cochlear implants, since these have strong permanent magnets in the charge coupler. The second is a sophisticated shunt that has been developed in recent years, the Medtronic Strata NSC Adjustable Pressure Valve, comprising

a rotor with a permanent magnet that is tiny enough to still be MRI compatible up to 3T. In both instances, the presence of a true magnet creates too strong of a contaminating field to allow practical recordings.

Otherwise, MEG has been successfully recorded on patients with GPS ankle bracelets, drug pumps, active VNS, pacemakers, anesthesia related sensor cables, hidden cell phones, etc. The electronic devices, such as VNS and drug pumps, can often be put in a “stand-by” or passive state. Cell phones should be prohibited, but in exceptional cases, they can be kept in “airplane mode” and at a distance from the helmet, but otherwise used to provide comforting music to the pediatric patient, for instance. Table 1 provides a more detailed overview of possible magnetic artifact sources and appropriate remedies. **NEVERTHELESS, IN SITUATIONS OF UNCERTAINTY OR DOUBT, ALWAYS CONTACT THE MEDICAL DIRECTOR OF THE MEG FACILITY.**

Patients often confuse the MEG exam with an MRI or PET exam that they may have already encountered, and they expect a stressful environment, confined in a narrow tube with a lot of noise and admonishments to stay absolutely still. They instead should be welcomed with statements that this will be a peaceful and restful measurement, in an unconfined and open helmet, with no radiation, no strong magnetic fields, nor sounds. They will be provided with a pillow and warm blankets, the lights will be dimmed, and asked that they literally take a nap for about an hour.

The patient is also given a short overview of why they are getting an MEG in addition to their EEG. The MEG helmet has hundreds of sensors in it, so the first advantage is a pure numbers game: The MEG helmet has ten times as many sensors as the standard 10–20 EEG array to detect abnormal activity. The second advantage is that given abnormal activity is detected, then the physics of MEG make it easier to estimate where this activity arose in the brain. The bottom line is that there is better detection and better localization of abnormal brain activity. This information will be presented directly to their epileptologist, who will provide the patient with the interpretation in the final MEG report.

MEG Preparation

The magnetically shielded room (MSR) and the MEG instrument therein are prepared prior to the patient’s arrival, and the MEG should be “tuned” using the vendor’s recommended procedures, if any. For quality assurance and later verification, a few minutes of empty-room data should always be recorded, with the MSR setup in the arrangement to be used with the patient, in the supine or upright position.

While many magnetically shielded rooms are initially installed with a small fixed camera, patients require more detailed monitoring and recording, as evidenced by the rich history of video EEG recordings. Surprisingly, modern MEG systems do not usually include such video capabilities, so each clinical site must custom install their own system. A high-quality “tilt-pan-zoom” (TPZ) camera allows flexibility in observing the patient’s entire body, or to zoom onto just their face, to observe behavioral changes related to seizure onset. A high-quality wall-mounted microphone allows better interactions with both the patient and a

possible caretaker in the MSR (Figure 2A). Although these cameras and microphones technically introduce some noise into the magnetic recording, many of these can operate on DC current, reducing their adverse effects on data quality.

If a child cannot stay still, the parent can be allowed to sit with the child. The parent should be dressed as if they were an MEG patient, ideally in a gown, but definitely with no electronics, glasses, jewelry, etc. Their main instructions are not to rock, nor continuously pat the child, but rather to keep working with the child to put them back as far as possible into the MEG helmet, and then sit quietly. The TPZ camera allows us the flexibility to monitor the parent as well.

EEG Preparation

Simultaneously recording EEG is recommended to complement the MEG time series analyses.¹⁴ The addition of the EEG data to the MEG recording yields several advantages. For electrophysiology-trained neurologists, the additional EEG data provide a familiar “bridge” to the more novel and dense MEG recordings. The EEG data provide a truly complementary measure to MEG, such that sources “silent” in one modality can be detected in the other in the analyses. Denser arrays of 40 or more EEG sensors allow for formal source localization analyses, either using the EEG data separately or in combined EEG/MEG analyses.¹⁵ Thus, per clinical practice guidelines, all MEG patients should routinely have simultaneous EEG recorded throughout their session.

Similarly, the electrocardiogram (ECG) should also be recorded simultaneously, to allow later identification of cardiac effects in the MEG data. Optionally some sites also prefer to record EOG to detect eye-blinks, so additional electrodes may also be applied.

Patient Preparation

With the MSR prepared, empty-room data recorded, and the patient informed of the procedure, the patient is then prepared for the MEG exam. A second technologist or assistant should always be present to assist the primary MEG technologist, particularly in the event of a seizure, but to also help in maintaining data quality. If the patient is known to be particularly vulnerable, then the nearby presence of a floor nurse is warranted.

The patient should ideally arrive sleep deprived, so that they quickly fall asleep during the exam; a sleeping patient moves less in the MEG sensor array, and the stages of light sleep may introduce additional abnormal interictal activity in the brain. Preferably the patient should be dressed in an MRI-compatible gown, one that has no metal snaps; however, outpatients often want to remain in their personal street clothes or keep their upper undergarments on. Unfortunately, many adjustment straps for bras have metal slides that magnetically interfere, and similarly t-shirts have inks that are also lightly magnetic, so the simplest approach is to have all patients disrobe into a gown, leaving underpants and socks on, but no street clothes nor upper garments.

As discussed above, the EEG or MEG technologist should apply EEG electrodes in the extended international 10–20 system, apply any optional EOG electrodes, and apply MRI-

compatible ECG electrodes.^{16, 17} MEG systems also employ “head positioning” coils that either intermittently or continuously monitor the patient’s head position in the MEG helmet. While three coils are the absolute minimum, practice indicates that five coils placed about the upper head give good coverage and redundancy in the event that a coil is bad or in a bad location relative to the array. The head positioning software can reject the bad coil and continue to operate with the remaining set of coils, without the need to stop the recording, extract the patient, and attempt adjustments of the errant coil.

All patients should undergo “degaussing” to remove excess magnetic contaminants, as shown in the Figure 3. Degaussing is achieved by applying an alternating magnetic field about the patient, typically at the main powerline frequency (e.g. 60 Hz), then slowly drawing away the degausser, about one cm/s, so that the alternating field around the patient slowly decays. PRIOR TO DEGAUSSING A PATIENT, A MEDICAL DIRECTOR MUST BE CONSULTED TO ENSURE THERE ARE NO CONTRAINDICATIONS. Modern medical practice has made most patients “MRI-compatible,” i.e. they are safe to enter an MRI facility for anatomical imaging, so that there is inherently no risk in degaussing them. Please note additional considerations in Table 1.

A degaussing coil for the old CRT monitors has a good diameter for encircling the patient’s head. The technologist should be instructed to not click it on and off; rather, position as shown (Fig. 3A), then click on, keep it on, and smoothly move away from the patient. This “shakes” the magnetic field around the patient and removes minor magnetic contaminations. This process is repeated in coronal and sagittal orientations to the head, to the EEG headbox, to any stuffed toys that a child may bring, and to the head of any caretaker that will sit with a patient.

Problematic magnetic fields are generally induced in dental work during an MRI. Such stubborn magnetized spots and other non-ferrous metal can be spot treated with a strong hand-held “tape-degausser” (Fig. 3B). AGAIN, HAVE THE MEDICAL DIRECTOR ENSURE THAT THERE ARE NO CONTRAINDICATIONS TO USING THIS MUCH STRONGER DEGAUSSER. NEVER APPLY DIRECTLY TO MEDICAL ELECTRONICS, SUCH AS PACEMAKERS, VNS, OR DBS GENERATORS. As in the CRT degausser, the tape degausser is placed against the jaw, clicked on and held on, while moving slowly away from the jaw.

Patient Fiducials and Landmarks

With the patient in MEG-compatible clothing, and the EEG electrodes and head positioning coils in place, then the three-dimensional locations of these electrodes, coils, scalp fiducials, and other head shape points need to be accurately measured. For MEG analysis, these scalp locations will be used to register the patient’s MRI, so a high degree of accuracy is required if the results are to be adequately interpreted. Classically, three points are acquired – the nasion and two pre-auricular points – in order to establish a subject coordinate system (SCS), also known as the head or patient coordinate system. Acquiring only three points, however, makes the accuracy of the SCS extremely sensitive to the exact position on the ear and on the bridge of the nose, in order to later register an MRI to the subject. Modern

practice is to acquire hundreds of points about the patient's scalp, in order to later "fit the cap" of these points to the patient's MRI.

The procedure is described in detail here on how to ensure high-quality digitization of the patient. Many MEG sites use a Polhemus FASTRAK localizer (Figure 4), although more recently some sites are starting to use IR-based and LED-based instruments. For patients, however, a "stylus pen" still has the unique ability over these other methods in finding scalp points, so that the technologist can part thick hair and locate the electrode or head positioning coil. Since the FASTRAK is so widely used, its specific use is detailed here, with implications for similar systems.

By pure coincidence with MEG, the FASTRAK generates its own magnetic fields for use in localization. So the same magnetic quality controls for its smooth operation need to be followed, and hence why the patient should already be magnetically prepared for the MEG before beginning the Fastrak operation. The patient sits in a wooden chair set some distance from any metallic objects, such as file cabinets, office chairs, and metal structural beams or metal door frames. The technologist should not be wearing a watch or necklace, both which can interfere with the accuracy of the system. When using the stylus, the technologist should stay to the sides of the chair and away from the FASTRAK transmitter affixed to the back of the chair, so that their body has minimal impact on the measurement field being generated by the transmitter.

In early MEG installations of the ISOTRAK system, the patient was required to remain virtually motionless in the chair, while the stylus was quickly used to collect landmarks. The more practical and accurate FASTRAK system today employs a reference receiver affixed to the patient, so that the stylus effectively makes referential measurements with respect to the receiver. Many sites have the patient wear a pair of false glasses with the reference cube attached, as shown in Figure 5A. The patient should hold the reference cable and be instructed to not tug or move the glasses, and they should try to stay relatively still.

Children, however, often bat away these glasses, so an alternative is to affix temporarily the reference receiver directly to their scalp using a custom holder, as shown in Figure 5B and C. The child is relatively unaware of the extra hardware, and immediately after the measurements are made, the holder is removed. Another workable and practical solution is a double "wig cap", in which the patient wears the first nylon wig cap on which the receiver cube is taped, then the second wig cap over it locks the cube into place. These digitization systems are sensitive to even minor movements of the reference, and the technologist must ensure that the reference cube remains absolutely motionless on the patient.

In practice, the technologist acquires the first three fiducial points, then immediately repeats the measurements and checks the discrepancy between the two measurements, which should generally be less than 2.0 mm, in good practice (and much less than the generous 5.0 mm that is often allowed). If discrepant, the technologist should immediately inspect the patient, environment, and themselves for contaminants, and adjust accordingly. Once there is good agreement on the fiducials and their repeat measurement, then the software establishes the subject coordinate system (SCS), and the other measurements are made. The HPI coils are

localized using the stylus, and again these measurements should be immediately checked with a repeat measurement, again expecting less than 2.0 mm repeatability. The patient can be advised that these first few measurements are critical for good alignment, and hence the need to repeat the adjustments and measurements until good repeatability is achieved.

With these first few important points reliably and repeatedly measured, the other measurements of the EEG electrodes and scalp points can be relatively quickly measured. At least 100 scalp points (preferably many more) should be uniformly sampled about the upper hemisphere, so as to leave no “holes” in the virtual “cap” that is formed (Figure 6). At the end of the measurements, for quality control, the final three points measured are the patient fiducials again, with only an approximate demand for repeatability with the original fiducial points. If highly discrepant, then the technologist must identify what changed in the environment and possibly repeat the entire set of measurements, but the crucial data were in the reliability of the first measurements, so it can be a judgement call whether or not to repeat the measurements. In post analyses, the final three points are easily identifiable by the analyst for confirmation on the reliability of the “cap” of points collected.

Patient Positioning

With the landmarks collected, the patient is brought into the MSR. Since the massive MSR door can be somewhat intimidating to some patients, the technologist can emphasize to the patient that the door is to make it as magnetically quiet as possible, and that there is no radiation nor strong magnetic fields. The patient is under constant monitoring on video and microphone, and in an emergency, the technologist can immediately re-enter the MSR.

The supine position makes it easier for the patient to completely relax and not move. Conversely, patients who are sitting upright in a MEG chair have a tendency, over an hour-long recording, to “slump” out of the helmet. For children (Figure 2B), a parent may accompany the child and help with their placement. For accuracy, the patient’s head needs to be as far in the helmet as possible, which some patients are initially reluctant to do, typically from earlier claustrophobic reactions to the MRI or PET machines. For comfort, MRI compatible pads can be put on the back of the helmet (unless the patient’s head is too big), then the technologist eases the patient into the helmet, where patients are generally relieved to see that their eyes are not occluded. The technologist can either place a rolled towel under the patient’s neck, or place a blood pressure cuff (Figure 7) under the neck and gently inflate it. The goal is to have the patient’s head roll back comfortably into the MEG array, so that their temporal lobes are also well covered by the helmet. Typically, the nose of the patient will rest comfortably against the edge of the helmet when well-positioned.

If audio transducers are used, they should be placed as far away from the helmet as the acoustic tubing will allow, and such that the transducers are not moving, i.e., not on the patient’s chest. EEG and head positioning cabling should be cleanly connected to the instrument. A pillow under the patient’s knees helps with the discomfort of being supine, and a blanket over them helps for comfort. If the MEG bed does not have side supports, the patient may need to be lightly buckled in, again emphasizing that it is for their safety to prevent rolling out of bed, and not to restrain them.

Monitoring the Recording

With the patient positioned, and optionally the child's parent comfortable in a wooden chair adjacent the child, the lights are dimmed and the MSR door closed to begin recording. After any initial recalibrations to the MEG sensors to ensure they are running correctly, the technologist activates the head position measurement of the MEG system and immediately confirms if the patient is well-positioned. While the experienced MEG technologist may be able to look at raw three-dimensional fitting data to make this determination, the better method is to immediately render a phantom picture of the patient in the MEG helmet. The research software packages "Brainstorm" can make this image in near-real time from any of the MEG manufacturers, showing quite precisely how the patient is positioned (Figure 8).^{18, 19} If space still exists between the top of the head and the helmet, the technologist should stop the recording and re-enter the room to adjust the patient further into the helmet. In some cases, a highly compliant patient can be simply instructed over the intercom to shift further into the array.

Since head position in the array is another vital link in high-quality recordings, the technologist should repeat the head position measurement until it can be confirmed that the patient is as far into the helmet as possible. In the case of children, their short neck with respect to relatively broad shoulders may limit their deep placement in the helmet, so the technologists should ensure their shoulders are against the helmet. Post-processing cannot repair data acquired from patients too far out of the helmet, so it is imperative for technologists to make best efforts to get the patient deeply into the helmet.

In the initial recording period, the technologist should watch closely for contaminants either from the external environment or from the patient and make any possible adjustments. Slow three-second wave-like patterns in the MEG data often indicate a contaminant in the patient's clothing, which can be confirmed by asking the patient to momentarily hold their breath. Other contaminants can be confirmed by asking the patient to make small movements of their head or jaw up or down. If the interference is significant and identifiable, the patient should be removed from the MSR, and the spot degausser applied to the jaw or hair, or their clothing changed into a different MRI-compatible gown. Again, it is imperative that the technologists not tolerate substantial interference in the beginning of the measurement, but rather they should track it down and remove its source.

During the recording, the technologist should monitor the video and make periodic head position measurements to ensure that the patient remains deep in the array. The position can be determined indirectly, or some instruments may allow visualization of the head placement in near real time. A good TPZ camera allows the technologist to monitor the relative position and any excessive movement. Annotation software should be used to make notes in the recording of any unusual environmental events, or for any announcements by the patient that they are experiencing aura, or if the technologist sees clinical or electrographic signs of seizures. These annotations help the clinical MEG analyst to quickly find major events.

In the event of brief seizures, a quick intercom discussion by the technologist with the patient often suffices to reassure them and to continue the recording uninterrupted. In more

substantial seizures, paradoxically the technologist should keep the MEG machine recording while entering the MSR and attending to the patient. Although the MEG data will be badly contaminated by the open MSR door and by the patient seizure movements, nonetheless the EEG can continue to provide valuable data on the progression of the seizure. The other MEG technologist alerts the floor nurse, so that the team is aware and prepared for a potential status epilepticus and the need to administer rescue medication. Hence two personnel should always be present, one to attend to the patient directly, the other to assist in coordinating any seizure team.

As a general recommendation, the MEG records for an hour with the patient resting comfortably, preferably falling asleep if possible. Although interictal activity may not be evident during the recording, post-processing may reveal more subtle sources. If many interictal events are already evident during the recording, and/or the patient becomes uncomfortable, a shorter time may be allowed. If the patient is known to have very frequent or daily seizures, the recording might also be extended to increase the chance of capturing such seizure activity.^{20, 21} If the seizures are triggered by some stimulus (reading epilepsy etc.), a seizure could also be induced by licensed medical personnel, such that the MEG captures the seizure onset.

Preparation of the Data for Analysis

When saving the data, a highly consistent and relatively automated naming scheme should be used. These file conventions will make it much easier to later “crawl” through the data libraries looking for similar files. For example, spontaneous recordings can begin with “spont,” and somatosensory evoked fields can begin with “sef,” which makes it easier to instantly identify the classes of recordings. Similarly, suffixes such as “raw” vs. “avg” make it easy to identify the original recording or a later averaged file.

With these prefixes and suffixes always in use, it becomes relatively simple to arrange for computer-generated “scripting” of the data processing routines, which the MEG technologist can launch immediately at the end of the recording. Such scripting enforces that the same filters are always run in the same sequence and with the same parameters, with the result that the MEG analyst can expect a routine level of high data quality. When unusual data results are encountered by the MEG analyst, their possible sources can be more readily traced back to the patient or equipment, without the confounds of variations in the processing scheme. After the MEG technologist’s initial processing of the data, the MEG analyst can always re-run it using additional custom parameters tailored to the analyst’s expert judgement.

Summary

The quality of the recorded data determines the quality of the reported results, specifically the accuracy of localizing the sources of normal and abnormal cortical brain activity. Since localization accuracy degrades rapidly for sources outside the sensor helmet, and registration errors are nearly impossible to fix in post-processing, the MEG technologist must ensure that scalp points are accurately measured, and that the patient position is properly maintained in

the helmet. Consistency in preparation and processing yields consistency in data generated, so that apparent anomalies in the data are more identifiable as unique to the patient and not to variations in procedure.

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Key Points of Quality Paper

- A meticulous and standardized patient preparation is critical for overall MEG-EEG data integrity, including cross-checking procedures to measure accurately the patient landmarks and patient position in the MEG array.
- Degaussing removes minor magnetic contaminants, when done under supervision of a MEG Medical Director.
- Monitoring the patient position, MEG data, and EEG data continuously throughout the recording is important to overall data quality and patient safety.
- A MEG array designed for adults can be used for a wide range of patients, from newborns to elderly, with caregivers possible in attendance.
- While artifacts should be prevented as much as possible, MEG can handle a wide range of artifacts with suitable post-processing.

Figure 1:

If medical equipment is placed a sufficient distance from the helmet, then its artifacts may be reduced to an acceptable level, such that it could be removed in signal-processing. Shown here is a PICU patient during an MEG examination with an MRI-compatible ParaPAC ventilator (inset picture) positioned in the corner of the magnetically shielded room (lower right of picture). It is positioned as far as possible away from the patient and the sensor helmet. The separate side table minimizes vibration artifacts. For situations where anesthesia of a patient is needed, then the suction, oxygen, I.V. lines, pulse oximetry fiber optics cable, ECG leads etc. can generally be brought through port tubes in the walls of the room.

Figure 2:

A) TPZ camera installed inside the MSR (Sony, SNC-RZ25P). Just right of it is the all-directional microphone (Louroe Electronics, ASK-4[®] KIT #101). This equipment is frequently seen in epilepsy monitoring units. B) If a parent or caretaker accompanies a child during the MEG measurement, a “non-magnetic” wooden chair should be provided.

Figure 3:

A) A degausser used for demagnetizing CRT monitors is particularly effective for removing minor contaminants about the head, such as hair care products, dust, make-up, and other incidentals. B) A more powerful hand-held degausser can be used for spot treatment of non-magnetic dental work; however, it should not be applied directly to electronic devices, such as RNS, VNS, DBS, or pacemakers, nor should it be applied to any magnetic jewelry or other ferrous items. WHEN IN DOUBT, ALWAYS CONSULT A MEDICAL DIRECTOR.

Figure 4: Setup for digitization of anatomical landmarks, HPI coils, EEG electrodes, and headshape points. Of note, the MEG technologist is positioned sideways from the patient to minimize interference with Polhemus FASTRAK system, which is mounted to the back of the chair. A second technologist sitting at a computer display monitors the quality and accuracy of the digitization.

Figure 5:

A) Attached to the side of the eyeglass frames is a second receiver for the FASTRAK system, which provides a fixed frame of reference, while the primary stylus receiver is used to locate fiducials, electrodes, and head position coils. The patient wears the pair of false glasses for the few minutes it takes to gather the data, and it is critical that these glasses absolutely do not shift or move on the head during this time, if accuracy is to be maintained. For children who cannot tolerate wearing the glasses, a separate holder (B) can be mounted temporarily into their EEG array (C), then removed immediately afterwards.

Figure 6:

Coronal, sagittal, and axial planes of a brain MRI. Accurate digitization of the FASTRAK data (shown here as triangles) allows the digitized headshape points to spatially align the MEG and MRI coordinate systems. Such accuracy requires the acquisition of hundreds of headshape points, in addition to the three anatomical landmarks, HPI coils, and EEG sensors.

Figure 7:

A blood pressure cuff can be placed under the patient's neck and gently inflated, such that the patient's head comfortably rolls back into the MEG array. Alternatively, a rolled towel under the neck can also be used. The goal is to ensure that the patient's cheeks are well into the array, such that the temporal lobes are well covered by the sensors.

Figure 8:

A) During the recording, a scaled 3D phantom head model can be used to ensure that the patient is well positioned within the helmet. Such visualization may require the installation of additional research software,^{18, 19} if the vendor software is unable to provide the rendering. B) For subsequent MEG data analysis, the patient's actual 3D head model can be used for visualization of the head position during the recording, with respect to the sensor locations.

Table 1:

Device/Implant	Comments	Acceptable	Contra-indicated
Head = Generally, objects in the hair, scalp, or head are problematic in the recording or in the signal processing of the MEG data. Strong magnetic artifacts can prevent some MEG SQUIDS from recording. Other artifacts interfere in the analysis and interpretation of brain sources. Every attempt should be made to remove jewelry and hair care products.			
<i>Neurostimulators implanted in head (RNS)</i>	Unit should be programmed off for measurement. MEG sensors directly above RNS may not record, which may limit utility of recording. Other MEG sensors away from RNS may have artifact removed in signal processing, yielding useful results. If unit is on, then the artifact of both the generator and stimulation currents severely limits utility of recording. DO NOT DEGAUSS!	X	If unit cannot be turned off
<i>Cochlear implant</i>	With an implanted permanent magnet in its coupler, the magnetic field is too strong, and the MEG cannot record. DO NOT DEGAUSS!		X
<i>Surgical aneurysm clips</i>	If an MRI is not contraindicated, normal ring degaussing may be used. Many clips do not generate a measurable artifact.	X	
<i>Implanted shunt</i>	If MRI is not contraindicated, normal ring degaussing may be used. Many passive shunts do not generate a measurable artifact. For other shunts, the MEG sensors directly above shunt may not record which may limit utility of recording. Other MEG sensors away from shunt may have artifact removed in signal processing, yielding useful results. An exception is the <i>Medtronic Strata NSC Adjustable Pressure Valve</i> which uses a magnetic coupler to program it. This shunt has a too strong a magnetic field for MEG.	X	Medtronic Strata
<i>Metal fragments in body or eyes</i>	If MRI is not contraindicated, normal ring degaussing may be used. Any minor artifacts may be removable in signal processing	X	
<i>Piercing jewelry</i>	Remove if at all possible. Ring degaussing may be attempted cautiously, if piercing jewelry is non-magnetic.	X	Magnetic Jewelry
<i>Hair styling products</i>	Generally advised against all hair products, patient should arrive with clean hair. Otherwise attempt degaussing	X	
Mouth = Generally, dental work and related are not contraindicated in MEG recordings, since the mouth is outside of the helmet and therefore outside the modeling space. Attempts should be made to remove temporary dental appliances to improve the MEG recording. In signal analyses, the mouth is far enough away to allow modeling to remove the artifacts.			
<i>Braces or permanent retainers, metal rods, plates, screws in mouth</i>	Modern dental implants are usually MRI compatible. If an MRI is not contraindicated, ring and spot degaussing may be attempted. Any MEG artifact may be removable in signal processing.	X	
<i>Retainers, dentures, bridges (non-permanent)</i>	Remove if at all possible, otherwise see above.	X	
Body = Magnetic objects moving with the respiratory cycle (e.g. those on the chest) may produce very low frequency interferences. Since these objects are far enough away from the helmet, resulting artifacts can be readily handled in either real-time software or signal processing.			
<i>Cardiac pacemaker</i>	Relative low duty signal, sufficient distance from helmet, artifact can be removed in signal processing. DO NOT DEGAUSS.	X	
<i>Vagus nerve stimulator</i>	Unit should be programmed off before the MEG measurement. The lead wires in the neck may be degaussed with ring and spot degausser, unless an MRI is contraindicated. Any artifact from the VNS is generally at the very low frequency respiratory rate and can be removed in signal processing. DO NOT DEGAUSS GENERATOR.	X	
<i>Neurostimulators with generator implanted in body (DBS)</i>	If possible, unit should programmed off for MEG measurement. The lead wires in neck and scalp may be degaussed, unless an MRI is contraindicated. As with the VNS, the residual artifact from leads may be removable in	Bipolar stimulation mode	Monopolar stimulation mode

Device/Implant	Comments	Acceptable	Contra-indicated
	signal processing. If unit cannot be programmed off but is in bipolar stimulation mode, then the MEG artifact is more severe, but recording is still possible, if only of limited utility. If active unit is in monopolar stimulation mode (current returns to generator in chest), the magnetic fields are too strong, severely limiting utility of the measurement, if it is even possible. DO NOT DEGAUSS GENERATOR.		
<i>Implanted pumps</i>	The device should be temporarily programmed to the lowest duty cycle possible for the measurement. Artifact may be removed in signal processing, but otherwise the recording may be of limited utility. DO NOT DEGAUSS APPARATUS.	X	
<i>Prosthetic heart valve</i>	Unless an MRI is contraindicated, most modern clips are MRI compatible and therefore may not generate much of an MEG artifact. Because the heart is a sufficient distance from helmet, any potential artifact may be removed in signal processing. Because of its location, degaussing the heart is probably ineffective and is not recommended.	X	
<i>Previous surgery or injury</i>	If MRI is not contraindicated (because metal may have been left in body), degaussing may be attempted but nonetheless futile, if item is deep in the body. Any artifact may be removable in signal processing.	X	
<i>Metal rods, plates, or screws in body</i>	If MRI is not contraindicated, modern surgical implants are usually MRI compatible, degaussing may be attempted, may be removable in signal processing.	X	
<i>Tattoos containing iron</i>	Such tattoos are only an issue for RF burns in high-field MRI, which is not an issue for MEG. Tattoo may be routinely degaussed, and any artifact may be removed in signal processing	X	
<i>GPS ankle bracelet</i>	If court-ordered and not removable, nonetheless the duty cycle is quite low (once every several seconds) and far away from helmet such that analyses can generally work around the artifact, or remove it in signal processing. DO NOT DEGAUSS.	X	
<i>Cellular phones, personal electronics</i>	Generally prohibit all personal electronics, including smart watches. Inconsolable patients who are soothed by their personal music may have small modern personal electronic player (e.g. phone, iPod) put in strict "airplane" mode and placed on nearby table. No laptops, nor larger tablets with magnetic clasps.	X	Laptops, Magnetic Clasps on Tablets
<i>Stuffed animals</i>	Prohibited if containing electronics, otherwise toy may be degaussed and placed next to patient. Discourage holding or moving toy.	X	
Medical Equipment= As possible, keep such equipment outside of shielded room and feed cables through ports.			
<i>Ventilator</i>	Keep devices by foot of bed, as far as practical from helmet. Suction and oxygen lines can generally be fed through ports in the walls of the room. See Figure 1.	X	
<i>Neurostimulator</i>	Feed stimulator cables through port, arrange for technician to sit with patient and communicate with second technician outside room operating the stimulator.	X	