Artifact Reduction™

User Manual

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

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Introduction

Beginning with SCAN version 4.3, there are options for online/offline removal of heart beat artifact, ballistocardiogram (BKG) and VEOG blink artifact. These are part of *Tool Box 2003*. The Tool Box is free to those who have a paid maintenance contract. It may be pruchased otherwise for $1000 for the first license, and $250 for each additional license.

To access the programs, you may need to complete the web site submission form for a new password. The password is then used to reprogram your software lock (dongle). Please see http://www.neuro.com/licreq.htm for directions. There is no additional software to install; it is already included in the SCAN programs you have installed. The options are activated when your dongle has been reprogrammed.

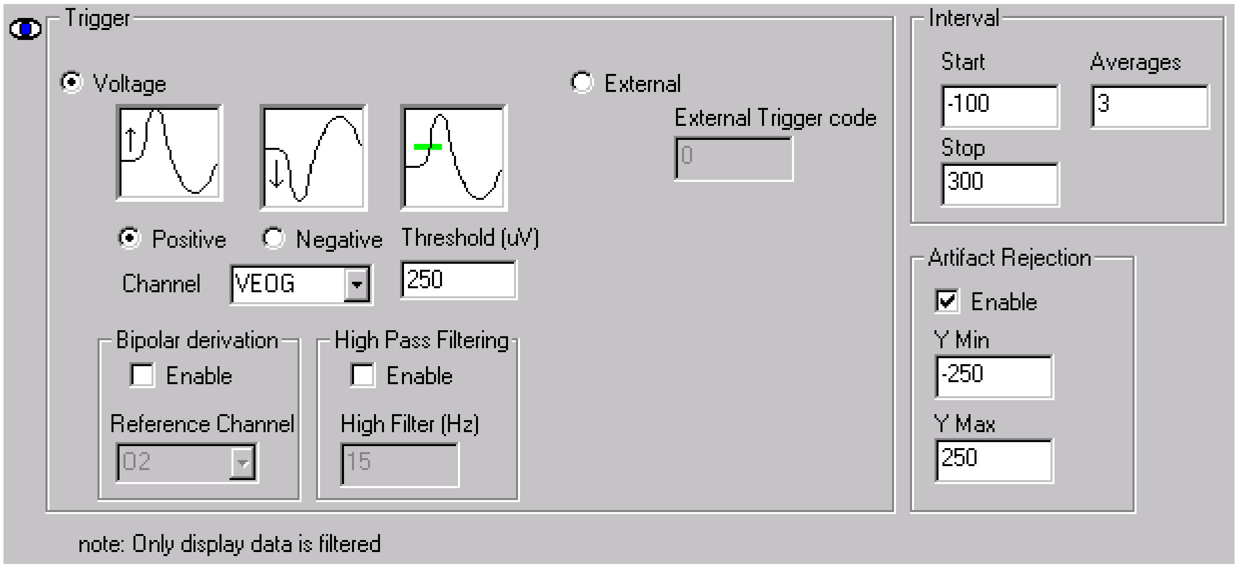
The artifact reduction techniques can be applied online or offline. There are a few slight differences between the online and offline applications, and these are all described below. The algorithms that are used for the EKG and Blink routines differ somewhat from each other. These are described in the sections below.

Online Artifact Reduction (in ACQUIRE)

Blink Reduction. The Blink Reduction computation is similar to the offline Ocular Artifact Reduction transform. Blink Reduction uses a rolling average of N sweeps, where N is the number entered for Averages. Based on those sweeps, an internal LDR file is computed and applied to all channels except the trigger channel (the coefficient is 1.0 for the trigger channel, therefore the corrected channel would be a flat line), and any Skipped channels. Linear transmission coefficients are computed, and there is a point-by-point proportional subtraction, based on the averaged artifact in the trigger channel. *Note: The data are buffered in the correction process, so you may notice a slight delay (about 40ms).* This is basically the same way that the offline Ocular Artifact Reduction transform works (see that section in the EDIT manual for more details). Unlike the offline Ocular Artifact Reduction transform, the Blink Reduction (and EKG Reduction) routine lets you reject sweeps using the Artifact Rejection criteria.

Note: The correction is applied to the displayed data only. To apply the correction permanently, use the Blink Reduction transform in EDIT.

From Edit, Overall Parameters, click the Blink Reduction tab. The are four sets of parameters: Trigger, Interval, Artifact Rejection, and Bipolar Trigger channel derivation.



Trigger. The artifact sweeps are initiated by triggers, and triggers are based upon a voltage threshold or a stimulus type code.

Voltage. With the Voltage option, an artifact sweep is initiated when the voltage in a designated channel exceeds a criterion you set. Select the Positive or Negative direction for the blink artifact. Select the channel that you want to be monitored. Enter the threshold value. This value should be sufficiently large to differentiate the blink artifact from other activity. The selection of the trigger point uses a peak detection algorithm. The waveform must cross the threshold two times, and the maximum (or minimum, depending on the settings) value during that interval is used for the placement of the trigger.

Bipolar Trigger channel derivation. In some situations you may want to create a derived *bipolar* trigger channel. Enable the option, and select a channel to be used for the reference. The reference channel will then be subtracted from the trigger channel.

High Pass Filtering. This option lets you apply a high pass filter to the artifact channel. Enable the option, enter a filter value, and frequencies below that value will be attenuated.

External. With the External option, an artifact sweep is initiated when a selected stimulus type code is received. Enable the option, and enter a desired type code. The event may come from STIM or from another external device that sends TTL pulses.

Note: If you are not using STIM, please see the section "Triggering SCAN from an external device", in Appendix B of the SCAN Vol. 1 manual - Installation and

Orientation manual (or the Overview.pdf) - as well as the pinout diagrams at the beginning of the appendix (specifically the "Back of SCAN connector" diagram).

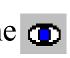
Interval. The interval is the section before and after the point at which the Threshold is met. This should be long enough to encompass a stable, consistently appearing section of the artifact. It is not necessary to capture the entire artifact. For blinks, you want to capture the section from the peak (point where the threshold is met), or maybe a little before it, through the section after the blink. You do not want the duration (the Stop time) to be so short that you get a second trigger within the same blink. At the same time, if you make the duration too long, you will be including more variability in the average, which could reduce the transmission coefficients, and thereby reduce the effectiveness of the reduction. You should experiment a little with Start and Stop times to get the best settings for your data. Settings of approximately 0 (Start) to 400ms (Stop) should be close.

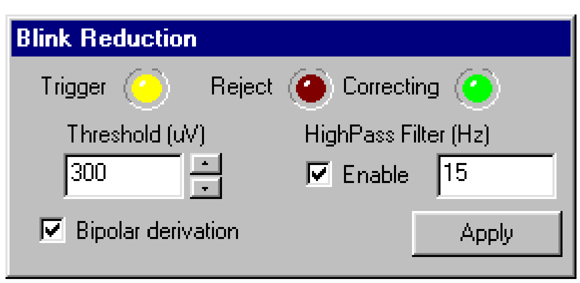
The Averages field determines how many artifact intervals are collected before the correction process begins.

Artifact Rejection. The Artifact Rejection criteria are used to monitor voltages in the designated Artifact Rejection channels. When enabled, artifact detected by the Threshold criteria is NOT included in the average blink artifact if the Min or Max criterion is exceeded within the interval specified for the trigger. This prevents artifacts in the designated artifact rejection channels from being included in the averaged blink artifact.

Note: If the artifact is present with nearly equal amplitudes in the designated artifact rejection channels, you should use caution when enabling the Artifact Rejection criteria. Blink artifacts in these channels could result in the rejection of perfectly acceptable sweeps.

Note: Unlike the EKG Reduction feature, you cannot correct the artifact channel with Blink Reduction. This is because the transmission coefficient for that channel will be 1.0, and, if applied via the LDR, the result will be a flat line.

Click the  icon from the Toolbar to see the Blink Reduction status bar. The Trigger light will blink briefly when the threshold is met. The Reject light will blink when an artifact interval is being rejected. The Correcting light will come on when number of Averages has been reached (indicating that the correction is being applied).



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The Threshold level can be changed during acquisition (you will see a line displaying the threshold in the Single Window display). If you set the Threshold level by entering a number from the keyboard, you must click the Apply button to register the change. If you use the up and down arrows to adjust the Threshold, you do not need to click the Apply button. You may toggle the Bipolar derivation on and off. If you enable the Bipolar derivation option, but did not select a reference channel from the Blink Reduction dialog screen, the program will select the first channel in the list as the reference (if you are using the bipolar reference option, be sure to select the reference from the Blink Reduction dialog screen first).

Both the Blink and EKG Reduction procedures can be applied offline in the EDIT program, as well. Both can be run in BATCH files (see the SCAN 4.3 version of the TCL BATCH manual for details).

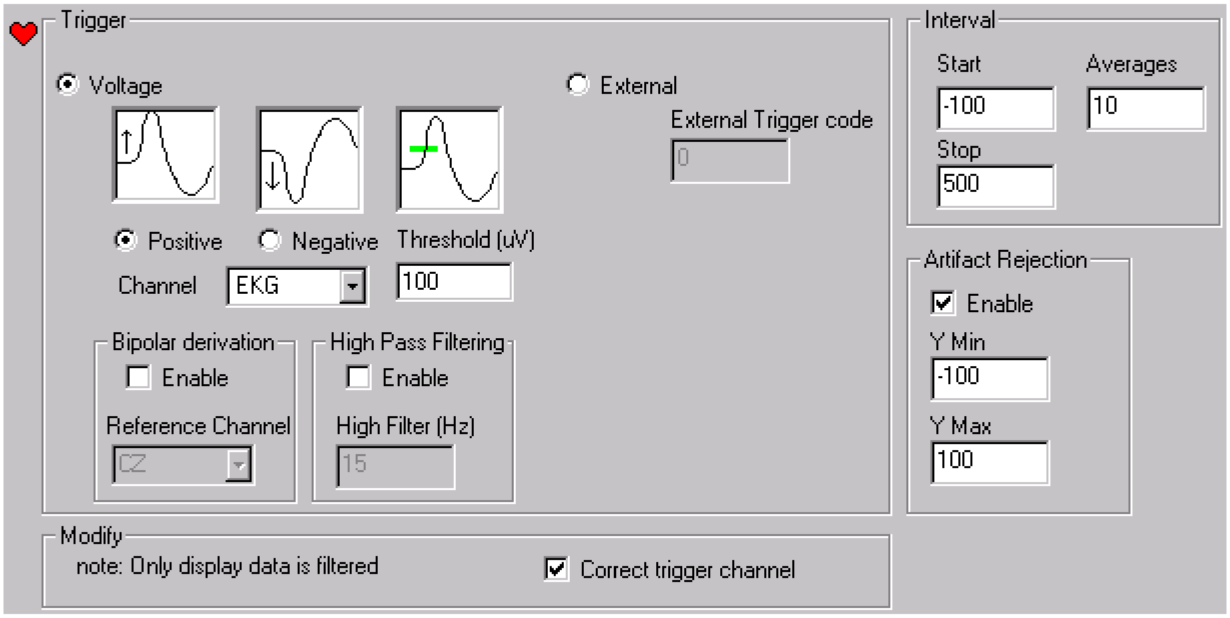
Note - Be sure to SAVE your setup files when have completed the settings. Then click OK to apply the current changes you have made if you wish to begin immediate acquisition. Clicking CANCEL will exit the Edit section without saving any changes you have made.

EKG Reduction. The EKG Reduction parameters are used to configure the online EKG Reduction routine (for CNT files only). It is intended for removal of ballistocardiogram (BKG) from recordings made in the MR bore, but may be used for routine heart beat removal also. The EKG Reduction procedure is somewhat different from the Blink Reduction routine. It uses a voltage threshold level for a selected channel (one where BKG/EKG was recorded, or at least prominent) to identify the artifact. A user-determined interval is created around that point to capture the artifact. You then select how many artifact intervals you want to be averaged. An averaged artifact is created for each channel. Once the average artifacts are created, they are subtracted per channel from each subsequent instance where the threshold is met. A rolling average is used to accommodate any changes in the artifact throughout the data file. The average will always be based on the N most recent artifacts (where N is the number you enter for Averages). In the offline analyses in EDIT, you have the option to use an existing AVG file that contains the averaged artifact, rather than the rolling average.

In practice, you will see the artifact in the beginning of the file until you reach the number of Averages that you selected. From there on, the artifact average will be subtracted from each channel. You can monitor the status bar (described below) to see when triggers are detected and new artifacts are being corrected. You may wish to allow some extra time in the beginning of the recording for the average artifact to be computed.

Note: The correction is applied to the displayed data only. To apply the correction permanently, use the EKG Reduction transform in EDIT.

From Edit, Overall Parameters, click the EKG Reduction tab. There are five sets of parameters: Trigger, Interval, Artifact Rejection, Modify, and Bipolar Trigger channel derivation.



Trigger. The artifact sweeps are initiated by triggers, and triggers are based upon a voltage threshold or a stimulus type code.

Voltage. With the Voltage option, an artifact sweep is initiated when the voltage in a designated channel exceeds a criterion you set. Select the Positive or Negative direction for the EKG artifact. Select the channel that you want to be monitored. Enter the threshold value. This value should be sufficiently large to differentiate the EKG artifact from other activity. The selection of the trigger point uses a peak detection algorithm. The waveform must cross the threshold two times, and the maximum (or minimum, depending on the settings) value during that interval is used for the placement of the trigger.

Bipolar Trigger channel derivation. In some situations you may want to create a derived *bipolar* trigger channel. Enable the option, and select a channel to be used for the reference. The reference channel will then be subtracted from the trigger channel.

High Pass Filtering. This option lets you apply a high pass filter to the artifact channel. Enable the option, enter a filter value, and frequencies below that value will be attenuated.

External. With the External option, an artifact sweep is initiated when a selected stimulus type code is received. Enable the option, and enter a desired type code. The event may come from STIM or from another external device that sends TTL pulses.

Note: If you are not using STIM, please see the section "Triggering SCAN from an

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external device", in Appendix B of the SCAN Vol. 1 manual - Installation and Orientation manual (or the Overview.pdf) - as well as the pinout diagrams at the beginning of the appendix (specifically the "Back of SCAN connector" diagram).

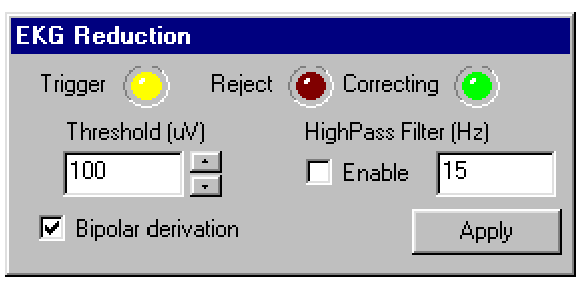
Interval. The interval is the section before and after the point at which the Trigger is placed. This should be long enough to encompass the entire artifact, but should not include the previous or subsequent EKG artifact. The Averages field determines how many artifact sweeps are included in the averaged artifact.

Artifact Rejection. The Artifact Rejection criteria are used to monitor the voltage in designated Artifact Rejection channels. When enabled, artifact detected by the Threshold criteria is NOT included in the average EKG artifact if the Min or Max criterion is exceeded within the interval specified for the trigger. This prevents artifacts in the designated artifact rejection channels from being included in the averaged EKG artifact.

Note: If the artifact is present with nearly equal amplitudes in the designated artifact rejection channels, you should use caution when enabling the Artifact Rejection criteria. EKG artifacts in these channels could result in the rejection of perfectly acceptable sweeps.

Modify. You have the option to correct the "trigger channel" (as specified in the Trigger section).

Click the  icon from the Toolbar to see the EKG Reduction status bar. The Trigger light will blink briefly when each threshold is met. The Reject light will blink when an artifact interval is being rejected. The Correcting light will come on when number of Averages has been reached (indicating that the correction is being applied when subsequent artifacts are detected).



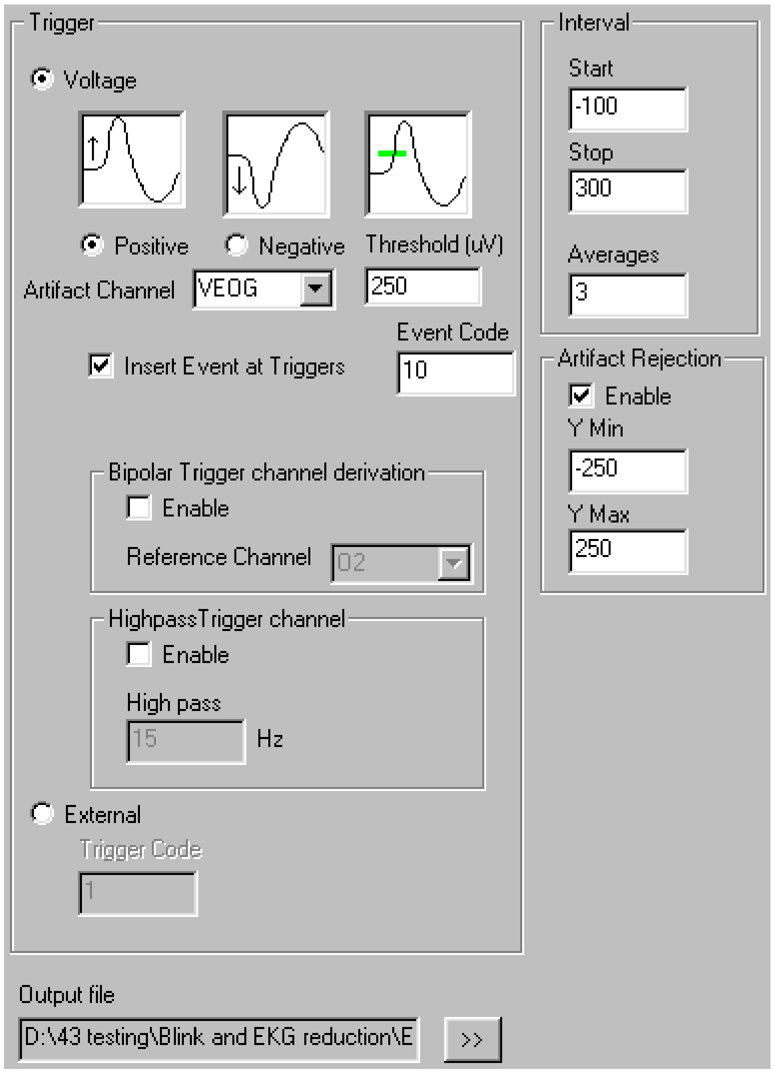
The Threshold level can be changed during acquisition (you will see a line displaying the threshold in the Single Window display). If you set the Threshold level by entering a number from the keyboard, you must click the Apply button to register the change. If you use the up and down arrows to adjust the Threshold, you do not need to click the Apply button. You may apply a High Pass Filter, if needed. Enter a number and click the Apply button to apply the filter. You may also toggle the Bipolar derivation on and off. If you enable the Bipolar derivation option, but did not select a reference channel from the EKG Reduction dialog screen, the program will select the first channel in the list as the reference (if you are using the bipolar reference option, be sure to select the reference from the EKG Reduction dialog screen first).

Why not use the blink routine to remove EKG, or the EKG routine to remove blinks? Blinks are volume conducted across channels, while EKG can show a time lag across regions (the time it takes for the pulse to reach different areas). The point-by-point subtraction used for blinks would be less accurate for removing EKG. On the other hand, EKG artifact does not vary greatly across time. Blink amplitude and morphology are far more variable. If they were removed with the EKG reduction procedure, the average artifact would vary quite a bit, and the subtraction would be less effective. However, the transmission coefficients (used in the Blink routine) are relatively stable despite the sequencing or blink variability. Therefore, the LDR approach is more effective for these artifacts.

Having the two routines allows you to run both of them at the same time, if desired. This would let you remove ballistocardiogram and blink artifact simultaneously.

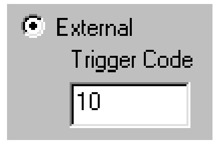
Offline Artifact Reduction (in EDIT)

Blink Noise Reduction (CNT) - The Blink Reduction transform in EDIT is nearly the same in operation as it is online. There are two new options. The dialog screen is shown below.



Trigger. In the trigger section, offline, you have the option to insert events at the points where the threshold is met (and what number you want to use for the event code).

External. Additionally, you have the option to use stimulus events in the data file to trigger the averaging. For example, you could use the Voltage Threshold transform to place triggers in the file for the blinks, and then use the triggers to identify the blinks. To use the option, click the External button and enter the desired Trigger Code, such as "10". Artifact averaging will be initiated when type 10 events are encountered in the file.



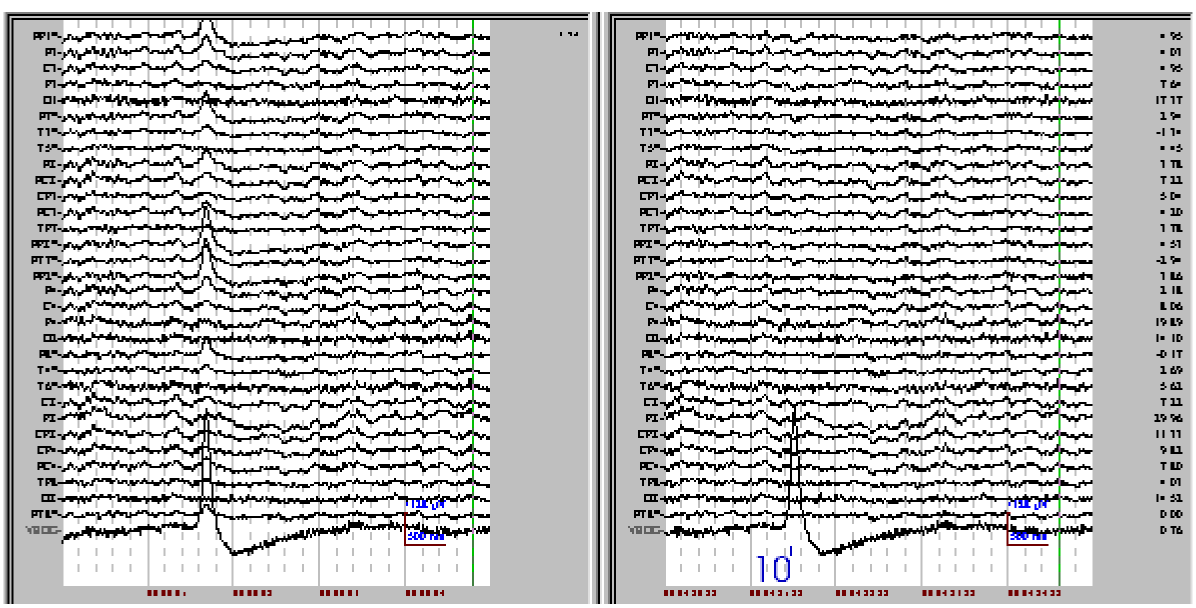
When the External option is selected, the Voltage parameter fields are grayed out.

Output file. Click the Browse button to access the standard Save As utility window to save the CNT file.

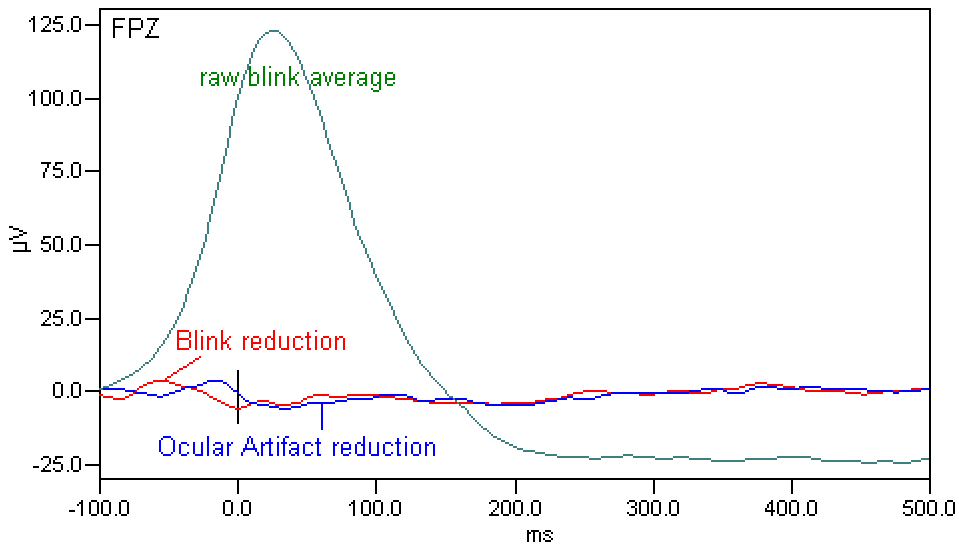
Using Blink Reduction

Removing VEOG blinks. With blinks, ideally, you should record a long enough section at the beginning of the CNT file to create the averaged artifact. If, however, you don't have that blink section, you can always append the CNT file to a copy of itself, then use part of the first half of the created to compute the average artifact, and the correction will be applied throughout the rest of the file (original and copy). Then retrieve the corrected CNT file, and use Mark Block / Save Block to save only the last half of the file (from the SS event on).

In the example below, we used a 250uV threshold, from -100 to 300ms, with 5 sweeps averaged. The blink reduction routine did a good job of removing the blinks. Artifact Rejection was set for +/-250 uVs.

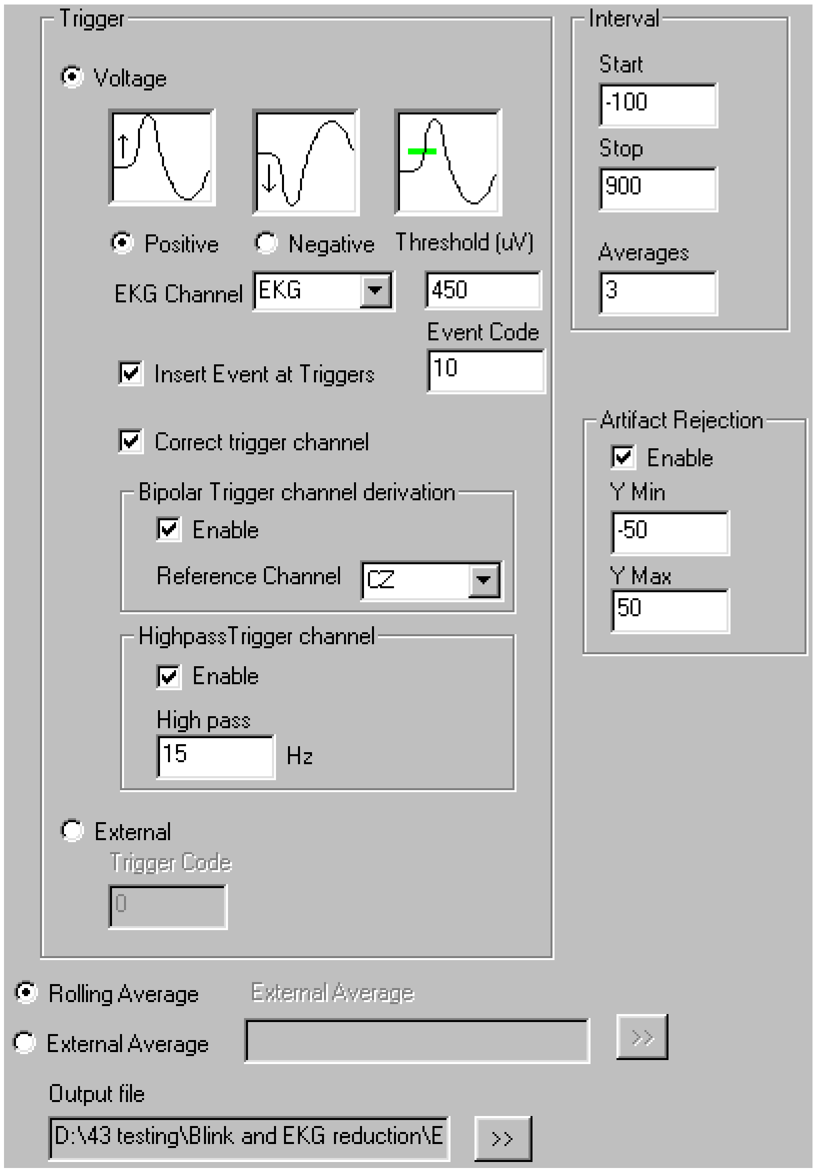


Does this routine work better than the Ocular Artifact Reduction (OAR) transform? We analyzed the same original file using the OAR transform, and used the Voltage Threshold transform to insert events at the 250 uV point (from the VEOG channel). This allowed us to compare the averaged blink results between methods.



The results (from FPZ) show very little difference between methods, as expected, and both methods were very effective in removing the blinks.

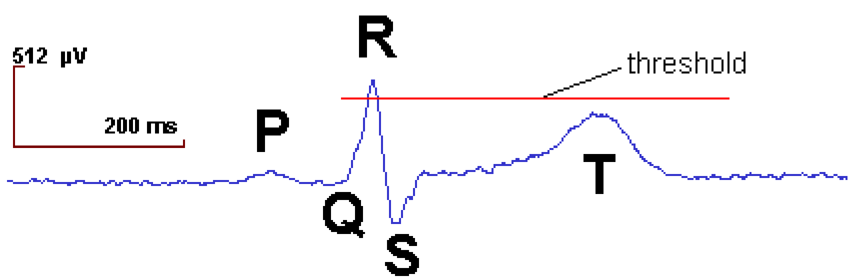
EKG Noise Reduction (CNT) - The EKG Reduction parameters in EDIT function very much like those described above in the online section. There are a couple of differences that you should note. These are described below.



Trigger. In the trigger section, offline, you have the option to insert events at the points where the threshold is met (and what number you want to use for the event code).

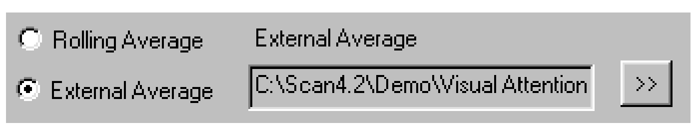
When the External option is selected, the Voltage parameter fields are grayed out.

Interval Start/Stop times. While these operate basically the same offline as online, there is a difference in the way the interval functions. Online, it operates like a refractory period. That is, any secondary triggers that might occur during the period will be ignored. This is not the case offline. The offline routine was made to be flexible as possible, and removing the "refractory" aspect decreases the discontinuity effect that may be present at the start and stop times. However, because of that, *you can get secondary triggers within the interval*. For example, if the T wave exceeds the threshold, even though it is within the inteval, it will create a trigger itself, and that sweep will be added to the average, which will disort the average and degrade the effectiveness of the reduction. You should therefore use precision when setting the threshold. It should be a value between the R and T waves.



Artifact Rejection. There is one slight difference with offline artifact rejection with EKG Reduction. You will see a trigger appear during the rejected interval; however, it will *not* be included in the average and the artifact surrounding it will *not* be corrected..

Rolling / External Average. With the EKG artifact reduction routine, offline, you have the option to use an existing AVG file rather than to use a rolling average.

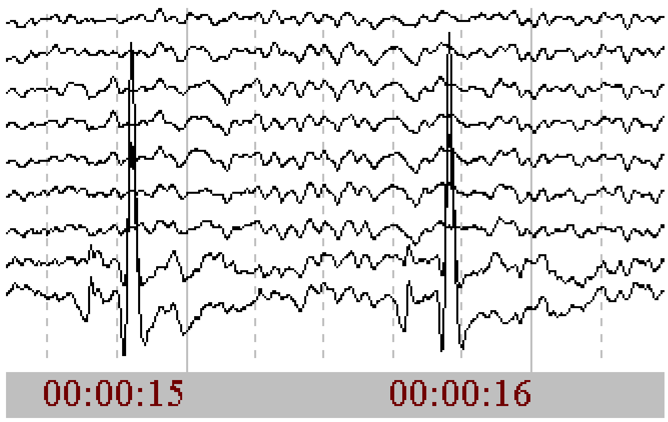


For example, you might use the Voltage Threshold transform to place events automatically at the peak points in the HB artifact, then epoch and average those sweeps to form an average HB artifact. Select that file using the External Average option, and that average will be subtracted from each HB artifact that is encountered.

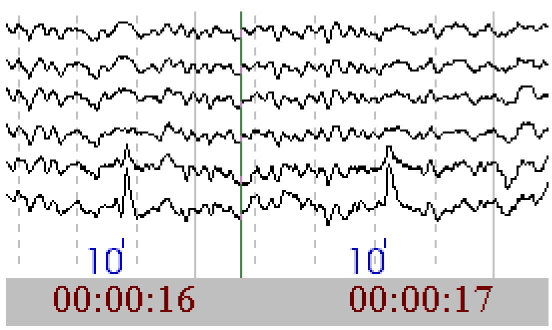
When you select the External Average option, the Interval fields will be grayed out.

Output file. Click the Browse button to access the standard Save As utility window to save the new CNT file.

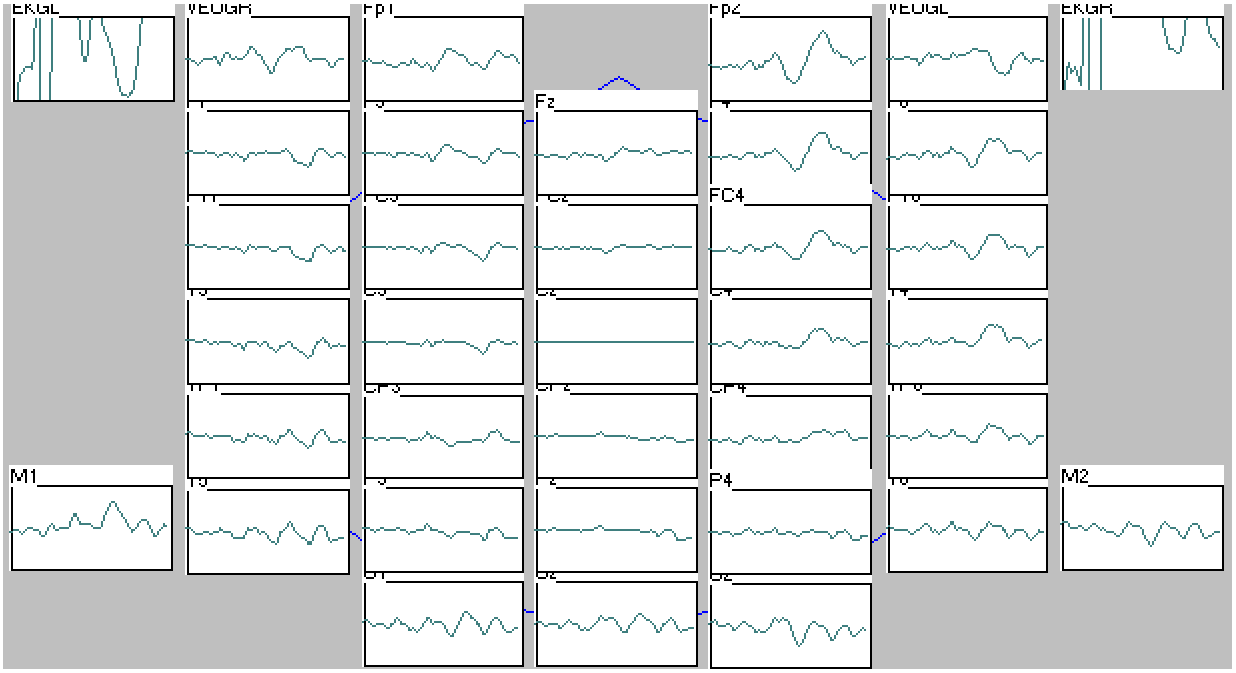
Removing Heart Beat artifact. In the first example, we will use the EKG Noise Reduction routine to remove basic heart beat artifact. The figure below shows a large heart beat signal.



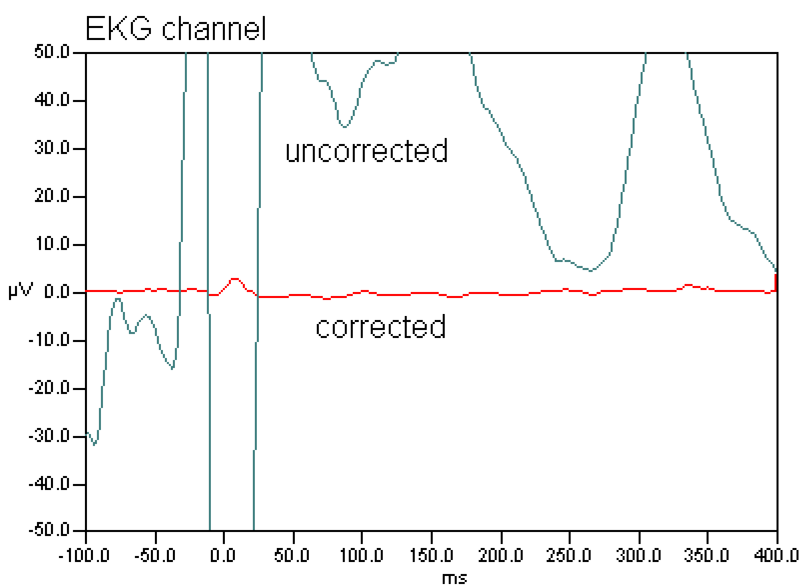
The pulse exceeds -500uVs, so we will use a Negative threshold of -500. The main parts of the pulse are from about 200ms before to about 400ms after the peak, so we will use those values for the Start and Stop times. We will average 5 sweeps, correct the trigger channel, and insert a type code of 10 where the trigger is placed. (Alternatively, we could create an AVG file with the average heart beat artifact, and use the External Average option to subtract that file from each subsequent artifact, rather than the rolling average). Artifact Rejection is not needed in this file, and is disabled. The results are shown below (for two corrected heart beats).



For demonstration sake, we used the Voltage Threshold transform to place events at the heart beat peaks, then created epochs from -100 to 400ms around the peaks, and averaged them. The *uncorrected* heart beat artifact is obvious in many channels.



We then averaged the sweeps *after* the EKG Reduction routine was applied, using the events that were inserted in the process. The HB artifact was greatly reduced, if not removed altogether.



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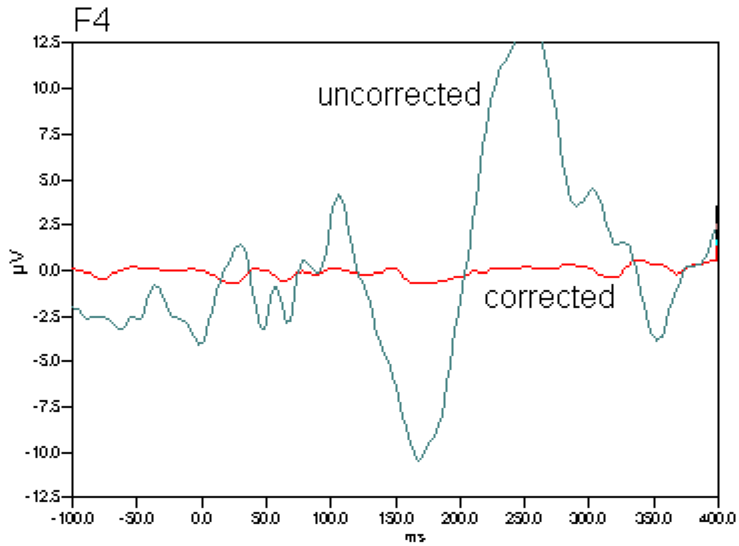
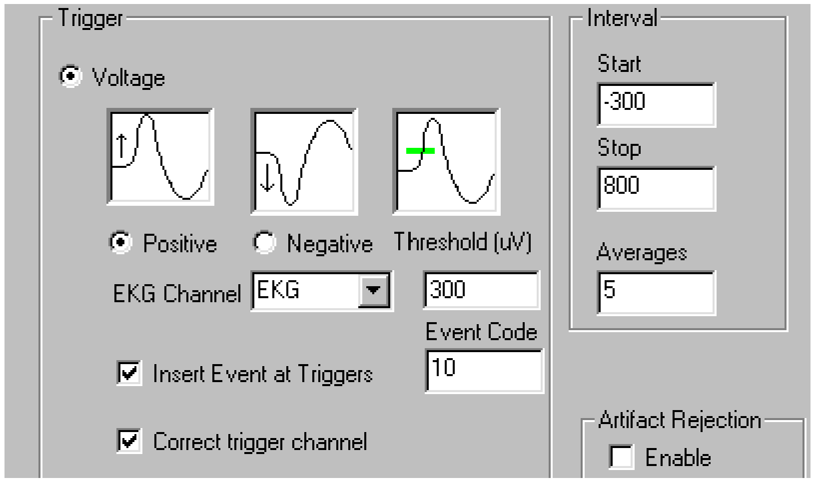


Note: Alternatively, you could take the averaged HB artifact created above, and use it with the External Average option (rather than the Rolling Average), and reduce the artifact that way.

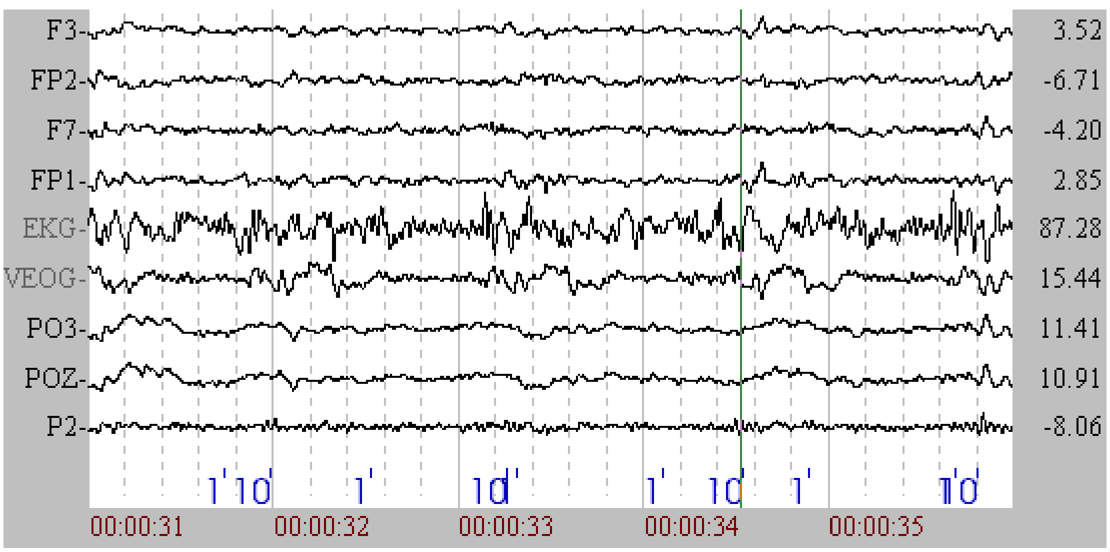
Removing BKG artifact. In the next sample data file below, click AEPs from within the MR bore were recorded every 800 ms (the 1's in the subsequent data figure below). There is considerable BKG artifact that we will reduce using the EKG routine. To determine the settings to use, first examine the BKG artifact to determine the amplitude of the artifact, and the Start and Stop time points to use.

Each artifact has a peak of approximately 400-500 uVs. If we set the threshold for 300 uVs, we should get reliable trigger placements in each artifact. The complete artifact will be captured if we select a Start time of -300ms and a Stop time of about 800ms. We'll select 5 Averages, correct the artifact channel, place an event type code of 10 at each trigger, and disable the

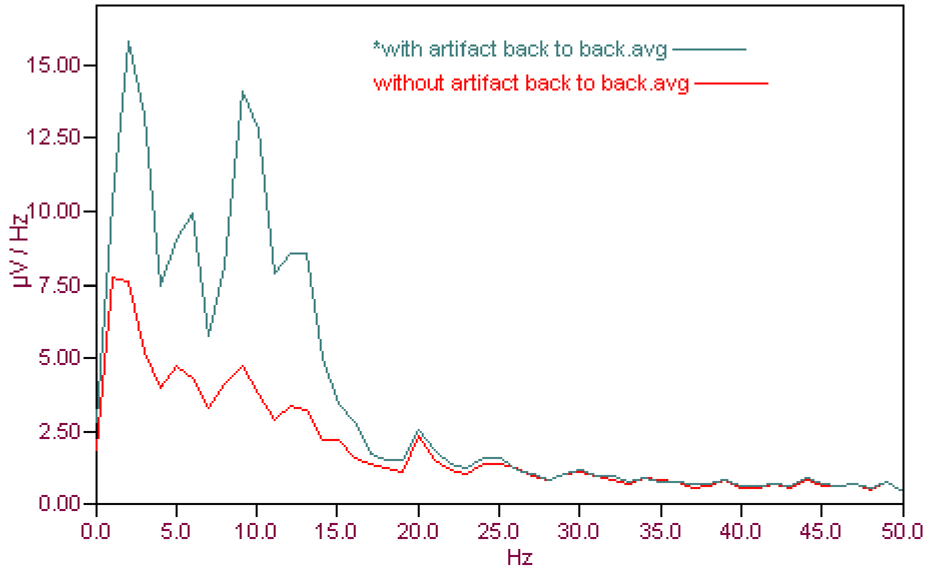
Artifact Rejection option. The parameters appear as follows (seetings not shown were disabled; a rolling average was used):



The results are shown below (remember to advance into the new file beyond the first 5 artifacts to see the effect of the correction). The scale sensitivity is increased in this figure as compared to the one above; see the voltage differences in the right hand column.

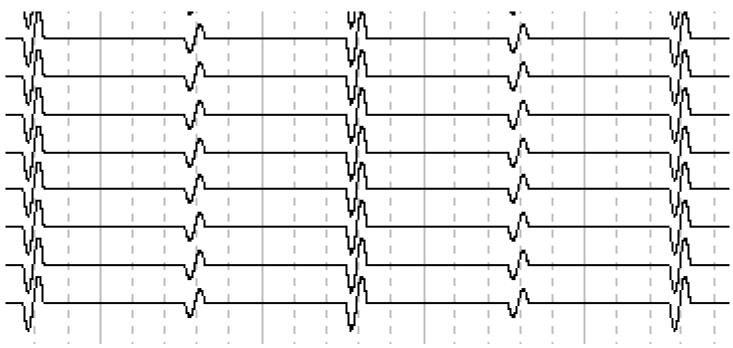


The BKG artifact has been greatly reduced. To see the difference more dramatically, we will create back to back sweeps from the file, average the sweeps in the frequency domain, and compare the FFTs. There is a large decrease in the slower frequencies associated with the BKG artifact removal.



Some Differences Between EKG and Blink Reduction Routines

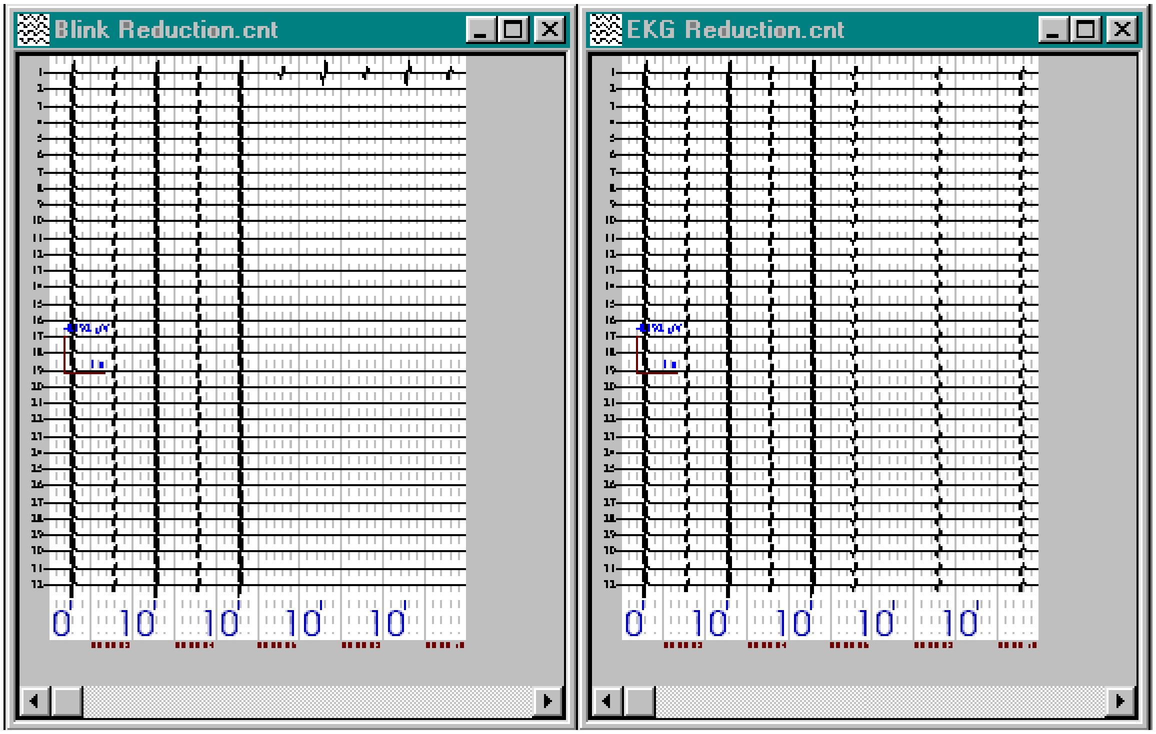
The basic differences between the EKG and Blink Reduction routines have been described above. The effects of these differences may not be so apparent without an example. We will use a simulated data file with a series of alternating amplitude, single cycle, sine waves.



The larger waves are approximately +/- 2700 uVs; the smaller ones are approximately +/- 1350 uVs. We will apply the EKG and Blink Reduction transforms using the following parameters:

Trigger: Positive, Channel 1, Threshold 2000, Correct trigger channel enabled, Insert "10" events
Interval: Start -100, Stop 250, Averages 3
Artifact Rejection: Disabled

With these parameters, the larger waves will be used to create the average artifact (using 3 sweeps), and trigger type codes of "10" will be inserted at the peaks of the larger waves. The resulting CNT files are shown:



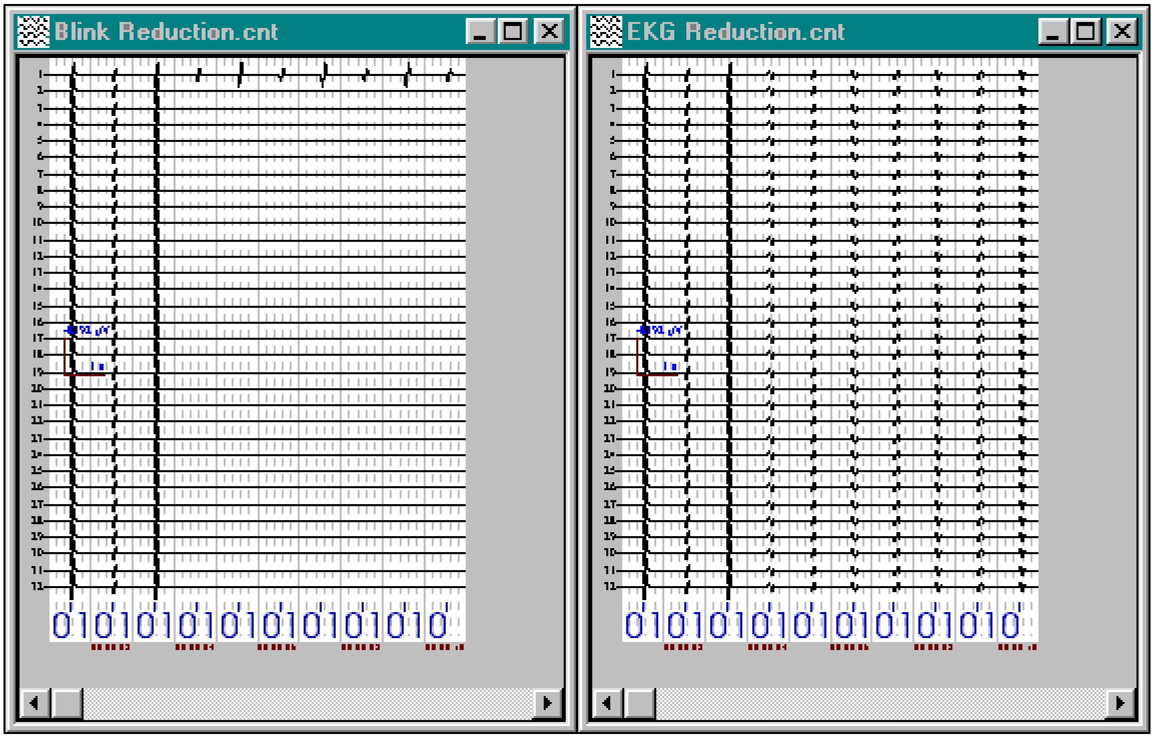
In the Blink Reduction.cnt file, note that the first channel (the trigger channel) is not corrected, and that all of the artifact (large and small waves) is removed from the remaining channels. This is because, like the Ocular Artifact Reduction transform, the Blink Reduction transform creates an internal LDR file Linear Derivation), which contains the transmission coefficients for each channel. A proportion of the voltage in the artifact channel is subtracted from each corresponding data point in the EEG channels. In this file, that proportion is always 1.0, and the channels are all the same, so whatever voltage is in the trigger channel is subtracted completely from each of the other channels. The results are flat lines (complete artifact subtraction). The artifact channel itself is not corrected with the LDR procedure.

In contrast, the EKG Reduction.cnt file has only the larger wave subtracted, and the subtraction occurs in the trigger channel as well. The first three accepted artifacts are averaged together (for each channel), and the average is then subtracted from the next interval in which the threshold is met. All of the large waves are the same, so the average artifact is identical to each single large wave, and the subtraction results in a flat line. Since the smaller waves do not reach the threshold criteria, they are not affected in the correction process.

Next, we recompute the analyses using the following parameters.

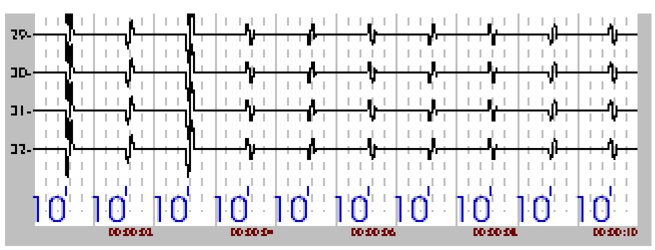
Trigger: Positive, Channel 1, Threshold 1000, Correct trigger channel enabled, Insert "10" events
Interval: Start -100, Stop 250, Averages 3
Artifact Rejection: Disabled

These parameters will cause triggers to be placed at all waves, large and small.



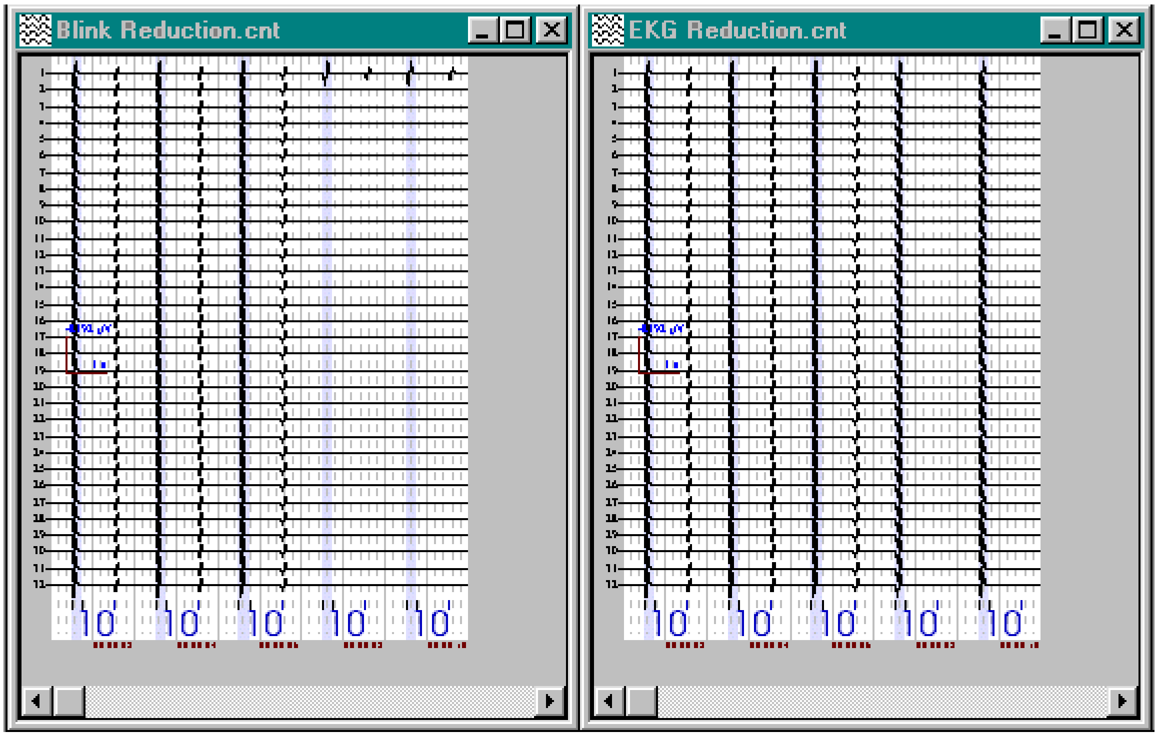
The results in the Blink Reduction.cnt file are the same as in the previous file. All of the artifact was removed, except for the trigger channel. Again, this is because the LDR file is applied throughout the remaining file, on a point-by-point basis. The weights are again 1.0, the channels are all the same, so the subtraction is perfect, regardless of whether the artifact is large or small.

In the EKG Reduction.cnt file, none of the waves are subtracted completely. Let's take a closer look at the results.



The first three waves - two large ones and one small one - are averaged together to form the averaged artifact. The amplitude of that average is greater than any of the smaller waves in the file. The next trigger occurs at a smaller wave, and it is subtracted from the average artifact. The result, in this file, is a small wave that is inverted with respect to the other waves. Now, the average artifact is "rolling"; that is, it is always recomputed for the three most recently detected artifacts. If you average the second, third and fourth artifacts, and then subtract that from the fifth artifact that is detected, you get a wave that is the same amplitude as the fourth wave, but inverted. Continuing this process throughout the data file, you will wind up with a series of alternating, inverting, smaller wave forms, as displayed. In reality, the blink artifacts will be far more similar to each other in terms of amplitude and phase than these simulated waves, and the artifact removal process will be much more effective, as we have shown with real data files elsewhere in this manual.

To illustrate another difference between reduction methods, we used the Voltage Threshold transform to automatically reject the intervals containing the larger waves. We then reanalyzed the data using the same parameters as in the last example.



In the Blink Reduction.cnt file, the results are the same as in the prior examples; all of the artifacts are removed except for those in the trigger channel.

In the EKG Reduction.cnt file, the artifacts in the rejected segments remain. Because the sections including the large waves are rejected, the threshold criterion is not met, and no triggers are inserted. Therefore, the large waves are not detected, they are not included in the averaged artifact, and the averaged artifact is not subtracted from them.

Lastly, we will look at the difference between methods if you use the Artifact Rejection option, with parameters set as follows:

Trigger: Positive, Channel 1, Threshold 1000, Correct trigger channel enabled, Insert "10" events
Interval: Start -100, Stop 250, Averages 3
Artifact Rejection: Enabled, with +/- 1500

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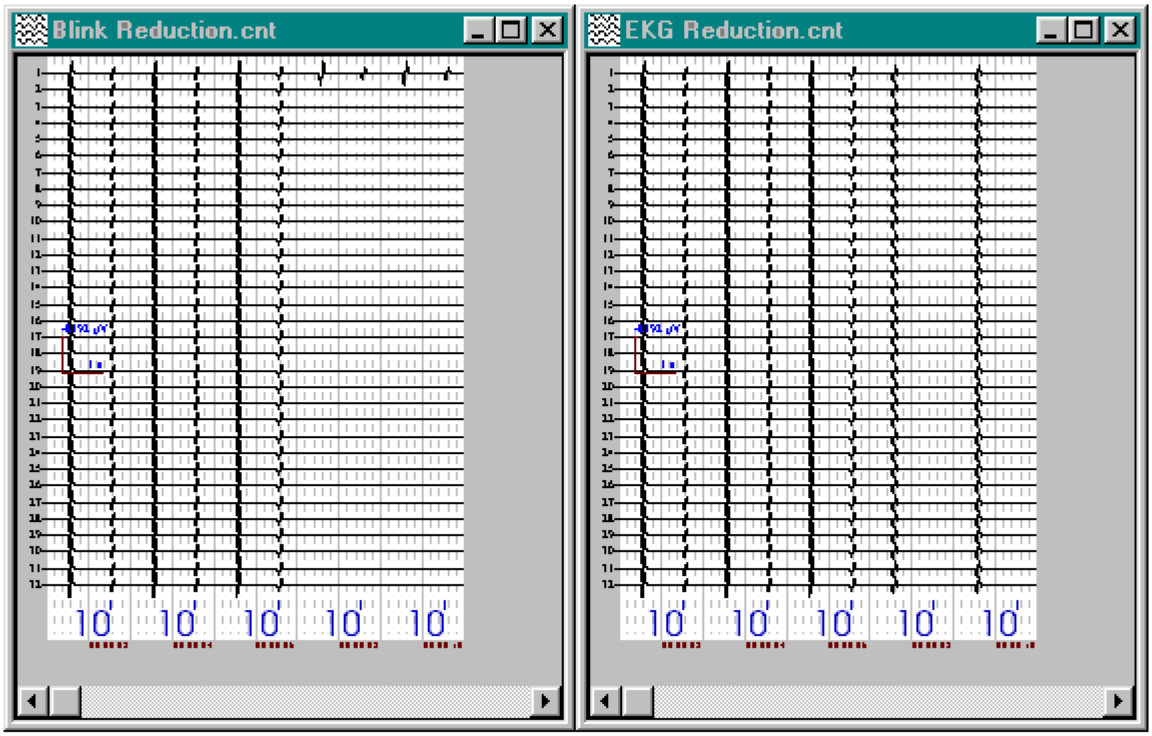
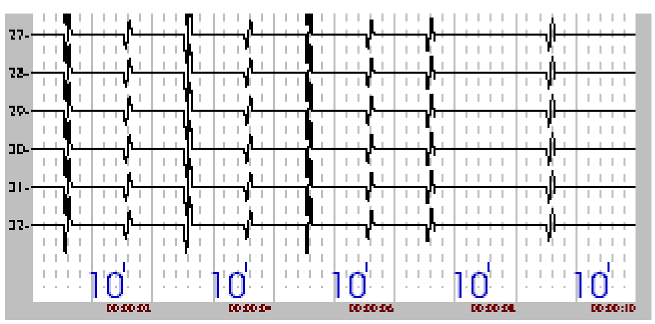
These Artifact Rejection criteria will exclude the large waves and include the small waves. The resulting CNT files are shown below.



As before, the Blink Reduction.cnt file has all of the artifacts subtracted except for those in the trigger channel (for the same reasons as described above).

In the EKG Reduction.cnt file (enlarged below), the small waves have been subtracted and the large waves remain, although attenuated.



The way the Artifact Rejection option works is as follows. If the voltage in any channel exceeds the Artifact Rejection criteria, at the time point where the Threshold criteria is met in the Trigger channel, then no trigger is placed (the artifact is rejected). In this example, we intentionally chose settings to exclude the large waves, so they are not included in the averaged artifact. However, the averaged artifact (based on the small waves only) is subtracted from the larger waves, when they are detected (even though no trigger is inserted). In reality, this is something you will not often encounter. In this file, the amplitude of the large wave is the same in all channels. With real data files, the trigger channel is typically the one that has the largest amplitude of the artifact. The Artifact Rejection criteria you select should be chosen to exclude lesser amplitude artifacts (such as, for example, DC drifting) than those you are trying to remove. Still, care should be exercised when using the Artifact Rejection option. If inappropriate settings are used, you could inadvertently include the artifacts that you are trying to remove.

Some Strategies for Using the Artifact Reduction Routines

The examples below use files recorded outside and inside the MR chamber. We have included some analysis steps to illustrate the effectiveness of the reduction routines. These are examples of strategies that may be useful when you need to validate your results for publication.

As mentioned 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 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.

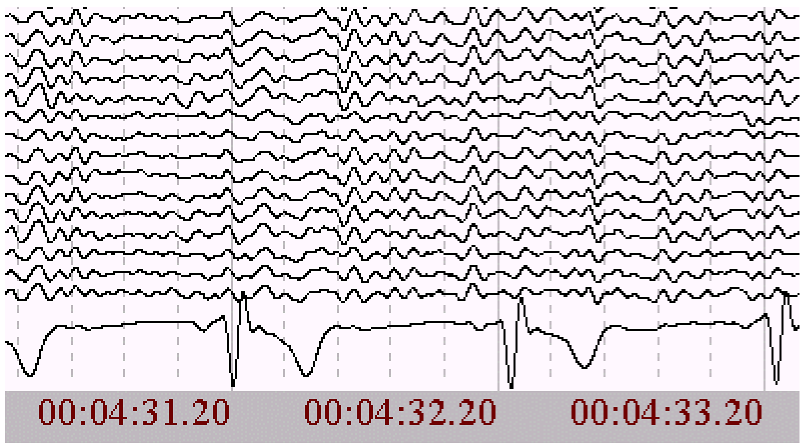
We will create three files for comparison with data recorded in the bore, or to verify that the artifact reduction techniques have been effective:

- An FFT power spectrum of the averaged resting EEG sweeps.
- An average of the evoked responses to the auditory stimuli.
- An average EKG artifact after the heartbeat artifact has been minimized.

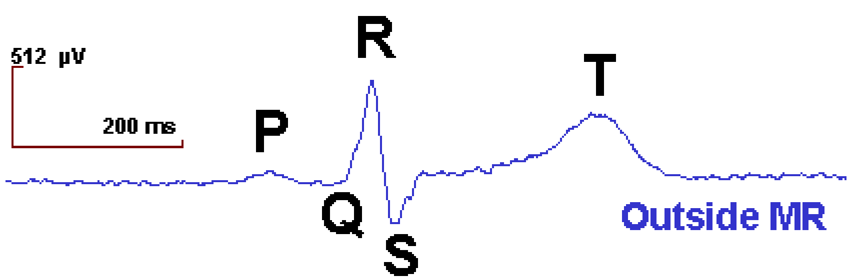
First we will perform some preliminary processing steps, including rejecting bad sections in the file, filtering the data, removing the heartbeat artifact, and removing blink artifact. At that point, the CNT file will be epoched in various ways to yield the average files described above.

1. Retrieve the CNT file. Look through the file to get a feel for the type and extent of artifact, and any obviously "bad" sections. Reject any grossly "bad" sections in the file, using Mark Block / Reject Block.

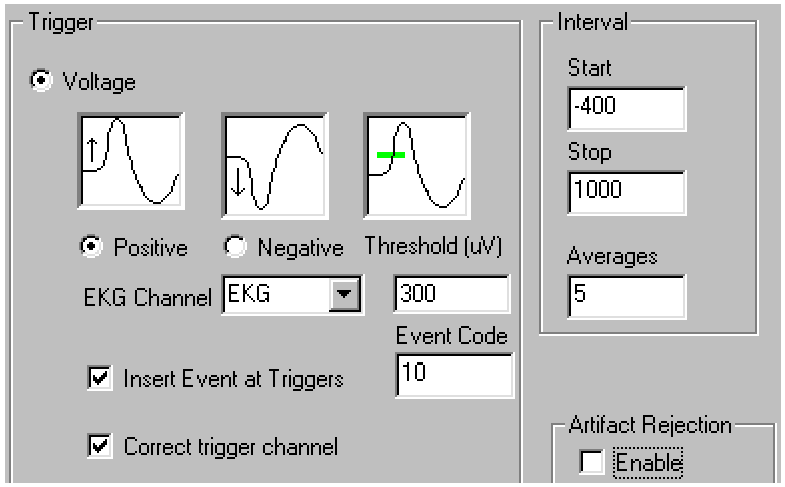
2. Filtering. If you have recorded in DC mode, but do not really care about the slowest potentials, then you should filter the data with a high pass filter (we are using .5Hz). Unfortunately, artifact from the MR scanner is quite broadband, overlapping substantially with the frequency range of interest for many EEG/ERP applications. We have sometimes encountered MR artifact at about 28-30Hz. If this 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.



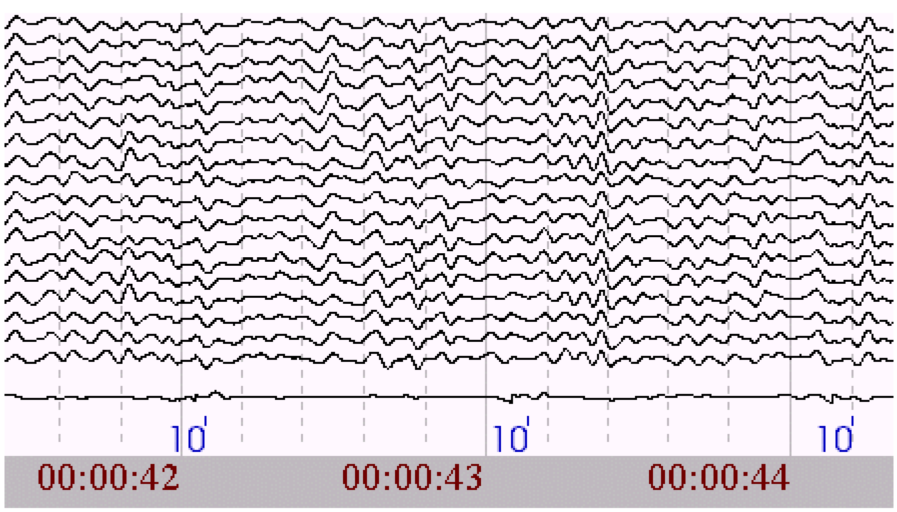
3. Removing the EKG. Since we will be using the EKG Noise Reduction transform with the files recorded in the MR, we will apply it to this file as well. To use it, you will need to measure a prominent, recurring peak to determine what to use for the voltage Threshold, as well as the time between those peaks to determine the Stop time (or refractory period). In our demo file, the main peak (the R wave) is about 400 uVs or larger, and the inter-peak-interval is just over one second. Therefore we will use the settings shown below (settings not shown were disabled; a rolling average was used).



An alternative method is to use the Voltage Transform to place event marks at the peak of the R wave, and the epoch the CNT file about the events to create sweeps with just the EKG artifact. The sweeps could then be averaged, resulting in an AVG file. That file could be used with the External Average option.

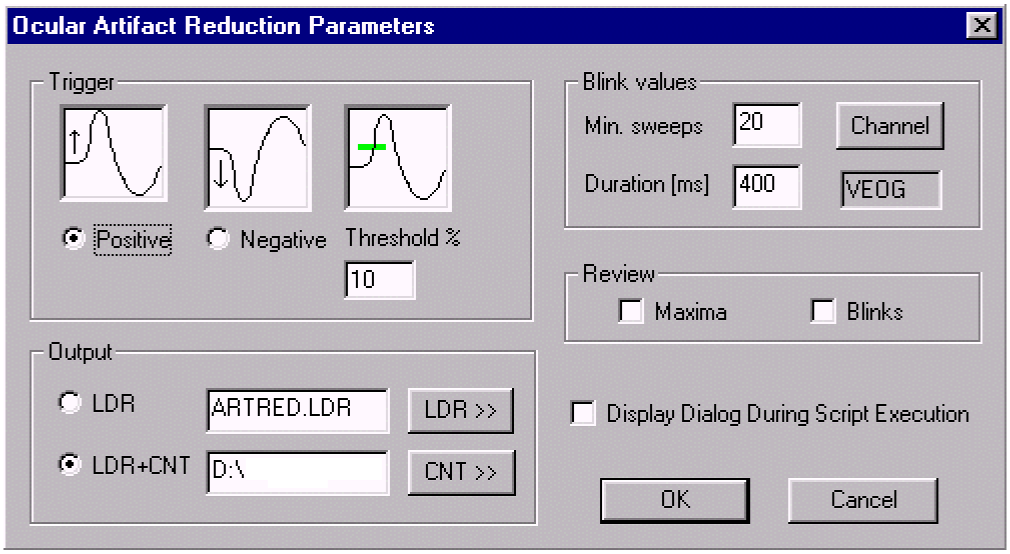
The difference is that the averaged artifact would be based on all artifact sweeps, as opposed to the 5 sweeps we had selected for the rolling average.

The file at this point appears as shown. Note the effectiveness of the heartbeat removal in the EKG channel (as compared to the file above).

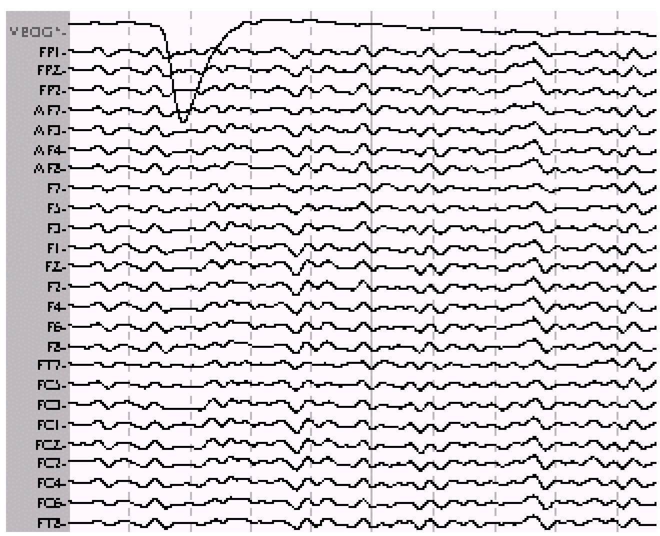


4. Removing the VEOG artifact. There are several ways to remove the blink artifact: the Ocular Artifact Reduction (OAR) routine, the Blink Reduction routine, or by using the Spatial Filter / Spatial SVD approach. For this file, we will use the regular Ocular

Artifact Reduction transform. We could have just as easily used the Blink Reduction routine and obtained very similar results.

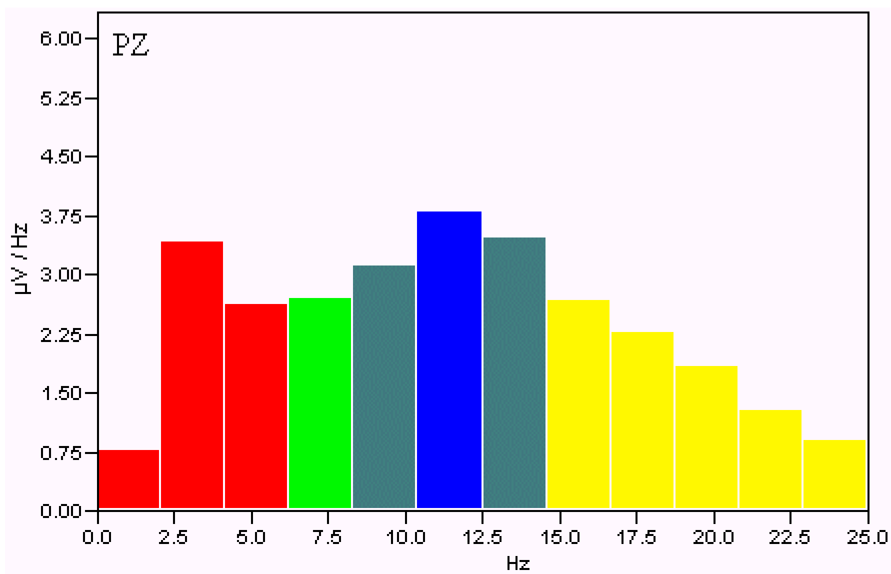


Below is one example of the blink corrected data (OAR does not correct the artifact channel).



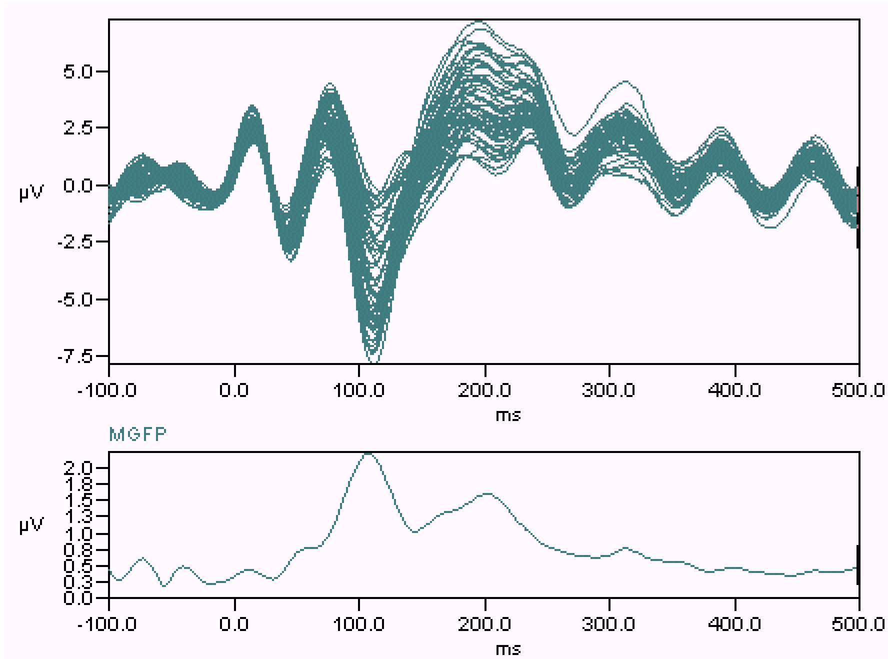
5. Epoch the file. You should make sure that the file contains all good sections, using Mark Block / Reject Block to reject any bad sections. Then epoch the file. For demonstration purposes, we will do this three ways: a) back-to-back in preparation for an FFT of the resting EEG, b) create epochs around 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.

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.



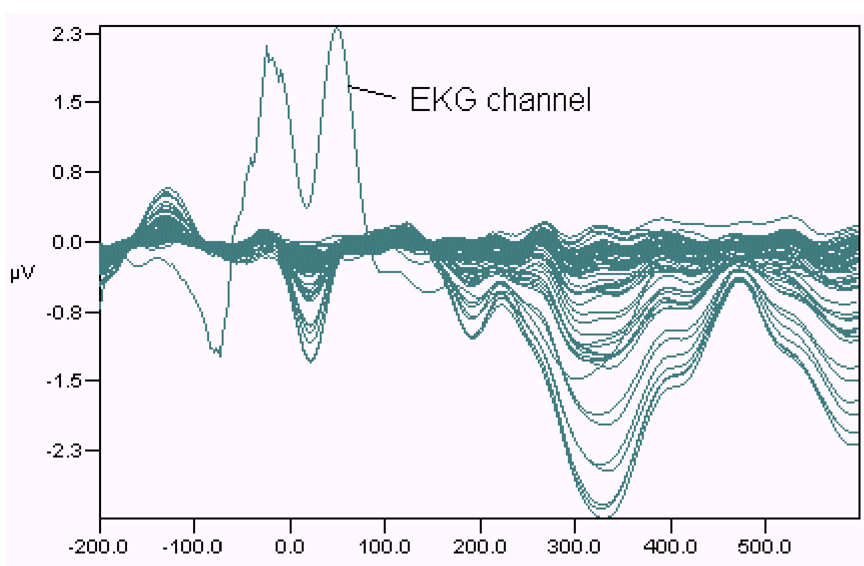
This is the best representative of the subject's resting EEG power spectrum. We will compare this to the resting EEG spectrum recorded in the bore.

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 stimulus 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.

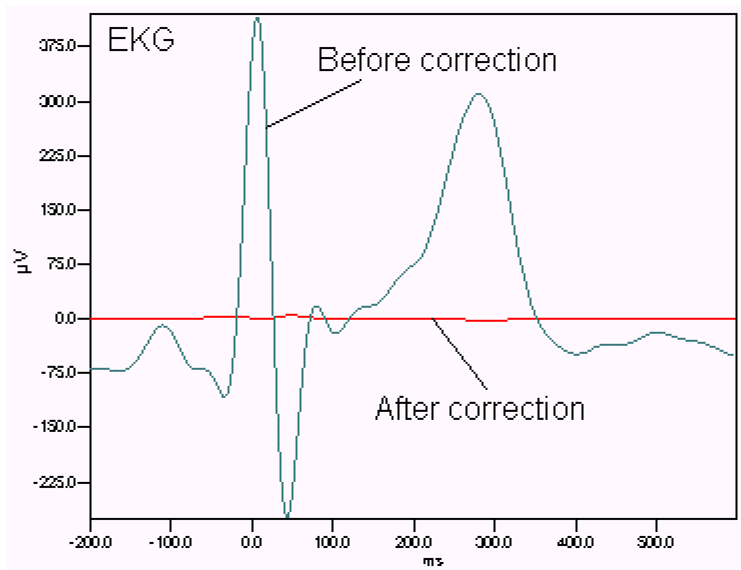


This is the best representation of the "clean" EPs and it will be used for comparison to those recorded in the bore.

c. Averaged EKG artifact. Lastly, for demonstration purposes, we will create epochs around the triggers inserted by the EKG Noise Reduction routine. This will be used to 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 *corrected* sweeps is shown below.



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. The following figure shows the average heart beat artifact before and after the correction.



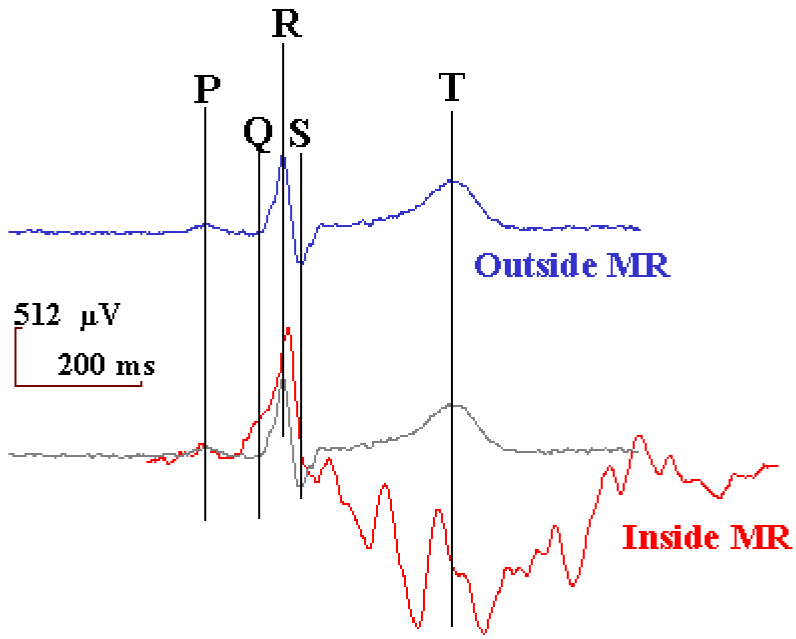
B. **Recordings inside the magnet**. In the demo file we are using, stimuli were presented between the MR sequences, but not during them. There are several meaningful comparisons to make:

- The ballistocardiogram (BKG) recorded inside 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.

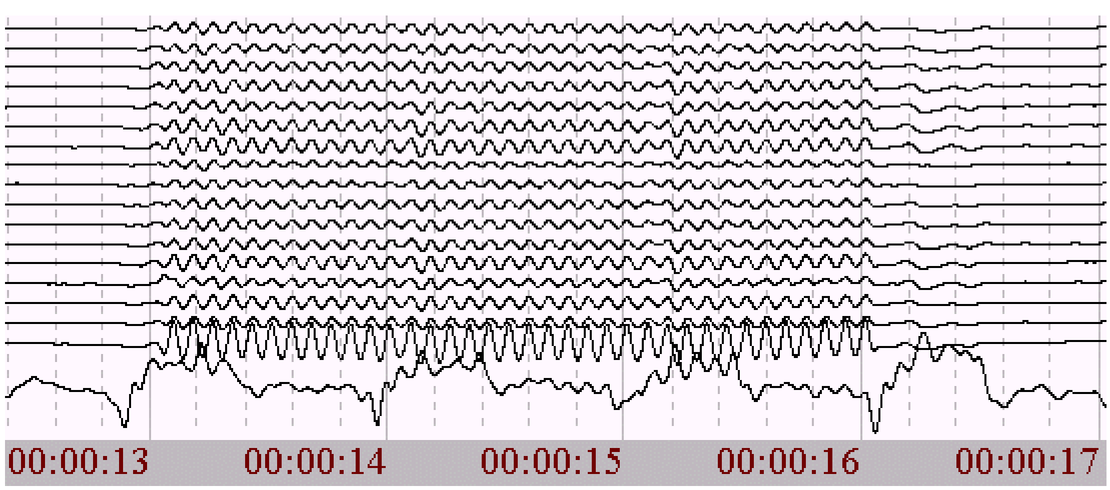
As before, you should go through the file first and reject any bad sections using Mark Block / Reject Block. Then Filter the file using the same filter settings used in the file recorded outside the chamber. There was virtually no VEOG artifact in this file, so we did not use the Ocular Artifact Reduction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

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 EKG Noise 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 EKG routine, however, a sliding window is used to average and re-average the BKG 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.



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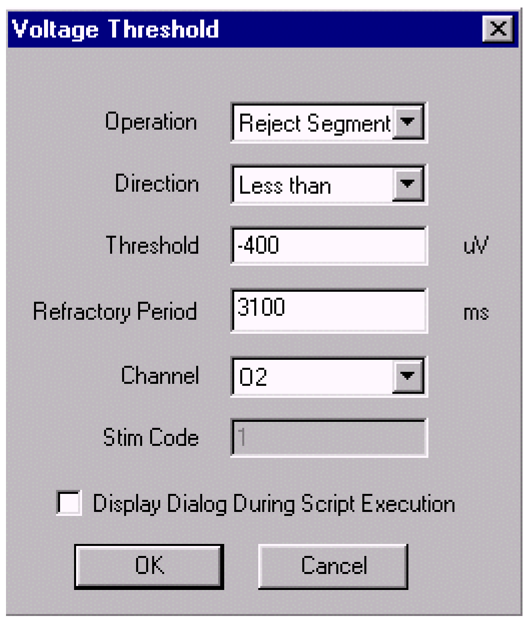
In other files we have seen, the BKG can be completely distorted during the MR sequence. The point is: in either case, you do not want to include the MR sequences in the EKG artifact reduction routine. The sliding average containing samples during the MR sequence will be distorted, and the BKG instances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

There are a couple of ways to deal with this. You could create new CNT files that have no MR sequences in them, or 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 EKG 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 EKG Noise 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:



The MR sections are all rejected automatically. We can then apply the EKG Noise 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.

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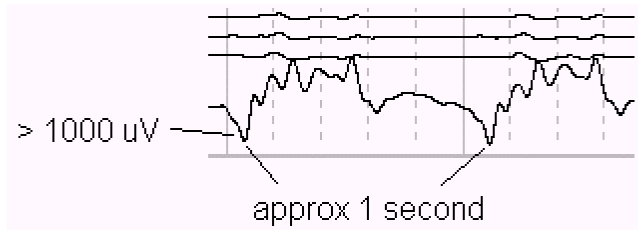
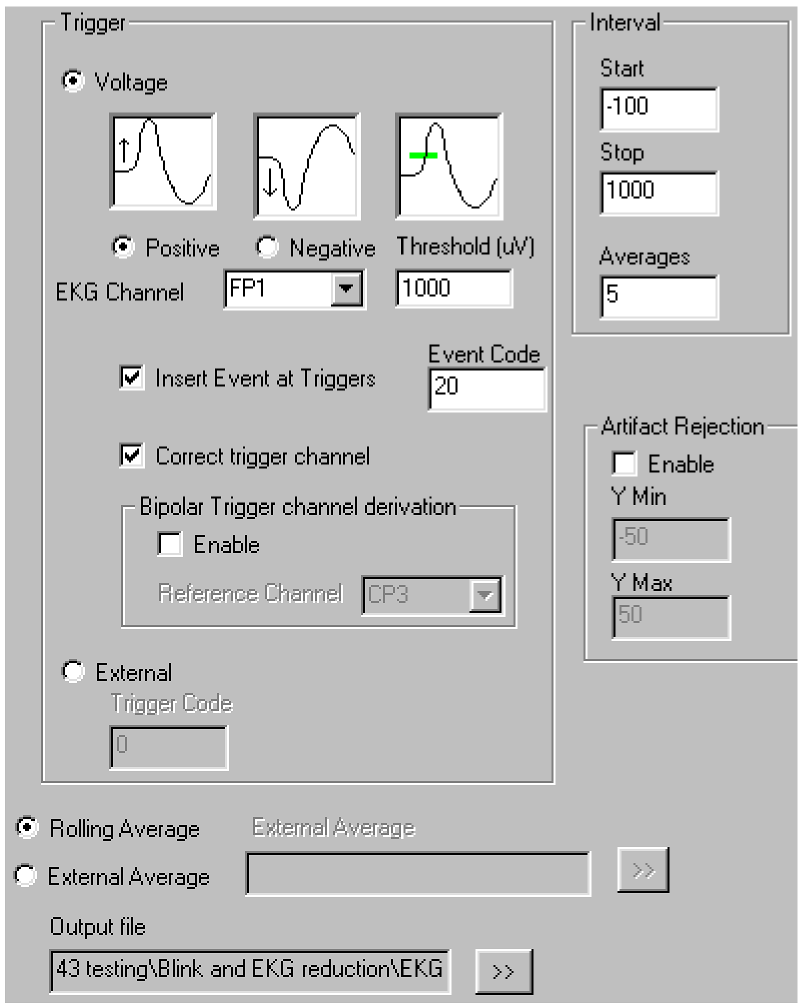
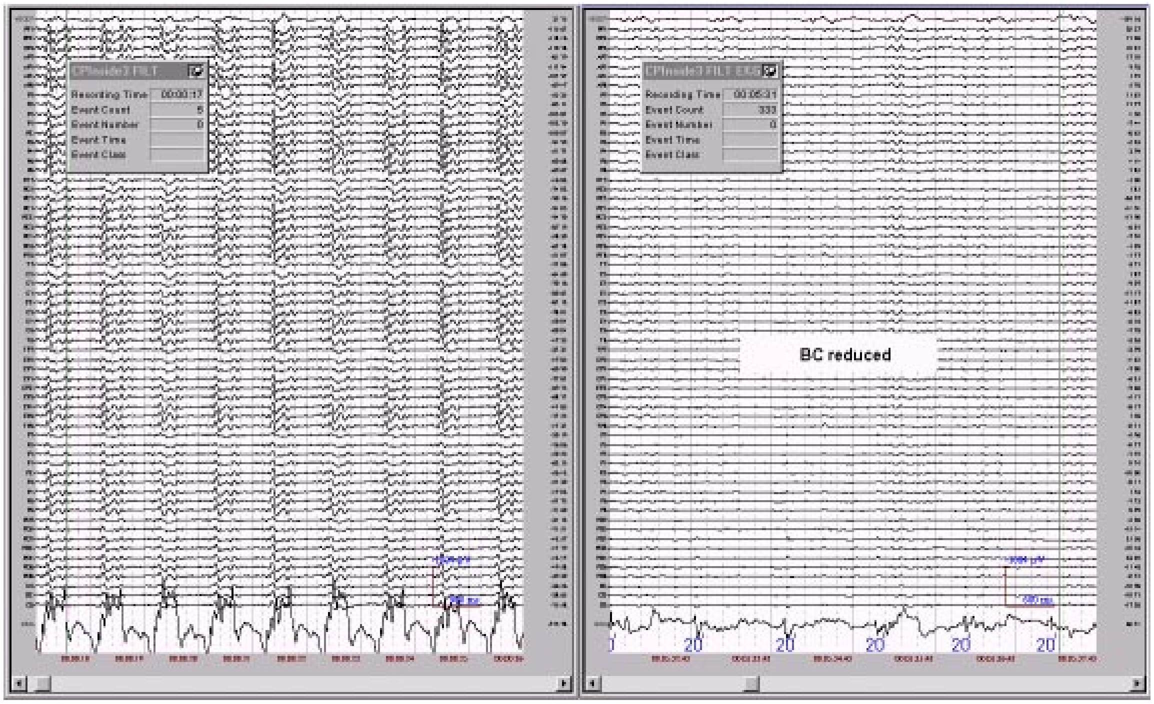


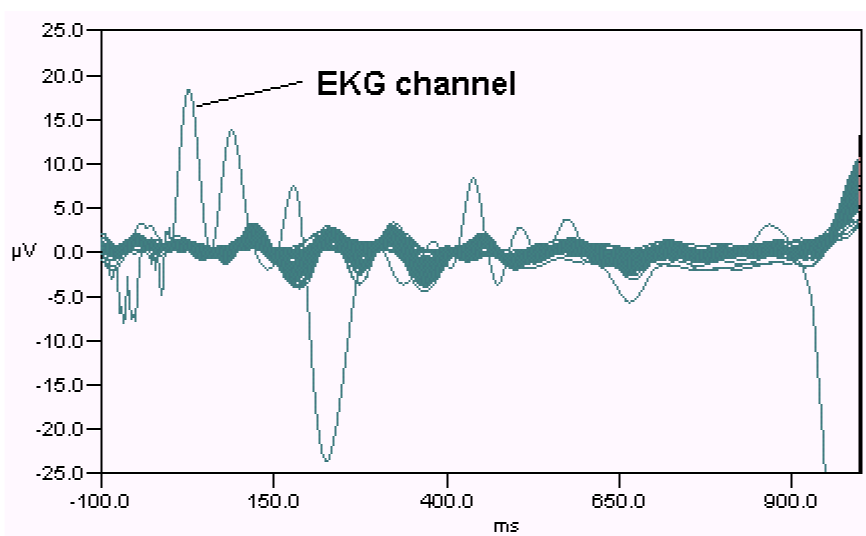
We therefore use the following settings in the EKG Reduction routine.



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

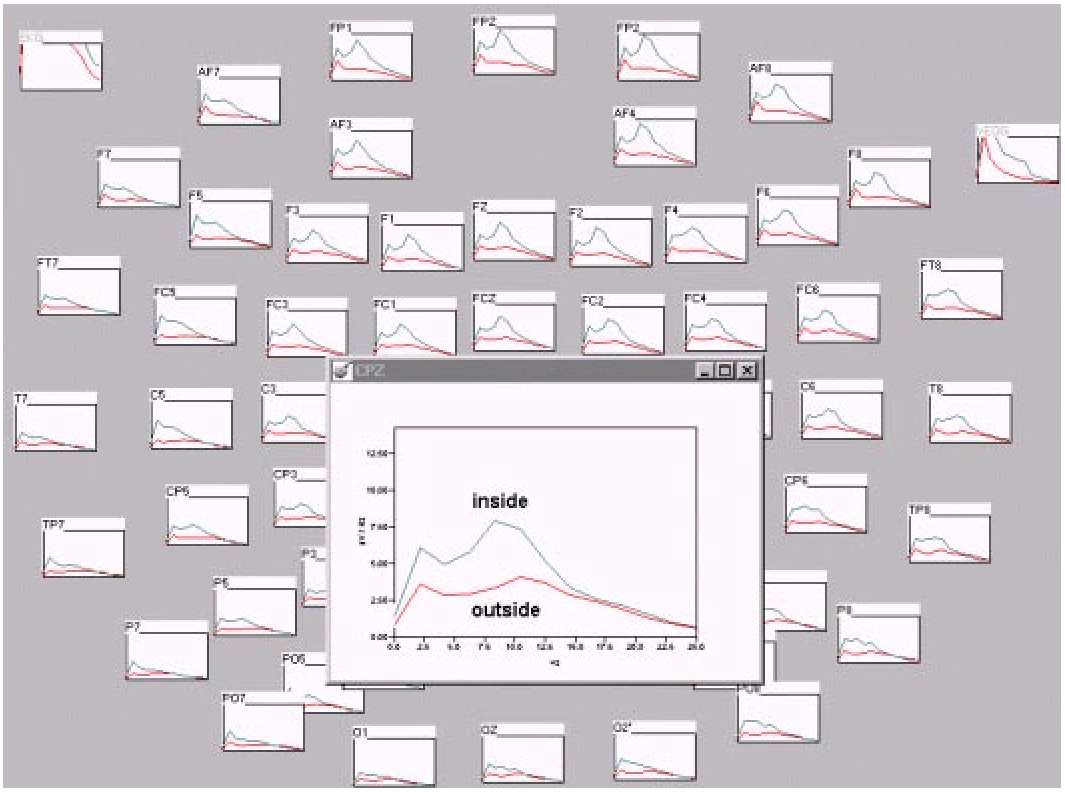


For demonstration purposes, we will average the epochs around the "20" type codes, to show the residual BKG artifact. The resulting file shows mild residual BKG in the EKG channel; however, the residual BKG in the EEG channels has been reduced to within about +/- 3 uV.



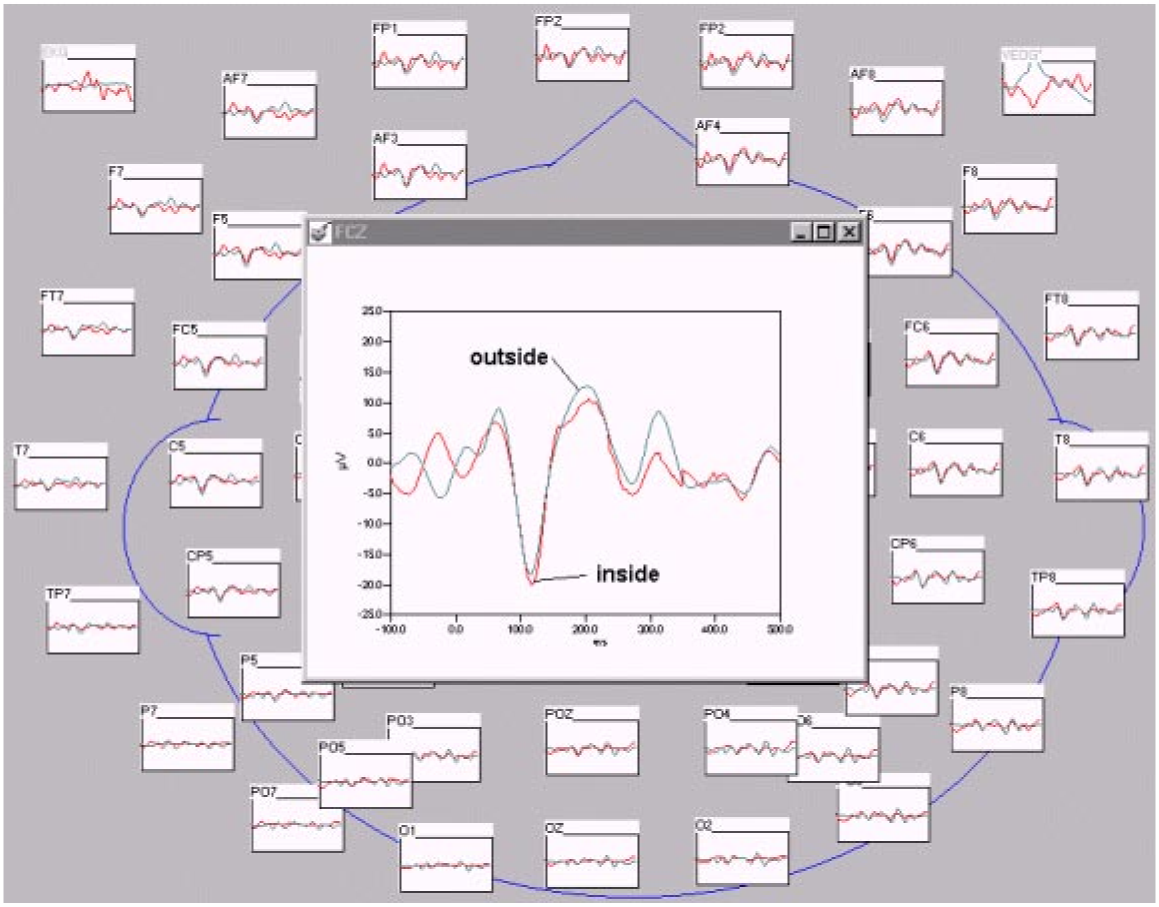
We conclude that there is minimal residual BKG artifact in the averaged EEG sweeps. The next step is to look at the power spectrum of the EEG in the bore.

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).



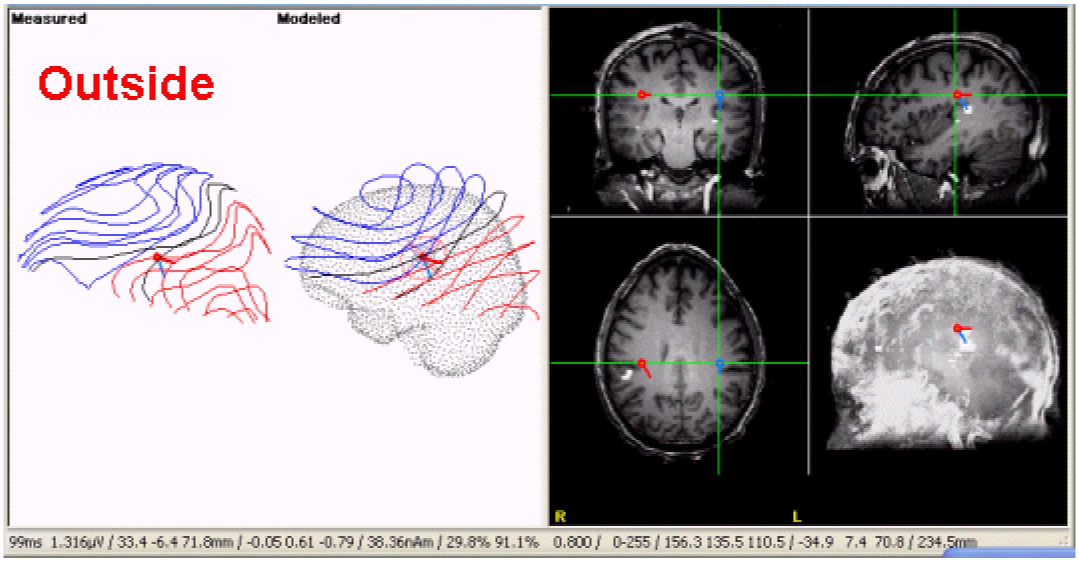
While the pattern is similar there is clearly some residual artifact in the recording within the bore. Looking at the waveforms, it is apparent that not all of the BKG was removed. The question is: will that significantly affect the EPs?

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.

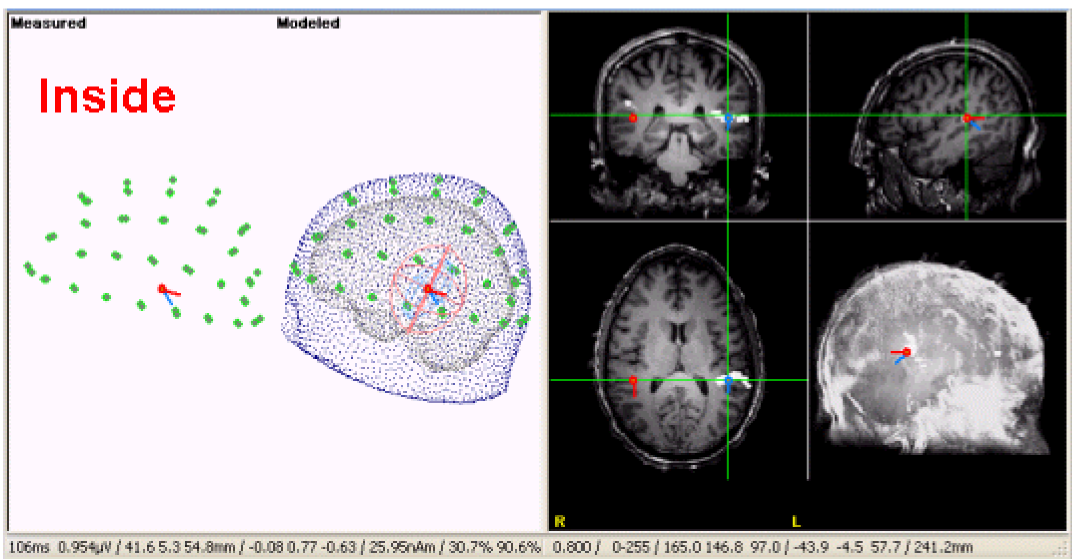


The EEGs channels inside the bore show evoked potentials that are very similar to those recorded outside the chamber. The residual BKG - not time-locked to the stimuli - tended to average out.

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:

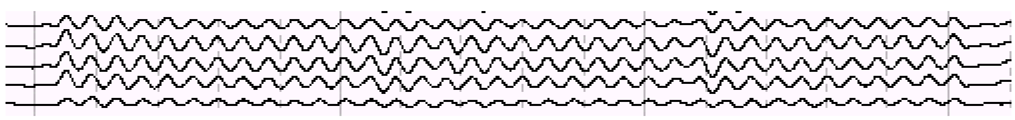


There were very few sweeps in these examples (<30), and that may explain the variation in localization. Nevertheless, the results are fairly similar for the two files. The results were nearly identical if we selected slightly different time points (such as 74 ms in one file, and 84 ms in the other).

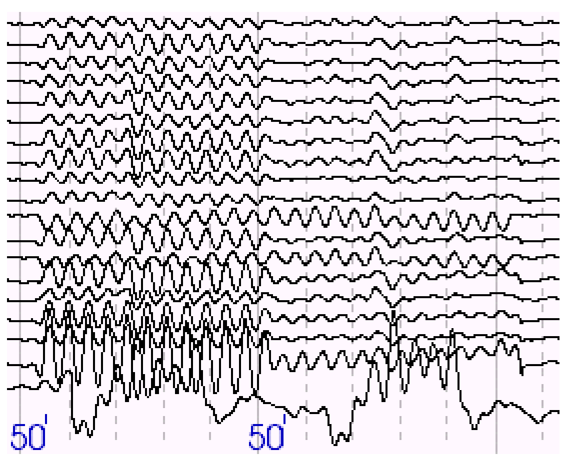
Summary. In the examples above we have demonstrated some of the analysis techniques used to remove or minimize artifact seen in fMRI EEG recordings. As mentioned, the parameters for some of the transforms, such as EKG Noise Reduction, for example, usually require some experimentation to find the optimal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

We have seen that BKG, for example, can be removed almost completely, or at least greatly minimized. 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.

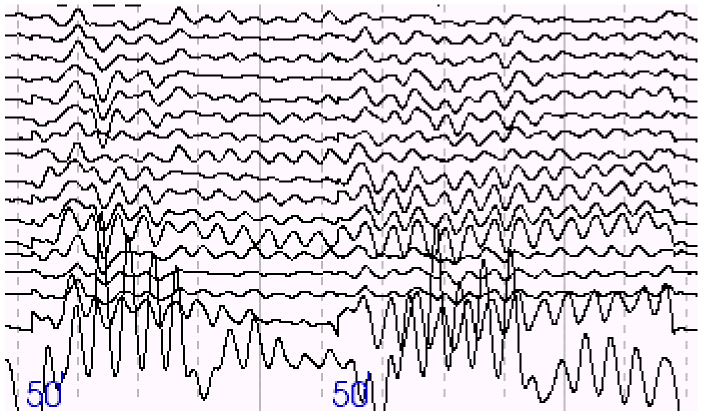
We have not addressed the MR Gradient removal in the demonstrations so far. Software techniques that average the MR artifact and then subtract it out are not completely effective. This appears to be due to the variations of the MR artifact during even a single sequence of samples, or it could be an aliasing problem (that could be solved by faster sampling rates). We have also seen that the artifact from more powerful magnets (3T and 4T) is more severe than that seen in 1.5T magnets. In the figure below, in which the sequencing artifact has been filtered using a digital high pass filter of .5 to 20 Hz, note that the artifact is not constant throughout the sampling interval.



The frequency and phase change 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.



Again, the subtraction is not precise enough. We are currently exploring other software and hardware solutions to the gradient artifact problem, and these will be contained in later versions of the software. In the meantime, you are encouraged to try using the blink reduction routine to reduce the gradient artifact. We have found that in some instances it is very effective.

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 any successful methods you have found. Please send all comments or suggestions to techsup@neuro.com.