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Updated 8.21.10b

Application Note 258 BIOPAC MRI Smart Amplifier Performance

This application note is concerned with the recording of real-time physiological data, from a human subject, during fMRI, using BIOPAC's series of **MRI Smart Amplifiers**. These MRI Smart Amplifiers are designed differently than BIOPAC's standard amplifier modules. MRI-specific amplifier modules feature internal circuitry which is designed to minimize MRI artifact (to the maximum extent possible) while still best preserving the amplifier bandwidth, phase, gain and signal to noise characteristics.

- ECG100C-MRI
  - ECG data
  - ECG data close-up
- EDA100C-MRI
  - EDA data
- EEG100C-MRI
  - EEG data
  - EEG data close-up
- EMG100G-MRI
  - EMG data
  - EMG data close-up
- PPG100C-MRI
  - PPG data
  - PPG derived BPM compared to ECG derived BPM

When recording physiological signals in the MRI, very considerable artifact is impressed on the monitored electrode site and recording leads due to the extremely strong time-varying magnetic fields produced by the MRI. Artifact typically manifests as voltage spikes which have been induced to occur on the recording site and recording leads because of magnetic field gradient switching, such as during EPI (Echo Planar Imaging).

Artifact voltage spikes are usually much larger than the physiological signal of interest, especially if the signal happens to be a biopotential, such as ECG, EEG or EMG.

ECG signals are on the order of 1mV and MRI induced artifact voltage spikes are often two orders of magnitude greater. Even if the physiological signal recorded is not a biopotential, such as EDA (electrodermal activity) or PPG (pulse plethysmogram), the MRI will induce voltage artifact on conductors that carry the signal away from the subject.

In addition to artifact generated by magnetic field gradient switching, artifact is also generated by high power RF (radio frequency) energy that is directed at the subject during imaging.

Atoms in the subject's body will precess at the Lamor (F) frequency:

$$F = (L*M)/(2*Pi)$$

where L is the Lamor Constant – depends on the atom
M is the magnitude of the magnetic field around the atom (generated by the MRI)

A rule of thumb is that the Lamor Frequency (in MHz) is 42.7 * Telsa field strength of MRI.

- For a 3T MRI, the Lamor frequency will be 42.7*3 = 128.1 MHz

If a pulse of RF energy with frequency of F is directed at an atom in a magnetic field of M, then it will radiate photons back at frequency F. If the atom is in a magnetic field less than M, it will radiate back at a frequency proportionally less than F. If the atom is held in a magnetic field greater than M, it will radiate back at a frequency proportionally greater than F.

The magnetic field gradient establishes the differing values of M that occur across what is called a "slice". These differing values of M allow discrimination (after applying mathematical transformations) between the types and locations of atoms in the brain.

When it comes to recording physiological data, the RF energy directed at the subject is simultaneously directed at biopotential and transducer recording sites on the subject's body. This RF energy will radiate into the conductor associated with the physiological recording and this RF energy requires removal in order to establish clean physiological signal amplification.

Typically, removal of this RF energy occurs at the site of the patch panel, which is a metal barrier separating the MRI chamber room from the MRI control room. This panel is typically constructed as an aluminum panel. This panel is provided so MRI users can send electrical signals, employing conductors (such as copper wire), from the chamber room to the control room and vice versa.

The requirement that the electrical signals, which pass between the two rooms, be filtered is very important. If the signals are not filtered, then two things will happen:

1) The physiological data recorded from the subject will be corrupted with RF energy at the Lamor Frequency (about 128MHz for a 3T MRI). This RF energy will typically distort the amplification process because this high frequency signal will be non-linearly amplified and integrated by physiological signal amplifiers.

2) Control room EMI (electromagnetic interference) generated from the control room computers and other electronic equipment will travel down unfiltered conductors and will usually corrupt the MRI image quality.

Accordingly, it is very important to properly filter electrical conductors that pass from the chamber room to the control room. These conductors are typically attached to a connector that plugs into a filtered connector installed on the patch panel. On the opposite side of the patch panel, another cable is attached to the filtered connector to direct the conductors to their proper location. The only item which “breaches” the patch panel is the filtered connector.

BIOPAC makes a filtered connector that is suitable for removing a very wide range of possible Lamor frequencies from physiological signal conductors. These filters are dual stage and they effectively operate over a range of 100kHz to 1000MHz to remove RF interference from the MRI. These filters also incorporate dielectric isolation to 1500VDC, to satisfy subject isolation requirements specified by IEC60601-1.

For more information on MRI filters and associated cable sets:

- Biopotential data (such as ECG, EEG or EMG), see http://www.biopac.com/mri-compatible-biopotential-filtered-cables-specifications
- Transducer data (such as EDA or PPG), see http://www.biopac.com/mri-compatible-transducer-filtered-cables

Several of BIOPAC’s amplifier modules, prior to the introduction of the MRI series, were also capable of collecting physiological data from a subject in the MRI, but usage methods had to be very exacting. For example, if the amplifier gain was set too high, the amplifier output signal would saturate from gradient induced artifact. If the filters of the amplifier were set to too low a bandwidth, then the filters would integrate the artifact, making removal of artifact difficult in post-processing. Finally, data from amplifiers had to be sampled very quickly in order to successfully use post-processing techniques in AcqKnowledge (ACK) to remove MRI artifact.

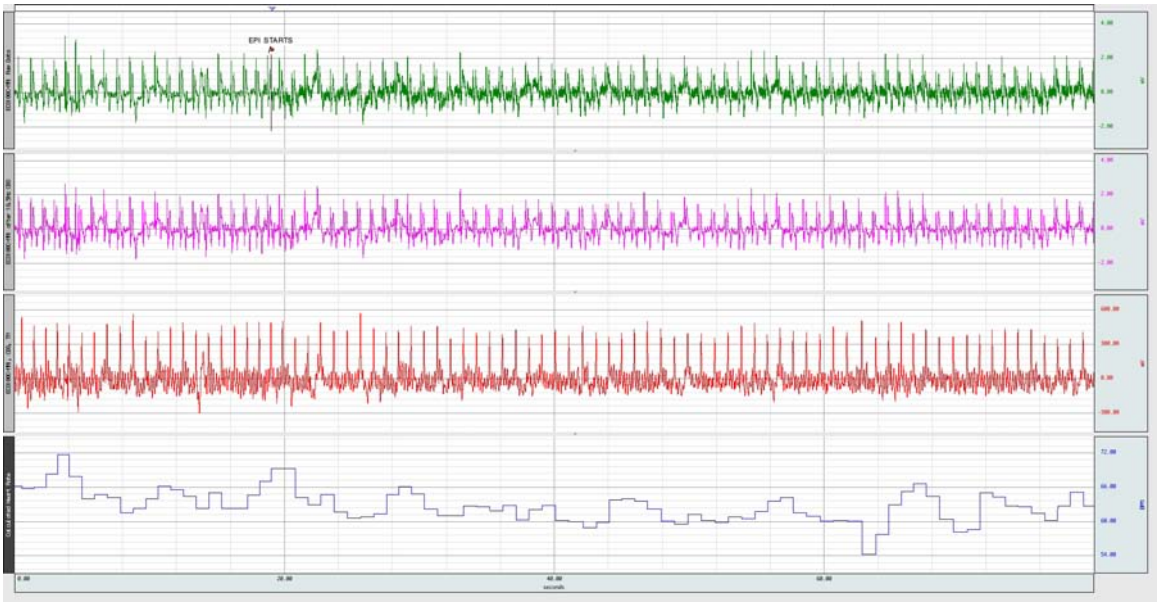
The MRI Smart Amplifier modules eliminate or reduce many of these problems to create a less “fussy” interface from subject to physiological data collection computer. It’s NOT accurate to say that the MRI amplifiers’ fully and completely remove ALL MRI generated artifact from the physiological signal collected from a subject during imaging. However a very significant reduction in artifact is obtained, thus creating a circumstance whereby the raw signal output of the amplifier is often of quite good quality. And in the cases where some artifact remains, it’s typically much easier to remove such artifact in post-processing using ACK.

A balance between artifact removal and physiological signal integrity has been established for each of the MRI series amplifiers. The signals associated with ECG, EDA and PPG are very robust and of sufficiently reduced bandwidth, so these MRI amplifiers produced raw output data which is high quality, largely completely devoid of artifact, in real-time. Of course, further real-time or post-processing the raw data in ACK will even produce better quality data.

The EEG and EMG series amplifiers, due to differences in physiological signal magnitude and associated frequencies, which typically collect some artifact along with the physiological signal, but the artifact collected will be about 100 times (40dB) less than what it would be for a normal physiological amplifier. This level of performance means that the amplifiers can be used in the same fashion they would be used outside of the MRI, in that gains and bandwidths can be adjusted without potentially saturating or radically disrupting the collected signal. Also, sampling rates can often be reduced to more typical levels, for the physiological signal of interest.

The following graphical data was obtained from test subjects during EPI in a 3T Siemens fMRI. The data was obtained using the MRI series of amplifier modules and collected with a MP150 system running ACK v4.1. All data was sampled at 2000Hz, except for the case of EMG data, which was sampled at 5000Hz. The LEAD108B (15cm long) Radio Translucent (RT) MRI compatible electrode leads were used and connected to EL508 RT MRI compatible electrodes to collect all physiological data. All physiological data collected from the test subject (in the chamber room) were routed through the appropriate filtered cable set, through the patch panel, to the respective amplifier situated in the control room.

ECG DATA



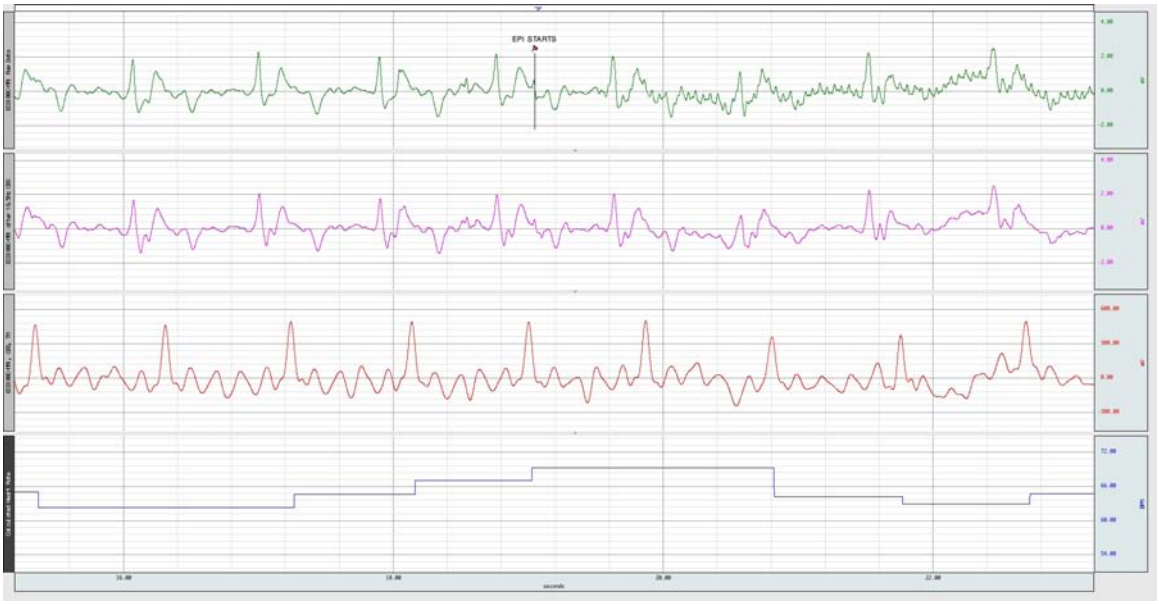
The top waveform in the graph is the raw electrocardiogram (ECG) data obtained from the ECG100C-MRI, set to a gain of 1000, with 1 Hz HP set to ON and 35Hz LPN set to ON. Electrodes were connected to the chest of the subject, so as to record a LEAD II ECG. Note that the top (green) waveform is relatively unaffected by the advent of EPI, in that R waves are clearly identifiable.

The second waveform (cyan) illustrates the results of a simple real-time or post-processing step in ACK to further clean-up the data. In this case, the raw data was run through a Comb Band Stop (CBS) filter set to 18.5 Hz, including all harmonics out to Nyquist. The reason that 18.5 Hz was chosen is that there were 37 slices being performed by the MRI every 2 seconds (37/2 = 18.5). With each slice, the magnetic field gradient is changed, thus introducing artifact at a 18.5 Hz rate. The CBS filter removes this synchronous artifact.

The third waveform (red) shows the result of a template match, performed in ACK, during post-processing. The template chosen was a single ECG cycle in waveform 2. This template was correlated with the entire record and the result is displayed in the third waveform. Note that each ECG cycle is now precisely identified by a “spike”.

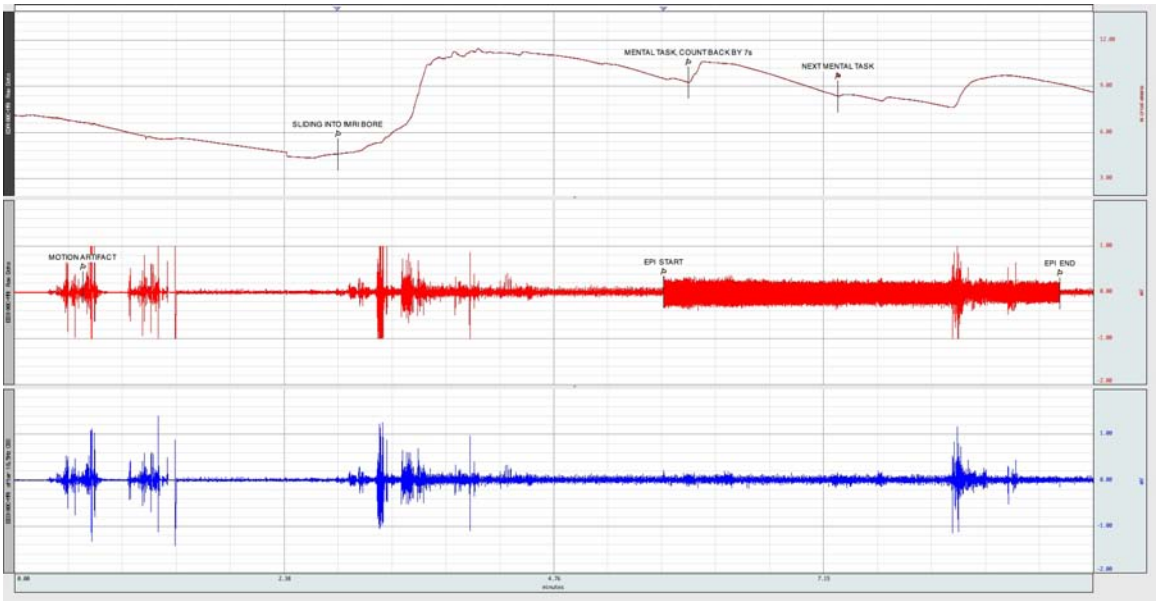
In the last waveform (blue) the data in waveform 3 was run through a rate detector set to calculate BPM using a simple threshold control. The subject’s BPM is displayed in this graph both before and during EPI.

ECG DATA CLOSE-UP



In this graph, a close-up is provided of the ECG data, right around the start of scanner EPI.

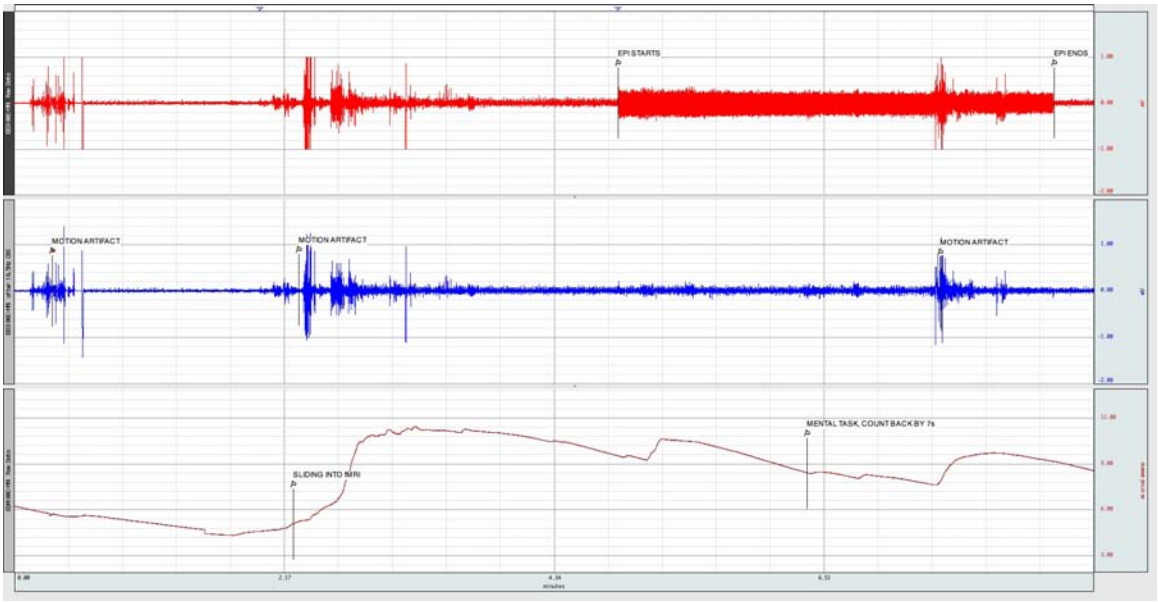
EDA DATA



The top waveform in the graph is the raw electrodermal activity (EDA) data obtained from the EDA100C-MRI, set to a gain of 5 uS/Volt, DC coupling set to ON and 1 Hz LP set to ON. Electrodes were connected to the index and middle finger of the subject, so as to record standard EDA. Note that the top (red) waveform is unaffected by the advent of EPI.

The second waveform (red) illustrates simultaneously collected raw EEG data collected from the EEG100C-MRI amplifier. The third waveform (blue) illustrates the results of a simple real-time or post-processing step in ACK to further clean-up the EEG data.

EEG DATA



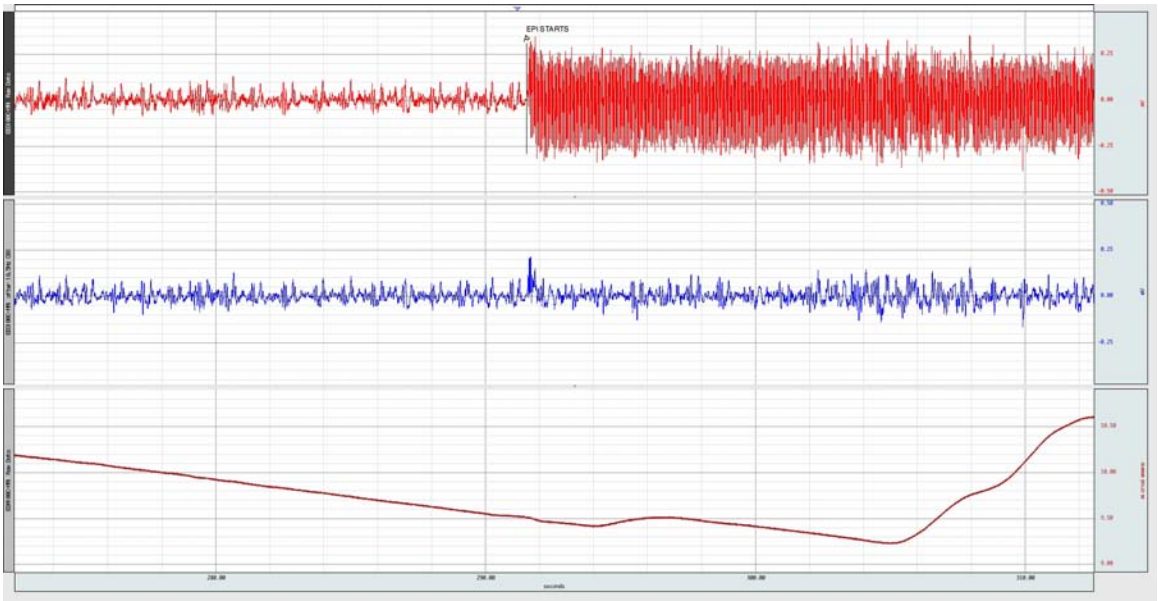
The top waveform (red) illustrates simultaneously collected raw EEG data collected from the EEG100C-MRI amplifier. The EEG data was collected from the test subject's left hemisphere. The amplifier was set to a gain of 10,000, with HP filter set to 1 Hz and 35Hz LPN set to ON. The signal range shown is +/- 1000 uV. Note that EPI artifact is clearly visible in the EEG data record. However, this artifact is well within the operational range setting of the EEG100C-MRI amplifier and is roughly the same order of magnitude as the raw EEG signal data.

The second waveform (blue) illustrates the results of a simple real-time or post-processing step in ACK to further clean-up the EEG data. In this case, the raw data was run through a Comb Band Stop (CBS) filter set to 18.5 Hz, including all

harmonics out to Nyquist. The reason that 18.5 Hz was chosen is that there were 37 slices being performed by the MRI every 2 seconds (37/2 = 18.5). With each slice, the magnetic field gradient is changed, thus introducing artifact at a 18.5 Hz rate. The CBS filter removes this synchronous artifact from the EEG raw data.

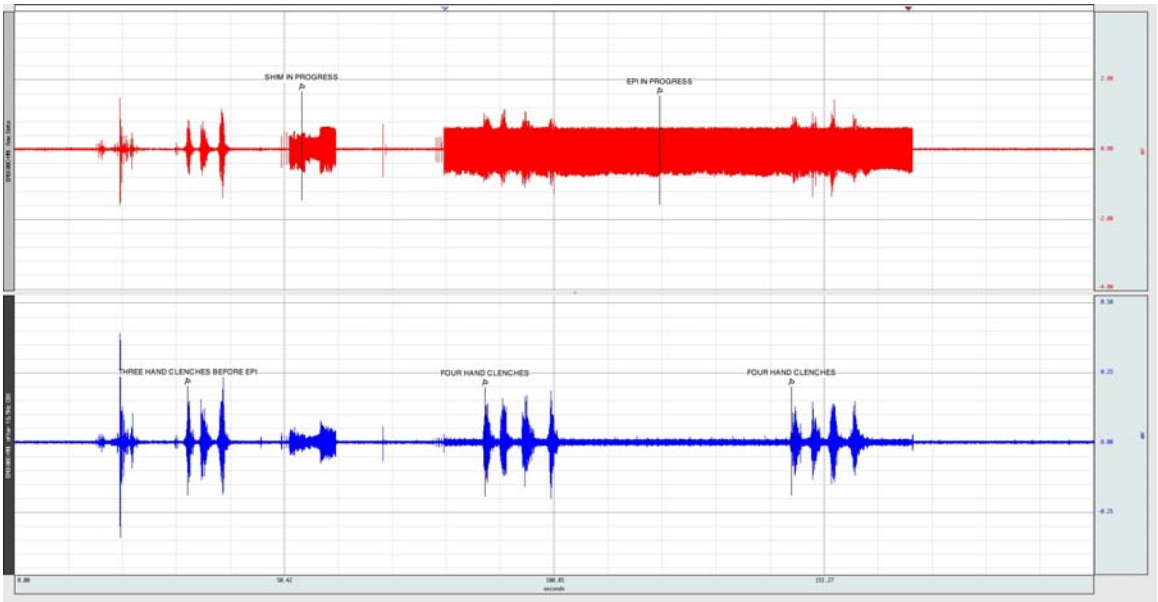
The third waveform (red) in the graph is the raw electrodermal activity (EDA) data obtained from the EDA100C-MRI.

EEG DATA CLOSE-UP



In this graph, a close-up is provided of the EEG data, right around the start of scanner EPI.

EMG DATA

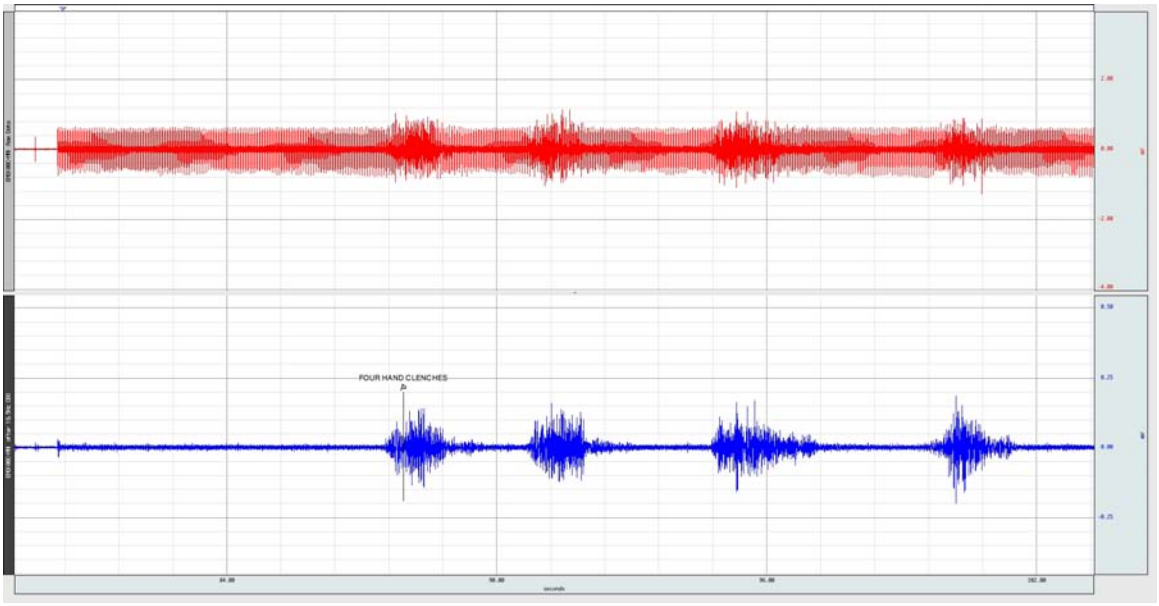


The top waveform (red) illustrates simultaneously collected raw EMG data collected from the EMG100C-MRI amplifier. The EMG data was collected from the left forearm of the subject. The amplifier was set to a gain of 1,000, with HP filter set to 10Hz and 500Hz LP set to ON. Note that EPI artifact is clearly visible in the EMG data record. However, this artifact is well within the operational range setting of the EMG100C-MRI amplifier and is roughly the same order of magnitude as the raw EMG signal data. Note that the sequence of four hand clenches, to manifest an EMG signal, are clearly evident as “raised bumps” in the raw EMG record.

The second waveform (blue) illustrates the results of a simple real-time or post-processing step in ACK to further clean-up the EMG data. In this case, the raw data was run through a Comb Band Stop (CBS) filter set to 18.5 Hz, including all harmonics out to Nyquist. The reason that 18.5 Hz was chosen is that there were 37 slices being performed by the MRI

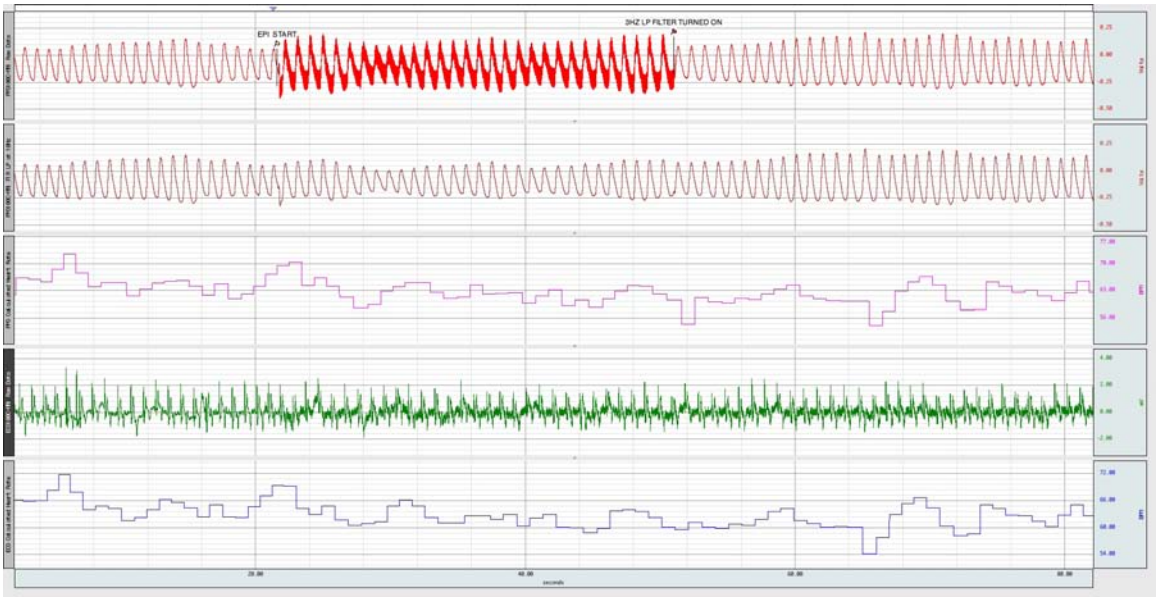
every 2 seconds (37/2 = 18.5). With each slice, the magnetic field gradient is changed, thus introducing artifact at a 18.5 Hz rate. The CBS filter removes this synchronous artifact from the EMG raw data.

EMG DATA CLOSE-UP



In this graph, a close-up is provided of the EMG data, right after the start of scanner EPI. Note the very clear “outline” of the EMG data in the first (red) waveform. The second waveform simply extracts this data using a basic CBS filter.

PPG DATA



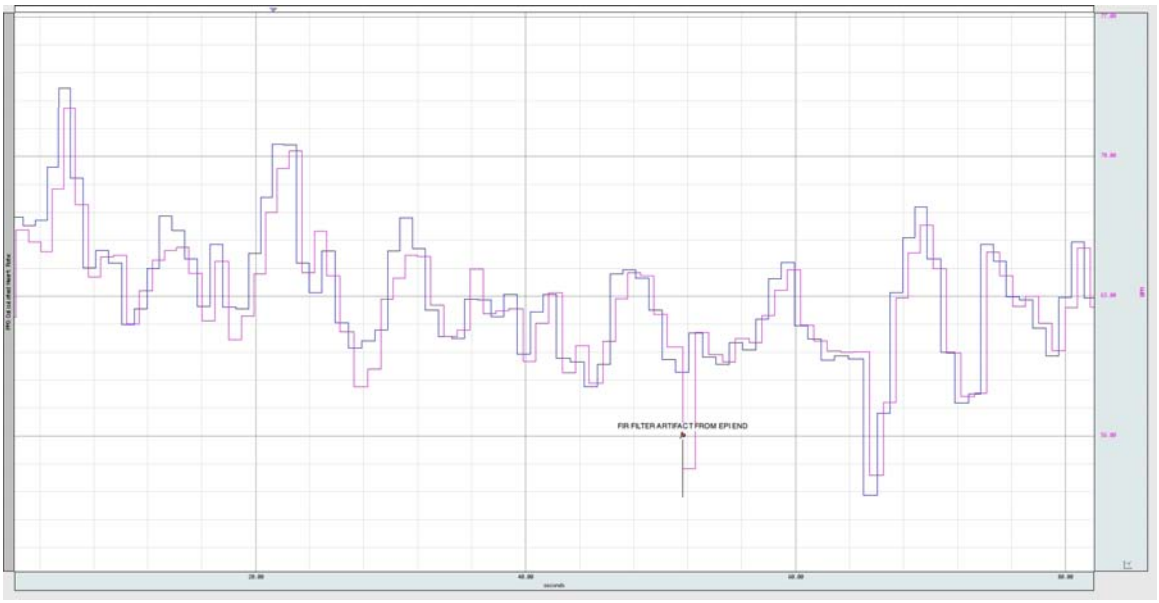
The top waveform (red) in the graph is the raw pulse plethysmogram (PPG) data obtained from the PPG100C-MRI, set to a gain of 100, with 0.5 Hz HP set to ON and the 3 Hz and 10 Hz LP filters were toggled during the recording. The PPG100C-MRI specific transducer was connected to the test subject’s index finger. In the first 60% of the recording, the 10Hz LP filter of the PPG100C was turned ON. On the last 40% of the recording the 3Hz LP filter on the PPG100C was turned ON. Note that when the 3 Hz filter is ON, the EPI artifact is completely removed from the PPG data.

The second waveform (red) illustrates the results of a simple post-processing step in ACK to further clean-up the data. In this case, the raw data was run through a FIR LP filter set to 10 Hz. The reason that a 10 Hz FIR LP filter was chosen is that the artifact was at a 18.5 Hz rate and the required PPG data was below this frequency. The FIR filter has a very steep cutoff, so the post-processing filter is more effective at removing artifact than the internal filter inside the PPG100C-MRI module. In any regard, the internal 3Hz LP filter associated with the PPG100C-MRI is completely effective at removing EPI artifact, so post-processing is typically not required when using the PPG100C-MRI.

The third waveform (cyan) shows the result of a rate detection operation performed on the second waveform, to determine the subject's BPM as a function of time.

The forth waveform (green) shows associated raw ECG data taken from the same subject using the ECG100C-MRI amplifier. This data was further processed to obtain the rate data in the fifth waveform (blue), which illustrates BPM data as obtained from an ECG, versus a PPG waveform.

PPG DERIVED BPM COMPARED TO ECG DERIVED BPM



The data is this graph illustrates an overlap comparison of the rate (BPM) data derived from a PPG100C-MRI amplifier as compared to BPM data derived from a ECG100C-MRI amplifier. Both the PPG data and ECG data were collected, on the same subject, at the same time. Note that the derived BPM results are very similar, excepting one point which is a result of switching artifact when the 10Hz LP filter on the PPG100C-MRI amplifier was switched to 3 Hz LP.

This data was collected to show that very reliable BPM subject data can be collected with the PPG100C-MRI amplifier and associated PPG transducer. It is generally much easier to perform a PPG measurement on a subject, as all that's required to perform a PPG is an accessible finger or toe. Only one attachment point is required to perform a BPM measurement, using PPG, versus three attachment points (via electrodes), using ECG.