MagLink EEG Recording System™

User Manual

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For Technical Support.....

If you have any questions or problems, please contact Technical Support through any of the following routes.

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Overview

The MagLink EEG recording system is a carbon-fiber based, passive cabling and cap system that is designed to record spontaneous and evoked brain activity in MRI environments. The MagLink system is designed to have a minimal impact on the quality of the MR data, while providing the ability to record EEG continuously through structural and functional imaging sequences in magnet strengths up to and including 4 Tesla. Technologies are incorporated into the design, based on independently conducted tests, that maintain magnetically-induced loop currents at levels below those allowed by IEC601 regulations. Materials and construction of the MagLink cabling and cap are designed to maximize subject/patient comfort during extended MRI/EEG recording sessions.

The MagLink system was engineered to be a simple solution to a complex problem. This is achieved by using a carbon-fiber system that is essentially insensitive to high-strength static magnetic fields. Therefore, for recordings obtained within the static field (in the bore of the magnet), EEG activity appears very similar to that recorded outside the field, with one difference: all leads will contain the ballistocardiogram artifact (described in detail later in this manual). This artifact is generated by the micro-movements of the body generated by cardiac activity. These movements cause the body and the electrodes attached to the scalp to cut the (static) lines of force in the magnetic field. This is manifested as a prolonged artifact in all electrodes associated with every heartbeat.

Unlike normal electrode and electrode cables, all connections within the MagLink system are pressure crimped - solder is not used for any connection from the cap through to the filter interface connection cable which attaches to the RF filters in the patch panel. Although the MagLink system is designed to be as robust as possible, carbon-fiber cables tend to be more fragile than normal electrical wire. Therefore, extra care should be taken when handling and using the MagLink system. In general-use MR facilities not dedicated to combined MRI/EEG research, it is strongly recommended that the MagLink system be removed and stored in a safe location when not in use. Avoid stepping on the cables. Do not pull on the cables to disconnect the MagLink from an interface cable - apply force to the connector itself, not to the cables.

MagLink Electrode Cap

Currently, the MagLink cap is available with Silver-Silver Chloride disk electrodes or sintered electrodes. The sintered electrodes contain the same materials (i.e., silver and chloride) as the Silver-Silver Chloride disks but are constructed as a compressed disk pellet containing a mixed Silver-Silver Chloride compound. The reported disadvantage of the sintered electrode is marginally higher impedances. We have found the differences in impedances between conventional and sintered electrodes to be negligible and the quality of the recorded EEG to be very comparable. The major advantage of the sintered electrode is the absence of an easily damageable electrode surface. While we recommend that due care always be taken in cleaning (see description of cleaning electrodes below) and handling all electrodes, sintered electrodes cannot lose a chlorided surface since the chloride is

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embedded in the structure of the electrode itself. Even with careful handling, silver-silver chloride electrodes will eventually require re-chloriding of the surface. This process is not necessary with the compressed structure of the sintered electrode.

Unlike normal electrodes and electrode cap assemblies, a 6.8 kOhm resistor is placed in series with each electrode (both silver-silver chloride and sintered electrodes) in the MagLink cap. This resistor serves to minimize any loop currents induced into the carbon-fiber electrode leads by the large magnetic field of the MR magnet, thus ensuring patient/subject safety. The use of nonferrous carbon fiber electrode leads is also an important aspect of the safety of the MagLink cap and cabling system. All cables on the electrode cap are also braided to minimize the creation of current loops, which further ensures the safety of the subject.

Like all other electrode caps, a successful recording of EEG depends on a good conductive path between the recording electrode and the scalp of the subject. There are several steps that can be taken to ensure a good contact between the electrode and the scalp of the subject. These steps are listed below.

Subject Scalp Preparation and Electrode Cap Application

(1) The night/day before scheduled testing, contact the subject and make sure that they wash their hair the morning of testing. They should wash their hair with a normal shampoo that does not contain any conditioner. Conditioner coats the scalp and makes it much more difficult to obtain low impedance connections. After shampooing, the subject should not use any conditioners or styling gels that would also coat the scalp and hair.

(2) Once arriving at the laboratory for testing, have the subject vigorously brush their hair and scalp with an old-fashioned bristle hairbrush for 3-5 minutes. This will help to exfoliate the scalp surface and will dramatically reduce (any in some cases eliminate) the need to abrade the scalp surface after loading the electrodes with gel. It is recommended that the lab be equipped with hairbrushes that can be used once and given to the subject at the end of the test session. We have found the inexpensive brushes ($1-$2 per brush) purchased from neighborhood department stores are of sufficient quality for this purpose.

(3) Prepare the skin areas where drop electrodes will be located. It is usually sufficient to clean these areas with an alcohol or acetone swab. It is important that these areas are clear of makeup and foundation to ensure low impedances.

(4) Position the cap on the head of the subject. This is typically a two-person process, one of which maybe the subject. While standing behind the subject, have a second assistant (or the subject) place their thumbs under the front edge of the electrode cap. Then pull the cap onto to the head, slowly, carefully ensuring that midline row of electrodes is properly aligned on the head.

(5) Attach all drop electrodes. If necessary, use two butterfly tapes to make sure the electrodes are in secure contact with the skin.

OPTIONAL - This is a good point at which to digitize the electrode positions on the scalp. Optionally, locations may be digitized at the end of the experimental session.

(6) Load all electrodes with electrode gel beginning with the ground and reference electrodes. *Remember,* the electrode gel is used to build a column of conductive medium between the scalp and the surface of the electrode. If too little gel is loaded, this conductive column will contain gaps. Consequently, contact between the scalp and the electrode will be intermittent. If too much gel is loaded, it will spread beyond the proximity of the electrode reservoir and (with high density electrode arrays) could result in a salt bridge with other electrode locations.

(7) If all electrodes are reading high impedances, this usually reflects high impedance at either the ground or reference electrode location. After loading the ground and reference electrodes, load all remaining cap and drop electrodes. It is a good idea to let the gel soak in before testing the impedances; the gel will lower the impedances significantly on its own without abrading.

(8) Perform the first impedance test. If the subject has clean hair and a well prepared scalp, many of the electrodes will have impedances that are sufficiently low (< 5-10 kOhm) so that no further preparation is required.

(9) When abrading is necessary, always begin with the ground and reference electrodes. Do not direct force down on the needle toward the scalp. It is usually sufficient to make sure that the needle has contact with the scalp, and then simply rotate the needle in a circular manner (rotate the needle in an arc). Place light pressure down the electrode holder with one hand while abrading with the other hand. This will ensure that the electrode gel remains confined to the reservoir of the electrode holder. Run the ACQUIRE module of the SCAN software while preparing the subject. Watch the impedances while abrading. As soon as the impedance for an electrode begins to decrease, stop abrading and remove the preparation needle from the electrode. Usually the impedance will continue to fall. An immediate increase in electrode impedance after removing the preparation needle usually indicates that the column of gel in the electrode reservoir is intermittent - the preparation needle is thus the conductor between the scalp and the electrode. In this situation, inject a little more gel into the electrode holder. Slightly withdraw the needle while injecting the gel. This will help to construct a column of conductor that is uniform and will last throughout the recording sessions. Use the extra gel that flows out of the top of the electrode reservoir to seal the opening - this will keep air out of the electrode and prevent the gel in the reservoir from drying out.

IMPORTANT - Always use a clean blunt-end needle when abrading. Never reuse syringes and blunt needles for more than one subject. Use a "sharps" dispenser to dispose of blunt needles, if available.

(10) Heads vary greatly in both size and shape. While we endeavor to make electrode caps that snugly conform to the surface of the head, some electrodes may not always be in good

contact with the scalp. In these cases, we recommend using the wound gauze mesh over the top of the electrode cap. The mesh can be cut into lengths of 10-15 cm in length and then pulled over the top of the electrode cap. Under most conditions it is not necessary to place the gauze mesh over the frontal pole electrodes as the cap is typically quite snug at these locations. Subjects/patients are likely to experience excessive pressure and some discomfort if the gauze is placed over these electrodes.

(11) Of special importance for EEG recordings in the MR is the placement of electrodes to record the electrocardiogram (EKG). This is critically important as this data will be used as a trigger for extracting the ballistocardiogram. Optimally, the EKG electrodes should be placed in locations above and below the plane of the heart. For ease of placement, these electrodes may be placed along the midline of the chest. Because of the location of these electrodes, it is important to clearly explain the need for these electrodes, particularly to female subjects.

Critical Tips for Subject Comfort

(1) **Prepare in advance**. Magnet time is expensive and subject time is also extremely valuable. Optimize your testing procedures by preparing all electrode application materials in advance. Prior to the arrival of the subject, load the necessary number of needles with gel to complete the entire cap (32-40 channels, 2 syringes; 64 channels, 3-4 syringes, etc.). Have the gauze mesh cut to the necessary length (10-12 cm). Have all butterfly tapes available and ready for placement. Have the SCAN software open and ready for testing electrode impedances.

(2) **Do not** place the mesh over the frontal pole electrodes Fp1 and Fp2 (or other frontal pole electrodes) - pull the mesh back off these electrodes. Usually, these electrodes do not require any addition force to be firmly in contact with the scalp. Placing the mesh over these electrodes may result in considerable discomfort to your subject.

(3) **Do not** place a drop electrode under the edge of the electrode cap. This will result in considerable discomfort for your subject. At frontal electrode locations, this discomfort can rapidly advance to nausea and/or headache.

(4) **Check for special medical conditions**. The electrode cap is secured to the head using a fairly snug chin strap, which can cause discomfort. This discomfort can be particularly acute for individuals with temporal-mandibular joint disease (TMJ - disease). Ask your subject in advance if they are affected by TMJ. If such individuals are to be tested, perform a recording sequence outside the MR environment to determine their tolerance (including time of comfort). Prolonged testing of TMJ subjects with the electrode cap can result in acute discomfort.

(5) **Subject Comfort is a Priority**. Have bottled water available for your subject. Routinely inquire about your subject's comfort during preparation and during testing.

EEG recordings in MR environments are qualitatively different from those performed in the relative comfort of a testing lab. Subjects are more likely to return for repeat testing if you have made obvious efforts to ensure their physical and emotional comfort.

Time Estimates for Electrode Cap Application/Preparation

With experience, and with the subject's cooperation (by following the above preparations) it is possible to complete the electrode cap application and preparation process for a 32-40 electrode cap in 15-20 minutes, even if there is only one individual involved in the application process. It is recommended that with higher electrode applications (64-128 channels) two lab technicians prep the subject. We have routinely prepped the 128 channel cap for use in the MR in 30-40 minutes.

Cleaning the MagLink Electrode Cap

Your MagLink cap represents a considerable investment. To maximize the life of the cap and the quality of data obtained from the cap, thorough cleaning is critical. To clean the electrodes, we strongly recommend the use of a WaterPik®-like device. This is a device consisting of a small water reservoir that projects a high-pressure stream of water through a nozzle that is designed for cleaning teeth. The jet-stream of water produced by these devices does an excellent job of cleaning the surface of the electrode and the electrode reservoir without using any object that comes in contact with and potentially damages an electrode's surface. When cleaning the cap using such a device, fill a sink (or basin) with moderately hot water. Hold the cap under the water so that the nozzle of the WaterPik® is also under the surface of the water. Direct the jet-stream of water from the nozzle into the electrode holder. It is important to keep the nozzle of the WaterPik® directed at the electrode and under water to prevent any back-spray onto the person cleaning the cap. Clean both the under surface and top surface of each electrode holder.

It is recommended that the cap be left to dry at room temperature. It can also be dried more quickly with a hand-held hair dyer. *However*, never use high temperature settings when drying the cap as it will rapidly degrade the elastic material of the electrode cap. USE ONLY LOW TEMPERATURE OR ROOM TEMPERATURE SETTINGS on a portable hair dryer to dry the electrode cap.

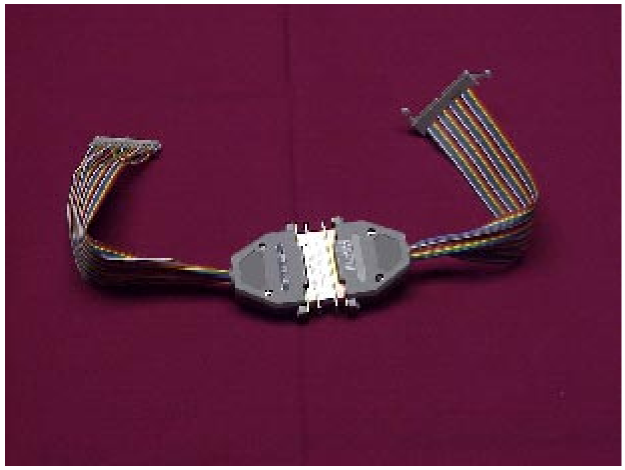
MagLink Cabling System

The MagLink cabling system consists of wrapped carbon-fiber wires. If you have more than one MagLink cable bundle (> 40 channel system), the cable bundles are interchangeable (note that for SynAmps-based systems, the filter cable connectors are not interchangeable - this will be described later). Every attempt has been made to make the cable bundles as flexible yet as resilient as possible. However, care should be taken so that the cables are not place in a location where they may be stepped on or crimped by a closing door.

Radio Frequency (RF) Filter and Connectors. The MagLink radio frequency (RF) filters are "Pi" type filters with a cut-off frquency of 0.8MHz (3 dB Max cut-off frequency), with 48dB attenuation at 100 MHz. The complete assembly includes one ribbon cable that connects from the RF filter to the electrode cap cable (inside the MR chamber), the RF filter, and a second ribbon cable that connects to the cable to the amplifier headbox (outside).

The RF filter is attached to the built-in D37 connector on the *inside* of the patch panel, and the inside ribbon cable attaches to the RF filter. The outside cable attches to the built-in D37 connector on the outside of the patch panel. The built-in D37 connector on the patch panel should have the male side facing the outside control panel (and the female side facing inside the MR chamber).

If you are using a waveguide, then connect the components together and run them through the guide. The RF filter shold be positioned inside the waveguide, more on the *chamber* side of the guide.



SECTION 2: Installation of MagLink System

Installation of the MagLink EEG recording system is relatively straightforward. Like any other EEG/ERP recording environment, special care should be taken to ensure that all cabling is located as far as possible from noise sources such as transformers and computer monitors. If at all possible, the RF filter should be mounted in a patch panel connecting the control room to the MR chamber. Consult with your MR physicist or technician before installing the RF filter in the patch panel. They may have specific locations available that will isolate the MagLink components from other hardware used in the MR environment. Mounting the filter assembly in the patch panel ensures the optimal filtering of RF so that it will not contaminate the MR images. As a second option, the RF filter may be positioned in the waveguide between the control room and the MR chamber. While this produces satisfactory results, movement of the RF filter or improper placement of the filter in the waveguide may allow RF leakage and reduce the image quality of the MR data.

NuAmps-based MagLink systems simply connect via the filter adapter cables to the RF filters on the inside of the MR chamber. Position the MagLink cables so that loops are not formed by the cables in the MR chamber. When the subject is placed on the bed and moved into the bore of the magnet, hand feed the cables so that they do not get caught or bind on other pieces of equipment or clothing.

SynAmps-based MagLink systems have two kinds of filter interface connectors for systems with more than 32 channels. This is to accommodate the bipolar channels used for EKG and eyeblink. For systems with 32 channels or fewer, the interface connectors are typically marked to indicate which filter interface connector is to be used for the bipolar recording channels and which SynAmps this needs to be connected to.

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SECTION 3: Initial Recordings with the MagLink System

Prior to initiating a formal set of experimental sessions, it is critically important to set aside the first few test sessions for pilot recordings. These sessions should involve the MR physicist or technician. The following sequence is recommended.

(1) **Record a Reference Set of Data Outside the MR**. Perform an initial series of recordings outside the MR. These recordings should include:

a. *Continuous EEG with eyes open and eyes closed*. Check for the detectability of and changes in the EEG spectra, specifically alpha activity. Note the simple and distinct structure of the EKG response and its restricted appearance in the EKG recording channels (this will change profoundly once the subject enters the MR).

b. *Reference recordings*. Record data for your evoked potential paradigm to act as a reference for data recorded in the MR. These data may also be used to generate reconstruction LDRs for data recorded within the MR environment.

(2) **Repeat Series Inside Static Field**. Repeat the series of tests described above with the subject in the bore of the magnet within the presence of the static field. It should be possible to clearly identify EEG activity. The major change will be the presence of a very large ballistocardiogram artifact. Examine the data recorded from EKG leads. You will observe that the very simple EKG signature obtained outside the MR becomes much more complex within the bore of the magnet.

(3) **Obtain a Structural Scan**. Prepare for a structural scan. Shimming procedures may require some adjustment to reestablish the homogeneity of the field with the added presence of the electrodes, cabling and electrode paste. Obtain structural MR data from the subject. The structural scans will show localized shadowing that should be restricted to within a small distance (2-4 mm) of the recording electrodes. Note that if initial tests are performed on a phantom, the artifact will appear greater than that obtained with the cap on a subject.

(4) **Obtain a Functional Scan**. The signal-to-ratio of functional MR scans is much poorer than that needed to obtain a quality structural scan. In your pilot investigations, record functional scans with and without the MagLink cap and cabling system. This is critically important when interpreting ambiguous fMRI data, as there will be a tendency to attribute poor quality MR data to the presence of the EEG recording system, until such recordings become routine.

SECTION 4: General EEG Data Acquisition for Optimal fMRI Recordings

Recording electrical signals within a powerful magnetic field is a challenging problem, and one that has yet to see the final, ultimate solution for dealing with the various artifacts that occur. The information below is based on our recording experiences in several MRI facilities, up to and including 4T magnets. These steps and techniques summarize what we have found to be most effective thus far. We have also found that there can be considerable variation in the artifacts among different facilities. Those techniques that work well for one facility may not be optimal for all labs. We present the information as a useful guideline; you may need to fine tune parts of it for your lab.

There are two major experimental design paradigms used in most fMRI experiments; so-called boxcar or block designs and event-related or sparse stimulation designs. A number of excellent reviews have been written describing the benefits and drawbacks of these techniques. The reader is encouraged to consult references on MR experimental design for the details of these procedures. Briefly, however, boxcar designs are experimental sequences in which stimulation is simultaneous with (occurs at the same time as) the imaging sequence. According to Horowitz et al. (2000), there are advantages and disadvantages to each of the techniques.

Advantages and Disadvantages of Boxcar Designs. Some of the advantages of the boxcar design experiments are higher levels of cortical activation resulting in greater statistical power. This in turn leads to faster fMRI acquisition times. Since the inter-stimulus interval is shorter than the hemodynamic response function for each stimulus item, data collected with boxcar designs are interpreted as a brain-state (task induced) dependent measure. The disadvantage of boxcar designs is that the acoustic noise of the imaging sequence is concurrent with the fMRI stimulation, which may have a significant impact on the arousal and attention. In addition, the acoustic noise of the imaging sequence will act as mask for experiments using auditory stimulation. The reader should review articles on the effects of broadband masking on psychophysical performance. A number of similar articles describing the effects of noise on evoked potentials (including lateralization of activity related to speech processing) should also be considered. Electrophysiologically, it is more difficult to extract evoked responses from the EEG due to the high amplitude artifact induced into the data by the imaging sequence.

Advantages and Disadvantages of Event-Related Designs. In an event-related paradigm, stimulus presentation is asynchronous with fMRI acquisition sequences. That is, stimulus presentation precedes the acquisition of the fMRI data by an interval equivalent to the buildup time of the hemodynamic response. Some of the disadvantages of the event-related design experiments are somewhat lower levels of cortical activation (compared to boxcar designs) thus resulting in lower statistical power. Lower levels of cortical activation leads to longer fMRI acquisition times. One advantage of event-related or sparse designs is that responses to a single stimulus type can be characterized by averaging activation across multiple stimulus presentations. The data are more easily interpretable relative to specific types of stimulus events. As such, the fMRI data recorded during event-related sequences are much more comparable to evoked (or event-related) potentials. Another major advantage of event-related paradigms is that since stimulus presentation precedes each scanning sequence, the arousal and attentional effects produced by the high noise levels of the imaging sequence are not superimposed on cortical activations produced by the stimulus events. Moreover, artifact removal from the EEG data is simplified since the only artifact that needs to be extracted is the ballistocardiogram.

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Recommendation: From the point of view of optimizing the quality of the electrophysiological data and minimizing the interaction of scanner noise with experimental stimulation (especially acoustic), we strongly recommend the use of event-related experimental paradigms whenever possible.

Software Versions: It is assumed that you have SCAN version 4.3 or newer software, and that you have the new artifact reduction features. Once you determine the processing steps you will use in most instances, you can create a BATCH file to do the routine steps. Automating the steps will save you time as well as insure that the same steps, in the same order, with the same settings, are used in each case.

I. General Recording Strategies

In general we recommend some variation on the following design when recording fMRI data. The recordings outside the magnet, in an artifact-free environment, are especially important to substantiate the validity of the findings within the bore. This includes "resting" as well as EP stimulation recordings (if you are recording EPs). The resting recording will allow you to compare EEG power spectra inside and outside the MR, providing further evidence that the findings in the bore are not due to MR related artifact.

		Inside the magnet	
	Outside the magnet	During MR	Between MR sequences
"Resting"			
Stimulation for EPs			

Inside the magnet, record resting and stimulation sections between sequences of MR sampling, as well as during MR sampling if you are interested in recorded at the precise times that the MRI is obtained. (Recording valid EEG during MR sequencing is the most challenging part of fMRI data analysis process. At present, we are looking at different approaches for dealing with the MR gradient artifact, and those results will be added to this manual at a later time).

II. Specific Recording Tips for Acquiring Optimal Data

A. **Reference**. To date, we have not found one reference site that is consistently and significantly better than any other location. We have acquired excellent data with a single mastoid reference, as well as CZ and CPZ. We suggest that you use the reference that is most appropriate for your subsequent analyses (for example, if you are doing source localization or coherence analyses, you should use a reference consistent with that recommended in the literature). A single mastoid or earlobe should work well.

Selection of a reference will also depend on whether you use an electrode cap, which may contain a hard-wired reference electrode (fixed for SynAmps-based systems, variable for NuAmps-based systems) or a quick-cluster set of braided electrodes.

B. **Record EEG data in continuous mode**. All EEGs should normally be acquired in continuous mode, but it is especially important for fMRI recordings. The new artifact reduction routines and other transforms require continuous files. Continuously acquired EEG provides the flexibility that is needed for many of the analyses; these are not available with epoched or averaged files.

C. **Record an EKG and a VEOG channel**. VEOG and EKG channels are critically important for use with the new artifact reduction routines, and are a good idea in any case.

D. **Get the lowest electrode impedances possible**. This may be the most important factor in obtaining good recordings in the MR. Electrodes with high impedances are especially susceptible to radiant artifact in the MR. Impedances above about 15 to 20 kOhms will almost certainly result in unusable data for those channels. Get the impedances as low as possible (< 5-10 kOhms).

E. **Positioning the patient and cables**. Ballistocardiogram (BKG) results from micro-movements of the subject or the electrode wires due to cardiac activity. You can generally minimize BKG by securely taping down the electrode wires, by immobilizing the subject's head, or any other technique that will minimize the micro-movements. Using the stretchable netting that we provide for the electrode caps will also help hold the wires in place and minimize their movements.

F. **Minimizing RF artifact in the MR images**. It is critical to ensure that the radio frequency (RF) filter array is installed in the MR chamber wall. In recordings we have made with the MagLink electrode cap, there are minimal distortions of the MR images as a result of the connection to the external EEG equipment when the RF filters are properly installed. Typically, this requires installing the RF filters directly into the patch panel that connects the control room to the MR chamber. Alternatively, the RF filters may be placed within the waveguide (often 8-10 cm aluminum conduit); good results have been obtained with this method, but it is critical that the RF filters be positioned correctly. If the RF filters are simply placed in the opening of the waveguide in the control room, sufficient RF may be present to distort the MR images. The RF filters should be placed in the waveguide at the depth of the wall separating the control room and the MRI chamber.

When the RF filters are properly positioned, there should be little effect on the quality of the MR images. With electrode caps containing up to 128 electrodes, shimming the magnet sufficiently restores the homogeneity of the MR field to obtain quality images. Shadowing by the electrodes and gel should be very local, without interference at the depth of the cortex. The scalp electrodes may be seen at the skin level in the MR images. Successful recordings and quality MR data have been obtained with MagLink systems containing from 37 to 128 electrodes.

SECTION 5: General EEG Analysis Strategies for Data Recorded in the MR Environments

As mentioned in the Introduction above, there is no absolute sequence of steps that will always result in artifact-free data. Below are steps that we have found to be effective in removing or minimizing the artifact in the data files we have acquired. You may find that these steps work for you, or that you may need to vary the order, or use different approaches for the optimal effectiveness in your setting.

A. **Recordings outside the magnet**. In the demonstration below, we are using a CNT file that was acquired outside the magnet, with both resting and EP stimulation sections. The left mastoid was used for the reference in all files. The EKG channel shows the expected pulse, and mild heart beat artifact was present in some EEG leads. The VEOG channel shows sporadic blink artifact. We will remove or minimize these artifacts, and also apply any other transforms that will be needed for comparison with the data recorded within the bore, such as Filtering, EKG Noise Reduction, Baseline Correction, etc.

We will create three files for comparison with data recorded in the bore, or to verify that the artifact reduction techniques have been effective:

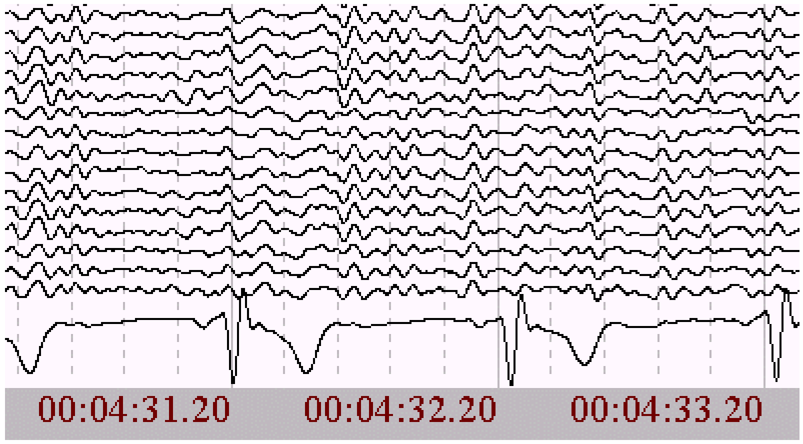
- Create a FFT power spectrum of the averaged resting EEG sweeps.
- Create an average of the evoked responses to the auditory stimuli.
- Create an average EKG artifact after the heart beat artifact has been minimized.

First we will perform some preliminary processing steps, including rejecting bad sections in the file, filtering the data, removing the heartbeat artifact, and removing blink artifact. At that point, the CNT file will be epoched in various ways to yield the average files described above.

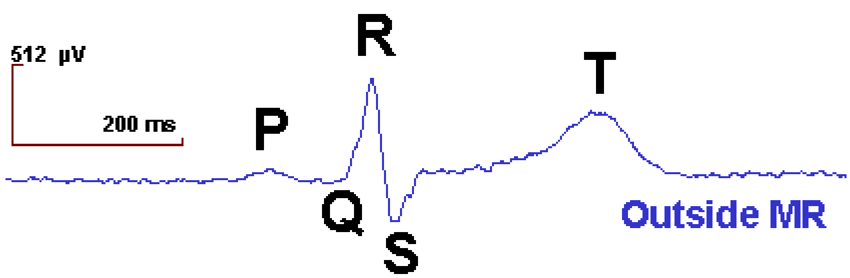
1. **Retrieve the CNT file**. It is critically important to examine each continuous file before advancing through the various stages of data processing and analysis. Scroll through the data, specifically attending to the type and extent of artifact, and any obviously bad sections (high amplitude activity associated with movement, electrode pops, etc.). Reject any grossly "bad" sections in the file, using Mark Block / Reject Block.

2. **Filtering**. If you have recorded in DC mode, but are not focusing on the low-frequency, slowest potentials, then filter the data with a high pass filter (suggested cutoff frequency = 0.5 Hz). Unfortunately, artifact from the MR scanner is quite broadband, overlapping substantially with the frequency range of interest for many EEG/ERP applications. If such artifact can be filtered out without affecting the EP/EEG components of interest, do so. In the file we will be showing, we used a band pass filter of 0.5 - 20Hz (48dB), with Zero Phase Shift (digital filter).

A section of the filtered CNT file, with the EKG channel, is shown below.



A single EKG response is shown in the figure below. Note that the EKG signal contains the characteristic P-QRS-T structure.



3. **Removing the EKG**. A number of alternatives are available within the SCAN software for removing the EKG. We will illustrate the simplistic technique based on generating a running average of the EKG signal, which is then subtracted from EKG channel. Since we will be using this EKG Noise Reduction transform with the files recorded in the MR, we will apply it to this file as well. The set up dialog for this transform is illustrated below. To use this transform, it is necessary to identify the most prominent, recurring peak in the EKG. This peak will be used a trigger for the execution of the reduction algorithm. In the demo file, the main peak (the R wave) is about 400 µV or larger, and the inter-peak-interval is just over one second (1000 ms). Thus in the dialog box we specify that the reduction algorithm should be triggered by a positive-going peak measured in the EKG channel that has a voltage threshold of at least 300 µV. Since the peak of the R wave is well into the ballistocardiogram, the averaging epoch should begin 200 ms (-200 ms) prior to the occurrence of the peak and to continue for 400 ms after the peak. Since we are interested in correcting the trigger channel, this option is activated. In addition, we have opted to insert trigger events to mark the occurrence of each R wave.

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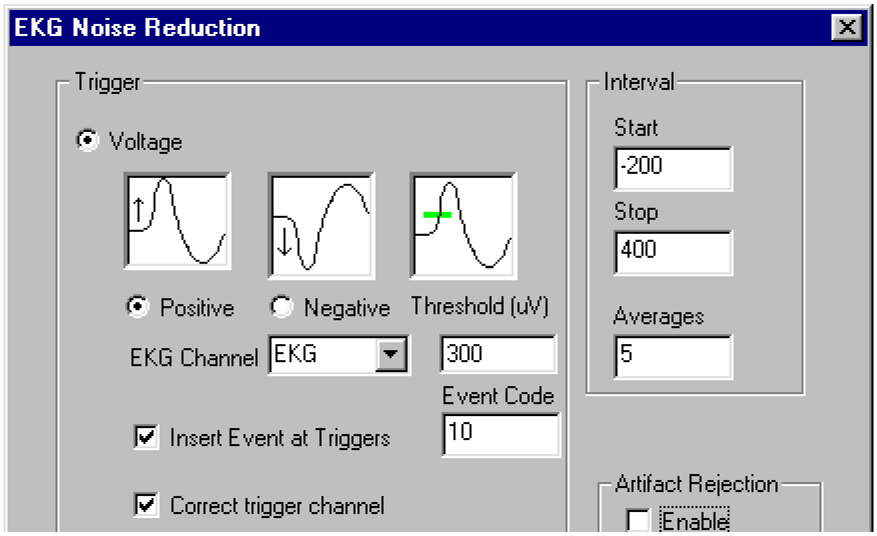
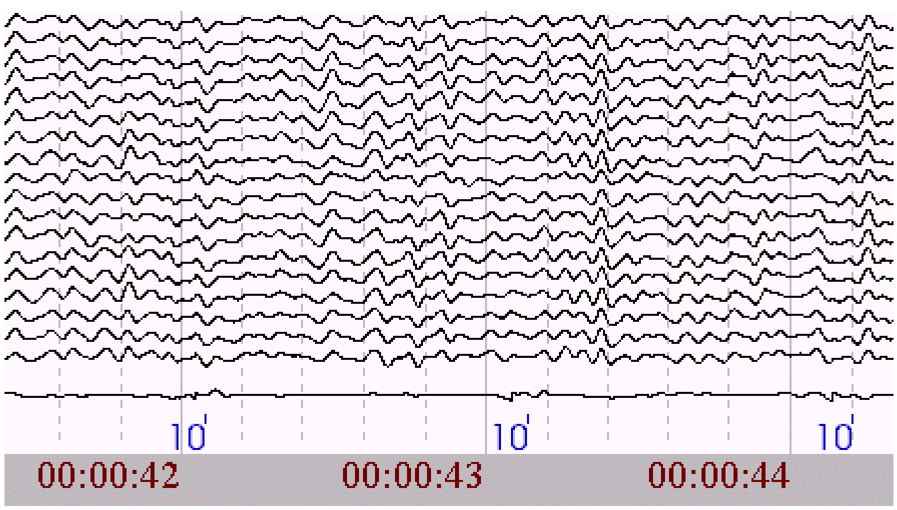
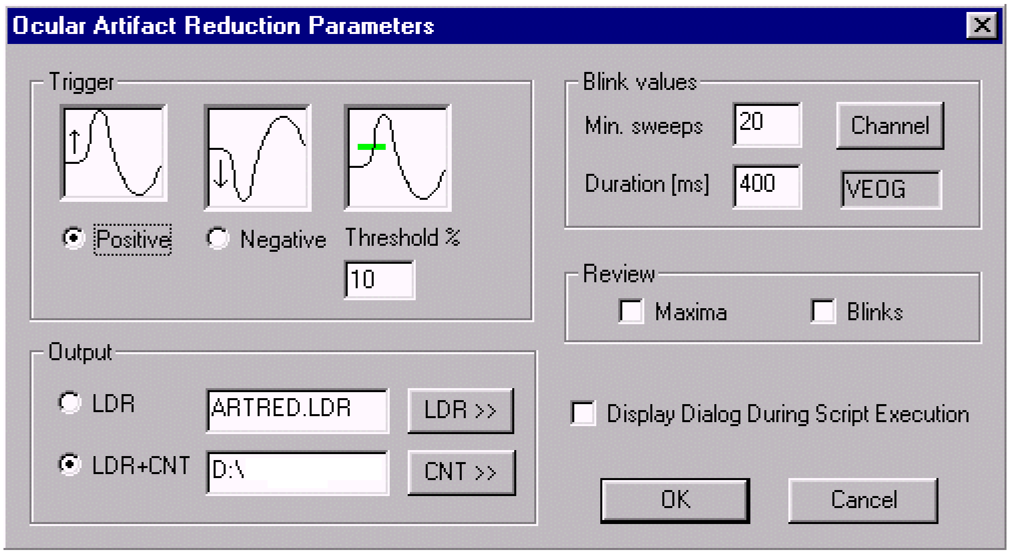


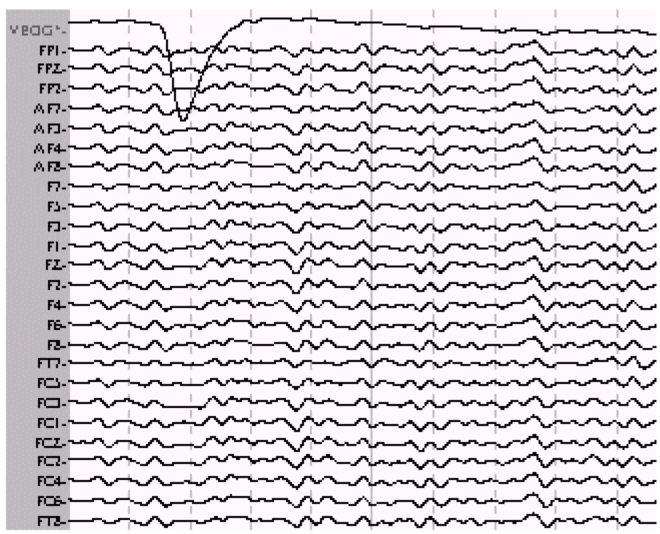
The corrected data are shown below. Note the effectiveness of the heartbeat removal in the EKG channel (as compared to the uncorrected data above).



4. **Removing the VEOG artifact**. There are several ways to remove the blink artifact: the Ocular Artifact Reduction (OAR) routine, the Gradient/Blink Reduction routine, or by using the Spatial Filter / Spatial SVD approach. For this file, we will use the regular Ocular Artifact Reduction transform.



Below is one example of the blink corrected data (OAR does not correct the artifact channel).



5. **Epoch the file**. You should make sure that the file contains all good sections, using Mark Block / Reject Block to reject any bad sections. Be sure to reject the section at the beginning of the CNT file before the EKG reduction routine was applied (the first 5 events in our case). Then epoch the file. For demonstration purposes, we will do this three ways: a) back-to-back in preparation for an FFT of the resting EEG, b) create epochs around the stimulus triggers to obtain the EPs, and c) epoch around the events inserted in the EKG Noise Reduction step above (to show the effectiveness of the removed EKG artifact). You will probably not need to do all of these on a routine basis.

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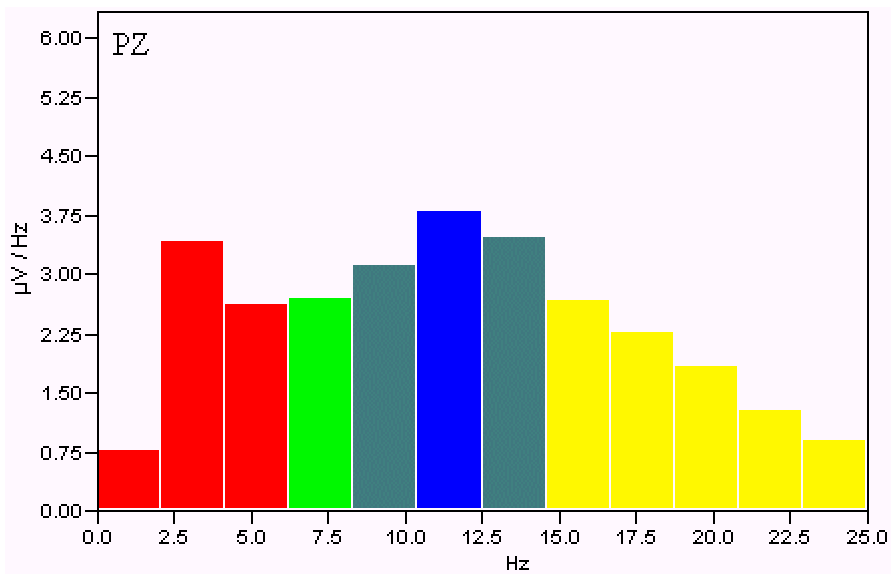
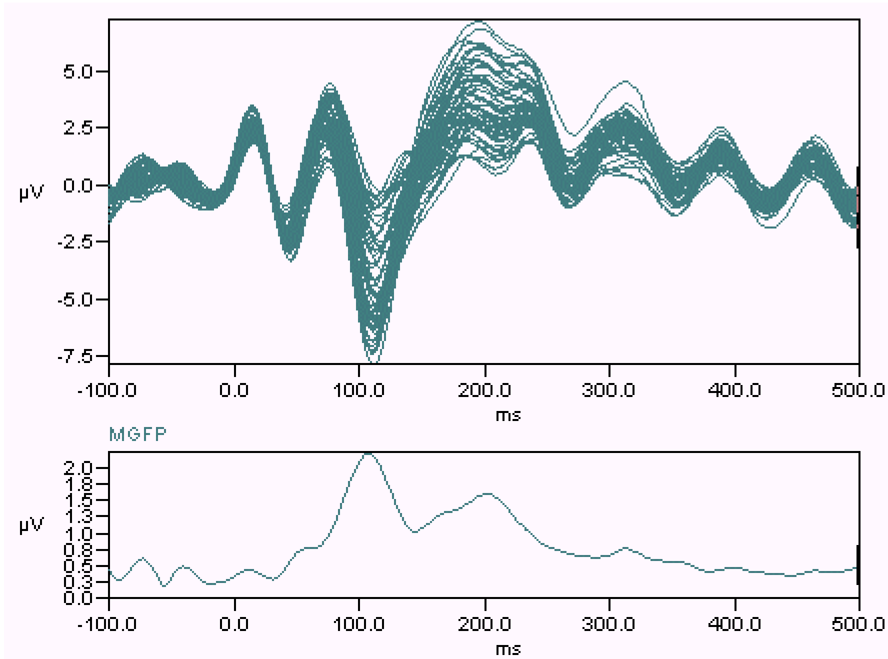
a. **Back-to-back epoching**. You should use only those sections that are free from stimulation (which may mean using Mark Block / Save Block to create a new file, or Mark Block / Reject Block to exclude sections containing the stimulus triggers). Select "No trigger" on the Epoch transform dialog box, and enter a Stop time to yield a number of points that is a power of 2 (such as 512). After epoching the file, you may want to apply the Baseline Correction, Detrending, or Artifact Rejection transforms, depending on your data file. We are using only the Baseline Correction (entire sweep) to remove any drifting that may be present. We then averaged the epochs in the Frequency domain.



This is the best representative of the subject's resting EEG power spectrum. We will compare this to the resting EEG spectrum recorded in the bore.

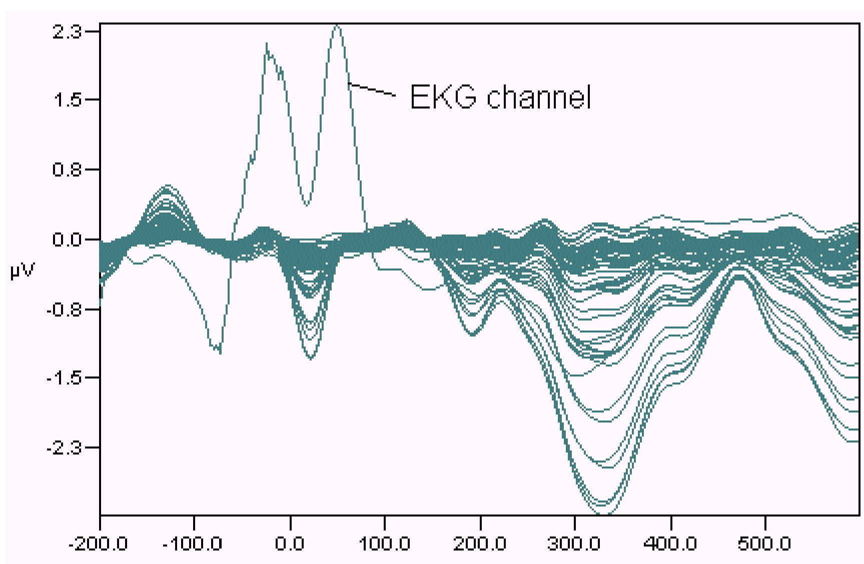
b. **Evoked potentials**. In this data file the subject was periodically presented a train of auditory clicks. Returning to the CNT file used in the step above, we will epoch the file again, creating sweeps from -100 to 500ms around the stimuli triggers.

Be sure to specify only the stimulus events when you do this, and exclude the events created in the EKG Noise Reduction transform. As in the step above, there are various additional transforms you may wish to apply, depending on your data file. We used Baseline Correction, selecting the pre-stim interval. The averaged results in the time domain are shown below.



This is the best representation of the "clean" EPs and it will be used for comparison to those recorded in the bore.

c. **Averaged EKG artifact**. Lastly, for demonstration purposes, we will create epochs around the triggers added in the EKG Noise Reduction routine. This will show the effectiveness of removing the heart beat artifact. (Be sure to select only those Type codes when epoching the file). The average of the sweeps is shown below.



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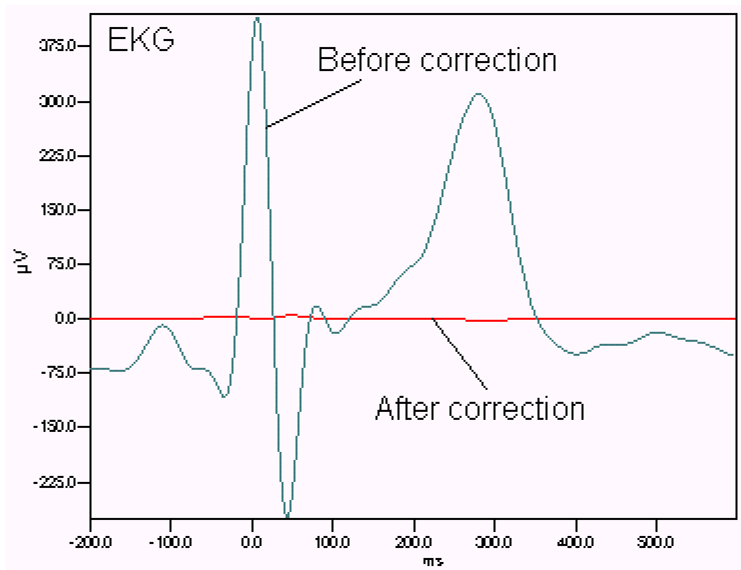
The original EKG artifact often exceeded 400 uVs. After EKG artifact removal, it is down to about 2 uVs in the EKG channel, and the residual EKG artifact in the other channels ranges from about 0 to -2.0 uVs, or less for most channels. The following figure shows the average heart beat artifact before and after the correction.

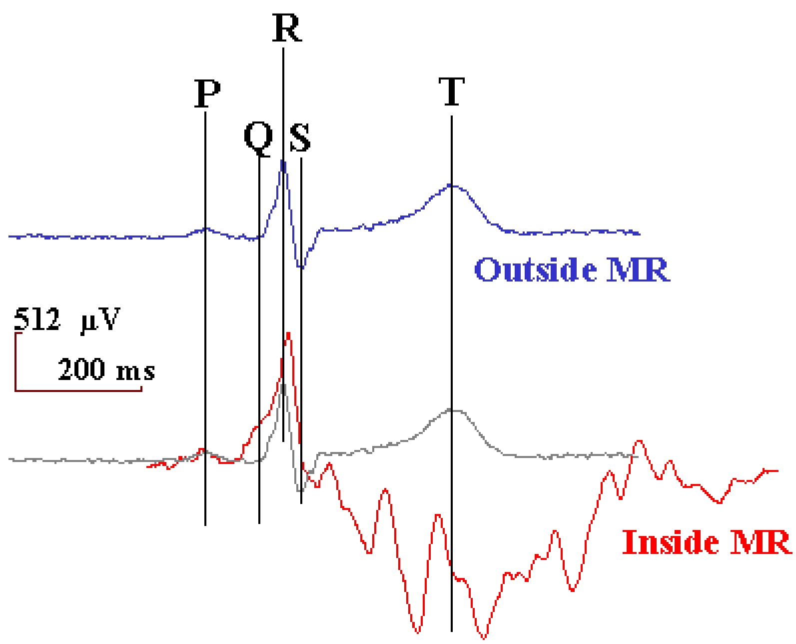


B. **Recordings inside the magnet**. In the demo file we are using, stimuli were presented between the MR sequences, but not during them. There are several meaningful comparisons to make:

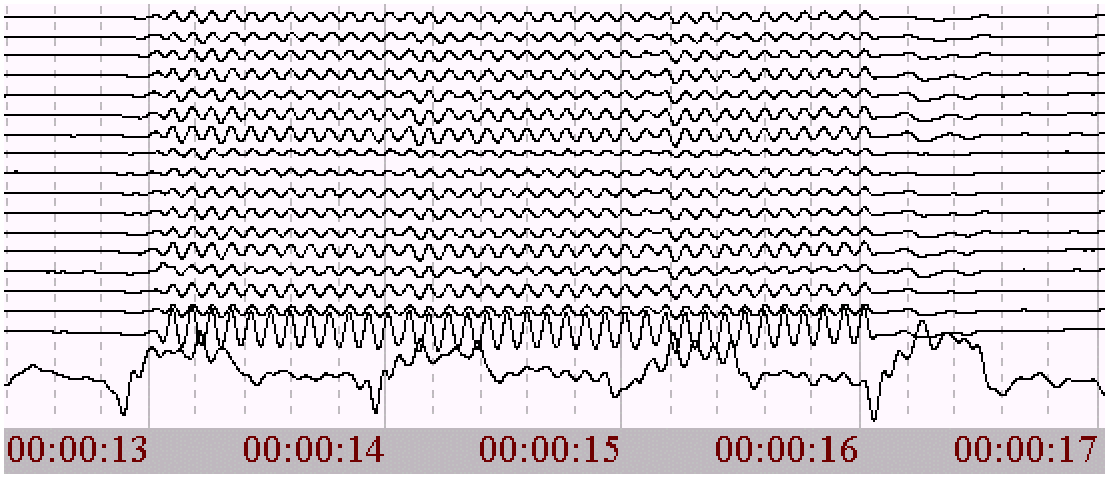
- The ballistocardiogram (BKG) recorded inside and outside the bore.
- The ballistocardiogram (BKG) recorded inside the bore before and after BKG artifact removal.
- The power spectrum of the resting EEG outside the chamber versus the power spectrum inside the bore between MR sequences.
- The EPs recorded outside the chamber versus the EPs recorded inside the bore between MR sequences.
- Lastly, we will compute the dipole solutions for the N1 component for the files recorded inside and outside the MR.

As before, you should go through the file first and reject any bad sections using Mark Block / Reject Block. Then Filter the file using the same filter settings used in the file recorded outside the chamber. There was virtually no VEOG artifact in this file, so we did not use the Ocular Artifact Reduction transform.

1. **BKG artifact reduction**. The next step is to remove the BKG artifact. This is a much more significant issue once the subject has been moved into the magnetic field. As shown previously, the cardiac response outside the MR environment is restricted to the EKG leads and is a multi-phasic but relatively simple signal. This changes dramatically in a strong magnetic field. The cardiac response recorded from the EKG leads inside the MR is superimposed on the response recorded outside the MR in the figure below.



The BKG Reduction algorithm is similar to the Ocular Artifact Reduction routine in that an average artifact is created and then subtracted from the waveforms. In the BKG routine, however, a sliding window is used to average and re-average the artifact throughout the file using a user-determined number of sweeps (i.e., the value you enter for Averages). The file we are using has sections of MR sequences in it, as well as BKG throughout. In this particular file, the BKG is not grossly overpowered by the MR gradient artifact.



In other files we have seen, the BKG can be completely distorted during the MR sequence. The point is: in either case, you do not want to include the MR sequences in the EKG artifact reduction routine. The sliding average containing samples during the MR sequence will be distorted, and the BKG instances immediately after the MR sequence will not be removed effectively (until the sliding average re-stabilizes).

There are at least two methods to reduce the ballistocardiogram. You could create new CNT files that have no MR sequences in them, and that have only MR sequences in them, using Mark Block / Save Block. Or, you can use Mark Block / Reject Block to reject the MR sections before you apply the BKG Reduction routine. (Note: you can reject the sections, then close the file without saving the changes, then retrieve the file to "restore" the rejected sections).

We will use the second option - reject the sections containing the MR artifact prior to using the BKG Reduction routine. This process can be automated using the Voltage Threshold transform. In this file, the MR artifact is greatest at O2, the beginning of the artifact exceeds -400uVs (in absolute value), and the artifact lasts for about 3 seconds. We set the Voltage Threshold transform to reject sections as follows:

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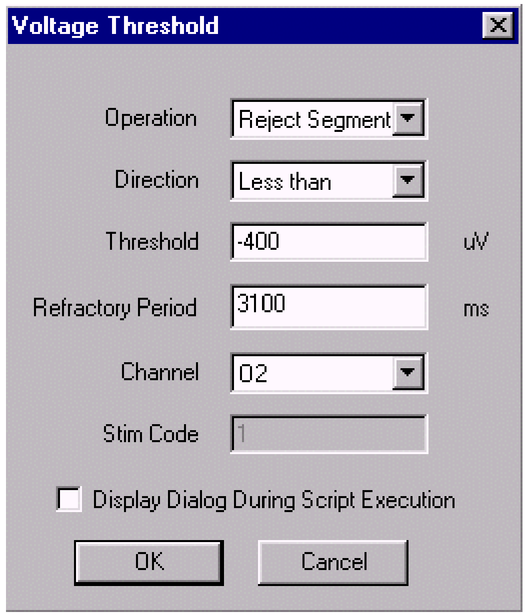

The MR sections are all rejected automatically. We can then apply the BKG Reduction routine without including the sections during the MR sequences.

Now, let's look at the BKG artifact itself. There is a repeatedly occurring peak in excess of 1000 uVs, every second or so.

We therefore use the following settings in the EKG Reduction routine. (Field not shown were disabled; a rolling average was used).

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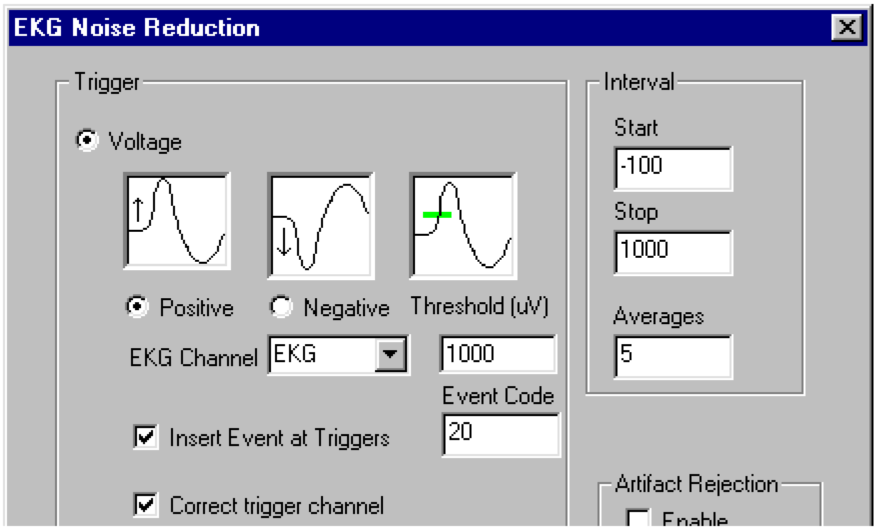
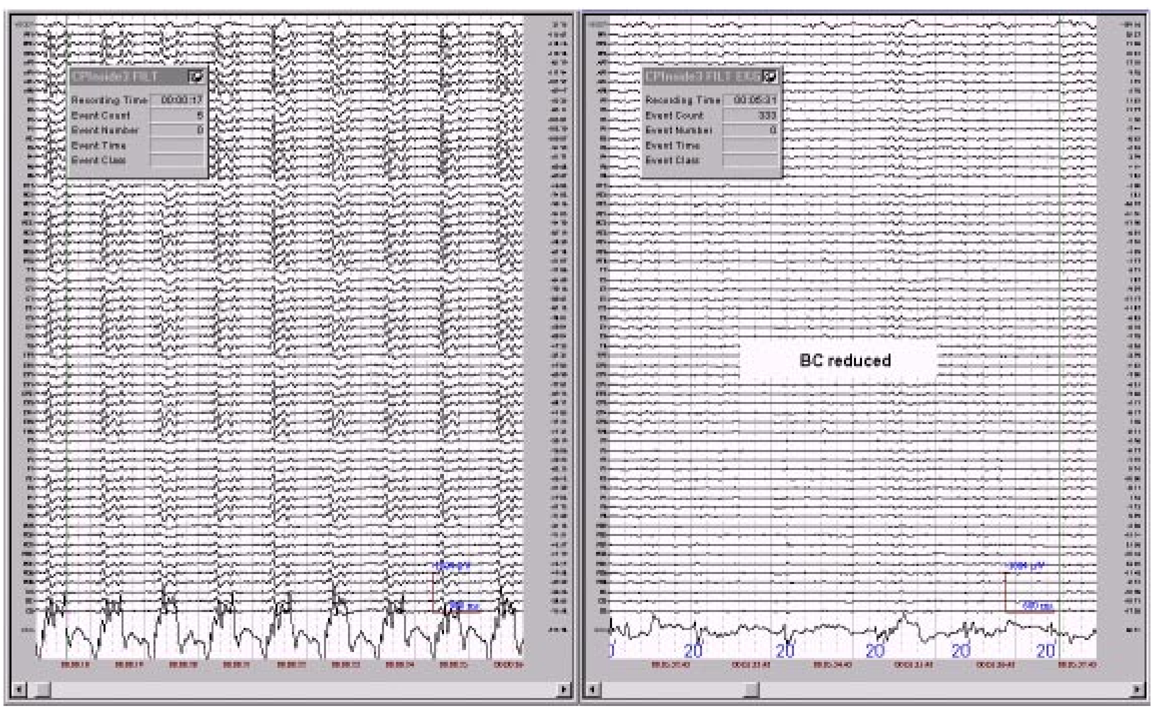
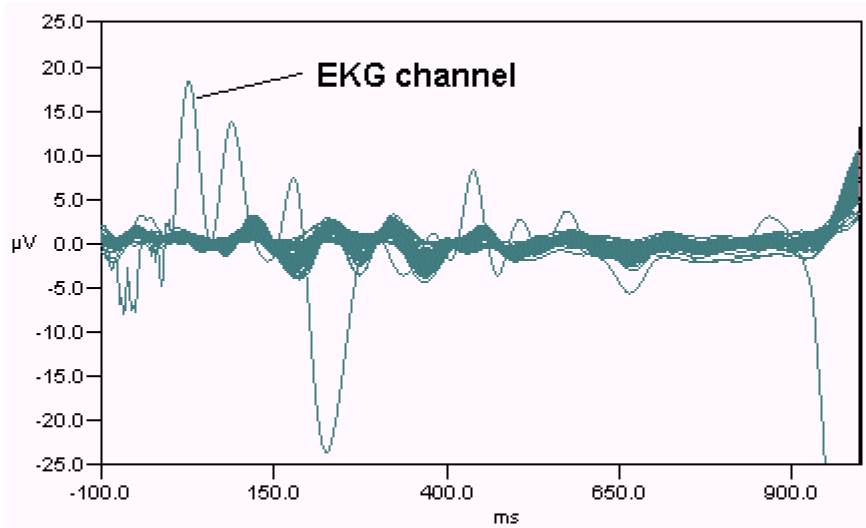


The BKG has been reduced. In practice you will likely need to experiment with the parameters to find those that give the best results.

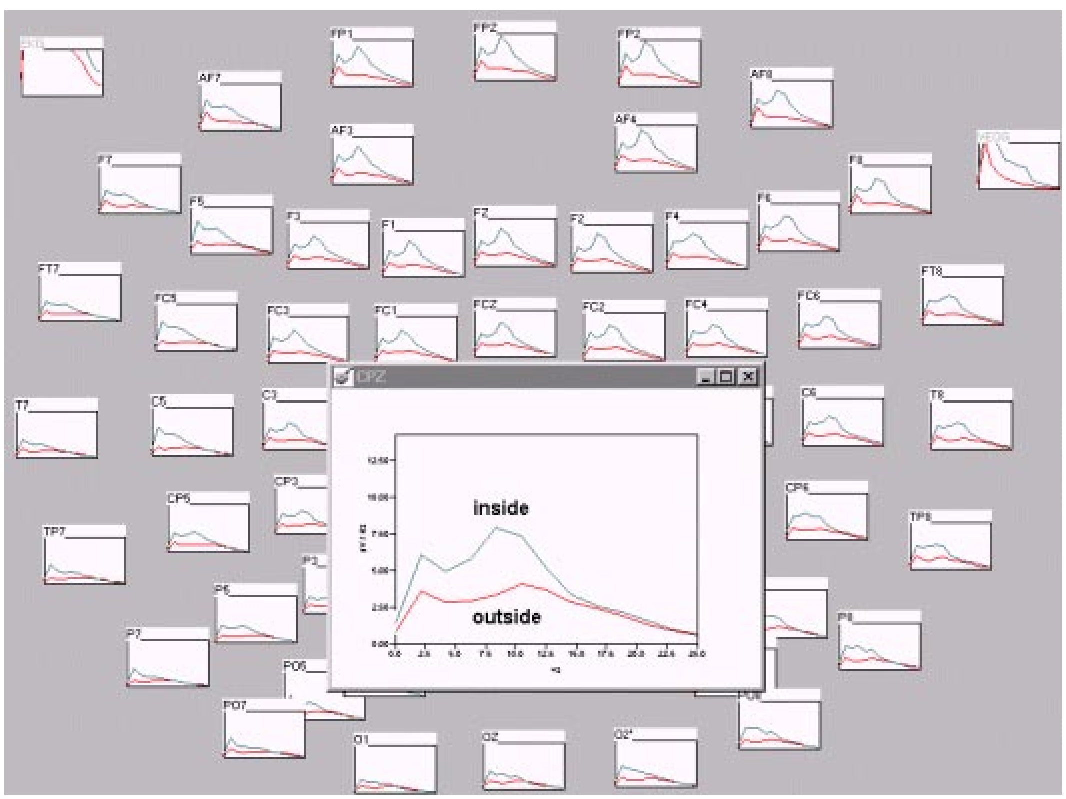


For demonstration purposes, we will average the epochs around the "20" type codes, to show the residual BKG artifact. The resulting file shows mild residual BKG in the EKG channel; however, the residual BKG in the EEG channels has been reduced to within about +/- 3 uV.



We conclude that there is minimal residual BKG artifact in the averaged EEG sweeps. The next step is to look at the power spectrum of the EEG in the bore.

2. **Comparisons of the EEG power spectra inside and outside the chamber**. We still have open the CNT file with the BKG reduced, the MR sections rejected, as well as any other bad sections rejected, so we will now compute the FFT using back-to-back sweeps (using the same Start and Stop times as with the file recorded outside the bore).



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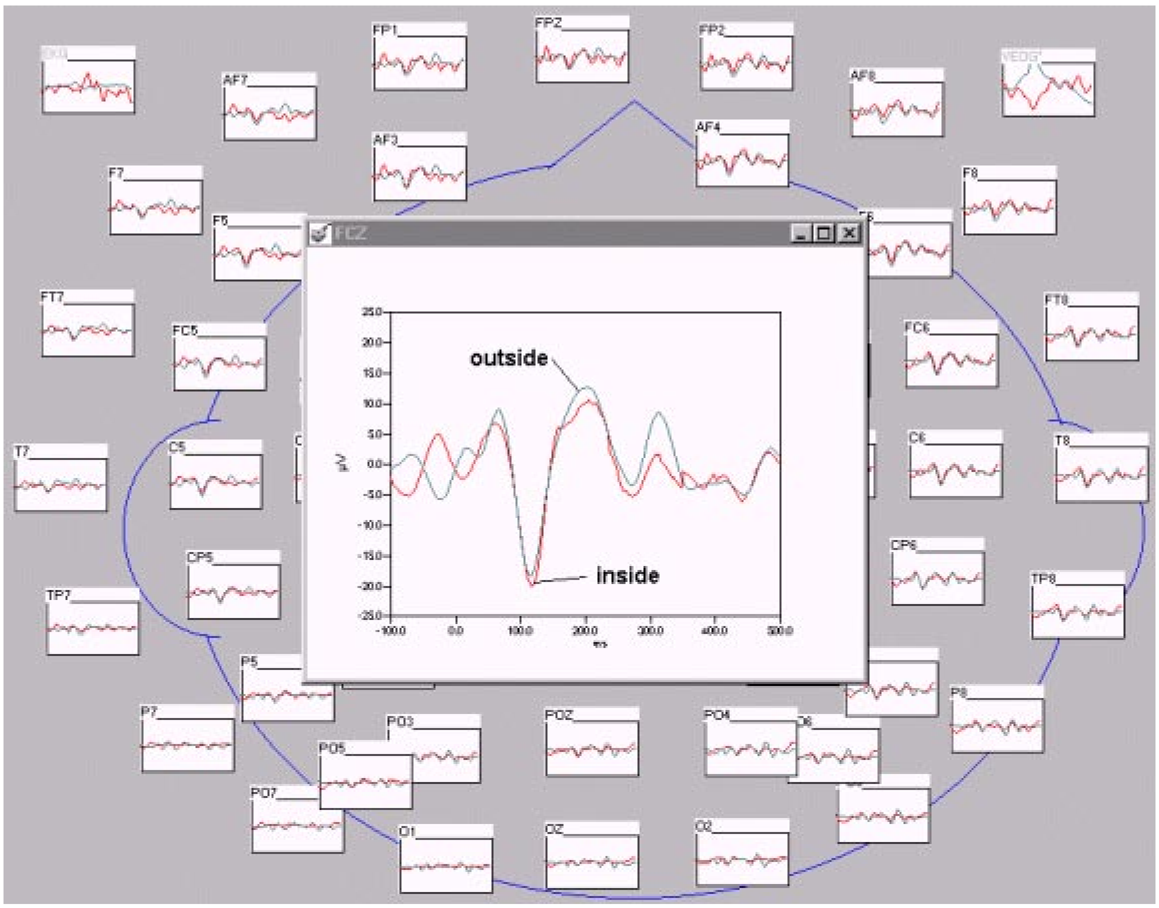
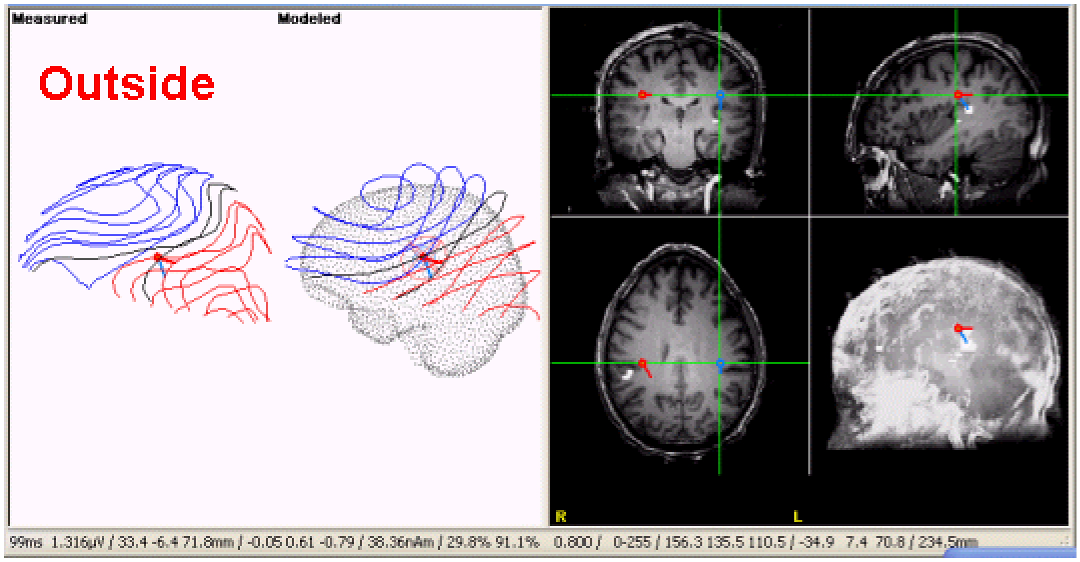
While the pattern is similar there is clearly some residual artifact in the recording within the bore. Looking at the waveforms, it is apparent that not all of the BKG was removed. The question is: will that significantly affect the EPs?

3. **Comparing EPs inside versus outside the chamber**. Returning to the CNT file that has the BKG minimized, we will create epochs around the stimuli, as we did with the file recorded outside the chamber.

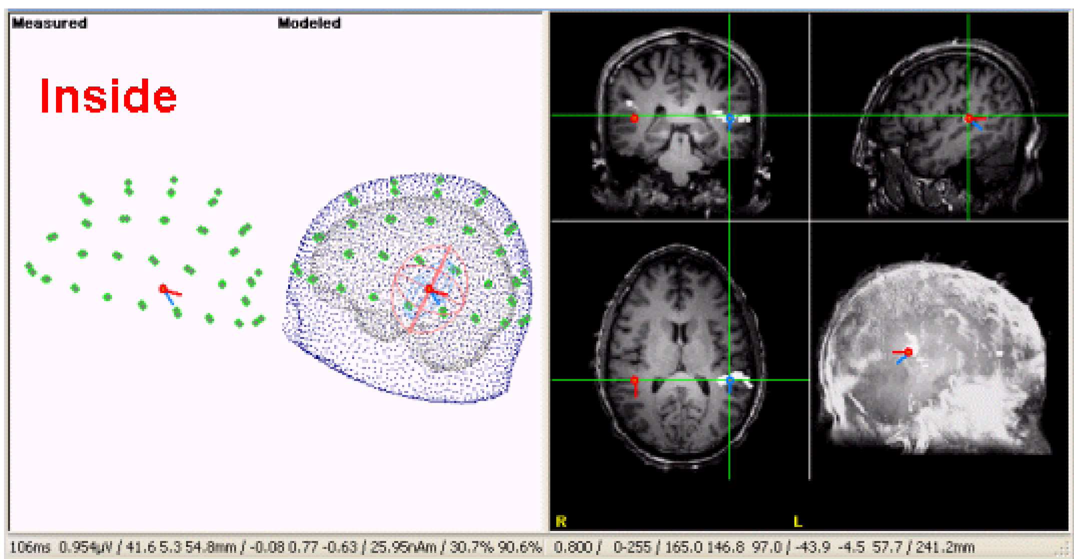


The EEGs channels inside the bore show evoked potentials that are very similar to those recorded outside the chamber. The residual BKG - not time-locked to the stimuli - tended to average out.

4. **Source localization of the data files**. As a further comparison, we will compute the source localizations for both data sets using the SOURCE software. We computed 2 Regional dipoles, mirrored, using a three spherical shell model, in the time interval of approx. 75 to 85 ms. The results for the EPs recorded outside the magnet are shown first.



The same analyses with the file recorded inside the bore show:



The results differ somewhat, which might reflect a number of factors, including the relative small number of single sweeps contained in each average.

Summary. In the examples above we have demonstrated some of the analysis techniques used to remove or minimize artifact seen in fMRI EEG recordings. As mentioned, the parameters for some of the transforms, such as EKG Noise Reduction, for example, usually require some experimentation to find the optimal values.

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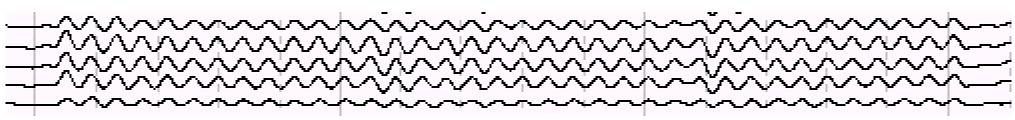
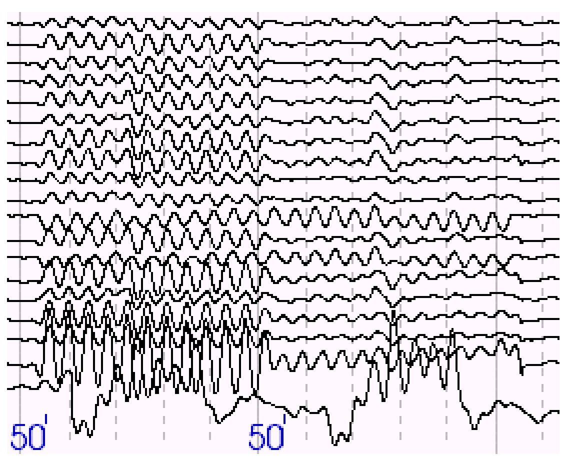
We have seen that BKG, for example, can be removed almost completely, or at least greatly minimized, as shown above. That which remains tends not to be a problem with evoked potential recordings. The degree to which the BKG artifact is successfully removed appears to be related to how consistent the artifact appears across time. Even though a sliding window is used to create the artifact that is subtracted, that is still an average, and the next artifact will be subtracted successfully insofar as it correlates with the averaged artifact.

We have not addressed the MR Gradient removal in the demonstrations so far. Software techniques that average the MR artifact and then subtract are not completely effective. This appears to be due to the variations of the MR artifact during even a single sequence of samples. In the figure below, in which the artifact has been filtered using a digital high pass filter of .5 to 20 Hz, note that the sine-wave artifact is not constant throughout the sampling interval.



The frequency changes across the sample. Regardless of the time interval you select, the average artifact will not accurately reflect any single interval. Therefore when you subtract the averaged artifact from a subsequent interval, the subtraction will be partially correct, partially incomplete, and in some cases actually add artifact. See the instance below. The second "50" event is the first one in which the averaged artifact is subtracted (10 were averaged).



You can see where the subtraction is imperfect, and in places it actually makes the artifact worse. Below is another instance later in the same file.

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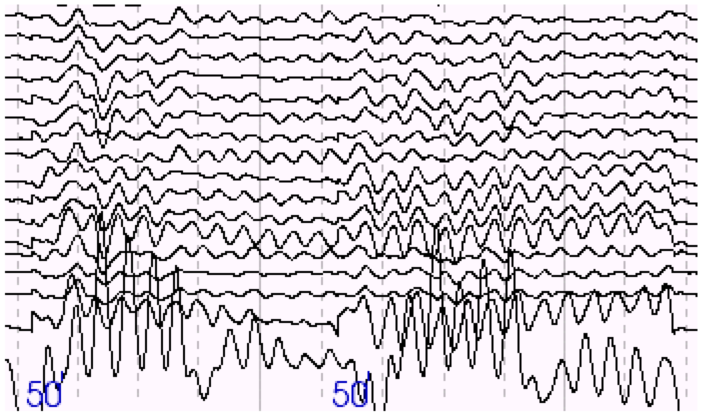
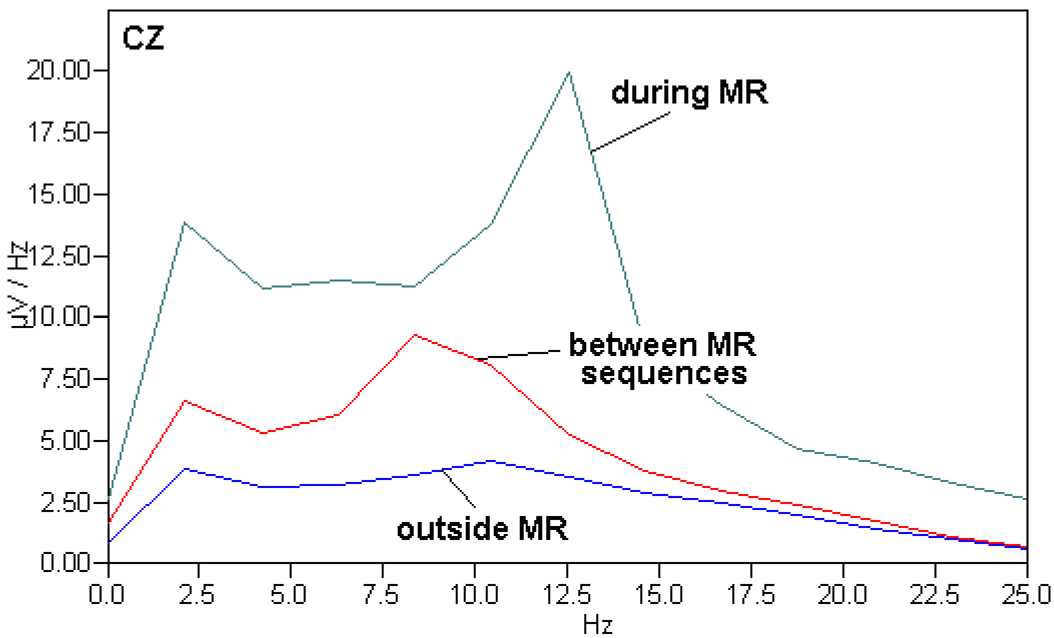


Again, the subtraction is not precise enough. The power spectra for sweeps during MR sequencing, sweeps between sequences, and sweeps recorded outside the chamber are shown below.



Clearly there is overpowering residual artifact. We are currently exploring other software and hardware solutions to the problem, and these will be described in subsequent releases of this manual.

Again, the steps presented above are those that we have found to be useful. You may find other transforms or procedural sequences that work better for your particular data files. We would greatly appreciate hearing about successful methods you have found. Please send any comments or suggestions to techsup@neuro.com.