

Application Note 265 Signal Processing Methods for use with MRI Artifact Corrupted ECG Waveforms

Overview

ECG waveforms can be “scrubbed” of MRI artifact with the judicious application of hardware and software tools. However, even with specialized hardware filtering (as with the MRI-specific amplifiers), some residual corruption from MRI-induced artifact is evident. In this note, various software filtering tools and approaches will be examined and performance metrics derived for the purpose of extracting a minimally corrupted ECG signal.

Hardware

To best perform ECG measurements in the MRI, use the ECG100C-MRI amplifier module. However, it’s also possible to perform ECG measurements with the regular ECG100C amplifier module. However, when using this amplifier, MRI-artifact will not be suppressed.

Typical MRI artifact, recorded from the ECG100C amplifier, is shown in Figure 1.

However, an ECG100C-MRI, which has specific internal hardware-based filtering results in a signal as shown in Figure 2. Even with the specialized hardware-based filtering in the ECG100C-MRI, there remains residual rippling embedded within the signal.

Given the method presented in Figure 1, software filtering is absolutely required to scrub the signals of MRI effects. Given the method presented in Figure 2, software filtering is not mandatory for evaluating the ECG waveform (during EPI), but it still can be helpful.

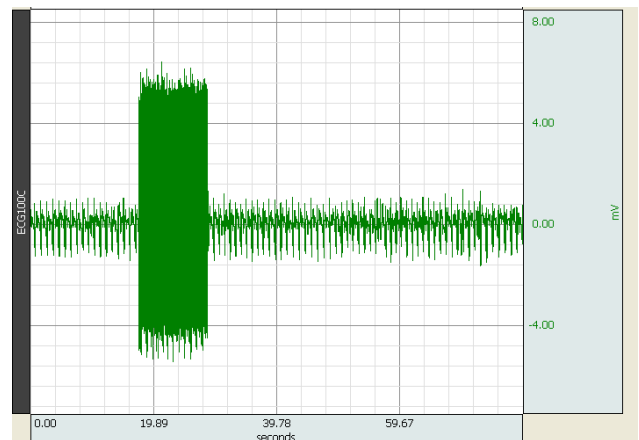


Figure 1: ECG signal corrupted by MRI pulsations – output from an ECG100C amplifier. Note that during MRI gradient switching, the ECG signal is swamped.

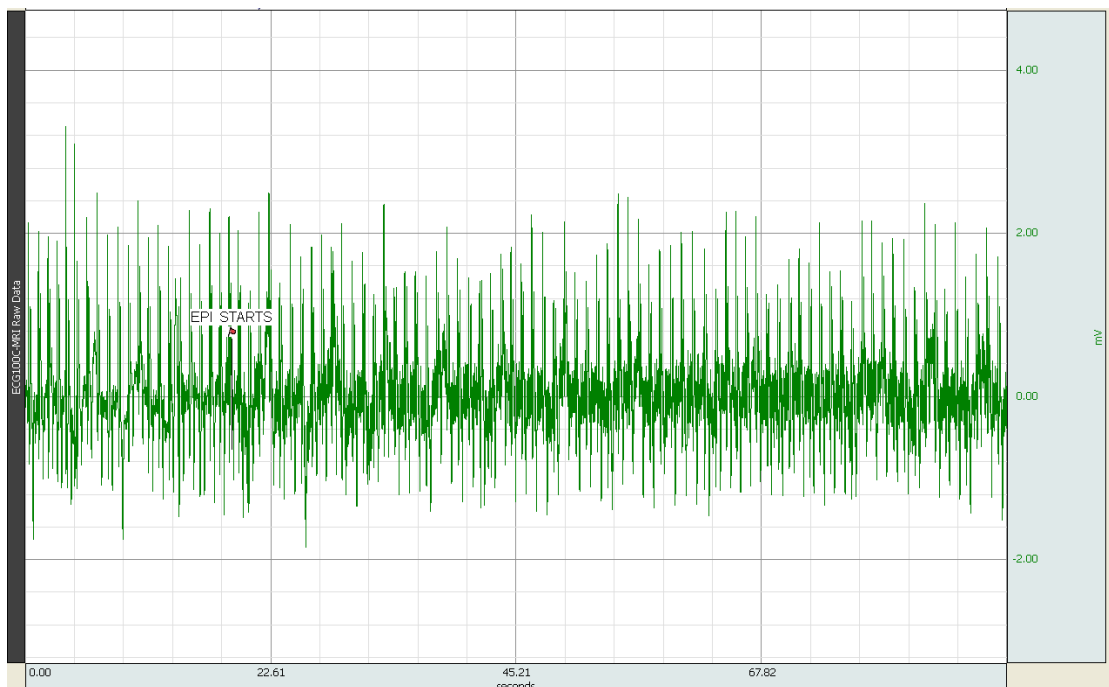


Figure 2: Raw ECG waveform extracted from the ECG100C-MRI module. Note that residual ripple is evident.

Software Filtering and Analysis Tools

AcqKnowledge comes equipped with a variety of filtering tools and aids. The tools most applicable are:

- Fast Fourier Transform
- Comb Band Stop Filters (CBSF)
- Event Classifiers
- Cycle Detectors
- Template Matching

Applying these tools in the proper sequence is essential to proper conditioning of the ECG signal and extracting the desired data. The general processing sequence can be summarized as follows:

Obtain Waveform > Apply Filtering > Apply Rate/Cycle Detectors > Extract Data

Figure 3 shows a flowchart of possible tool combinations for effective filtering.

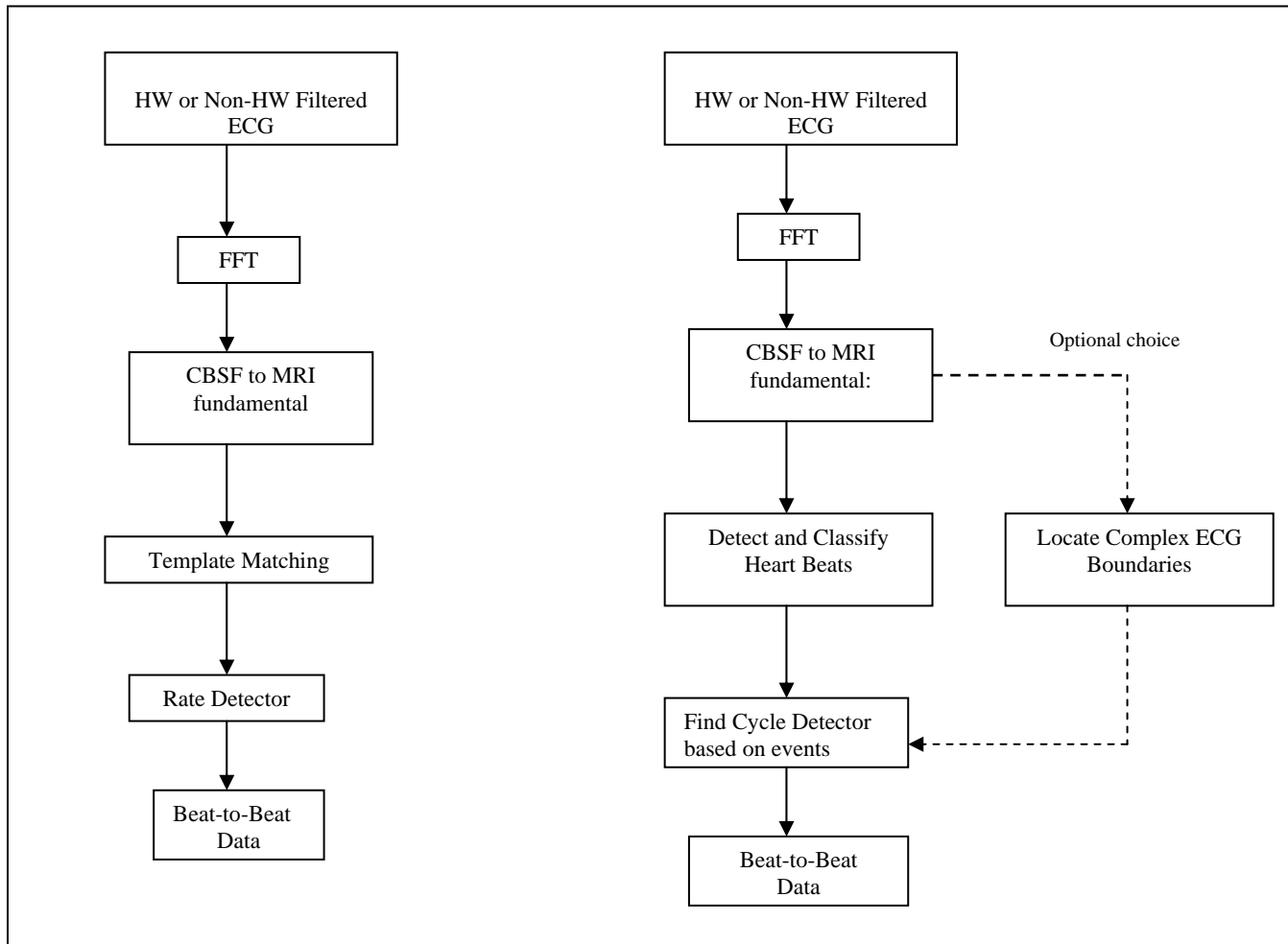


Figure 3: Two basic methods to filter MRI-corrupted ECG signals with various HW/SW tools. Note that any software tool can be used with HW filtered or Non-HW filtered ECG signals.

The available processing tools, as shown in Figure 3 above, perform very specific tasks.

Table 1 describes the filters and their associated functions and purpose within the processing chain.

Processing Tool	Function	Purpose
FFT	Fast Fourier Transform software routine.	To determine the fundamental frequency of the MRI pulsations that are superimposed on the ECG signal.
CBSF	Comb Band Stop Filter: A bank of software implemented IIR band stop filters.	This filter will attenuate the MRI fundamental frequency within the ECG signal
Template Matching	A group of software implemented mathematical algorithms that include: <ul style="list-style-type: none"> • correlation • convolution • mean square error • inverse mean square error • normalized cross correlation • adaptive template matching 	Applying these algorithms to the filtered ECG signal will create a secondary waveform based on match criteria of a particular property of the waveform. This secondary waveform can consist of a series of spikes denoting maximum waveform values upon which a rate/cycle detector will key off of to determine frequency.
Detect and Classify Heartbeats & Locate Complex ECG Boundaries	Algorithms that apply markers to waveform characteristics such as places of maximum/minimum values.	Cycle or rate detection algorithms use these markers to extract waveform metrics such as frequency.
Rate/Find Cycle Detectors	Algorithms that determine waveform frequency values based on cyclic peaks or event markers.	Waveform frequency extracted. Useful for HRV analysis.

Table 1: Software processing tools

Each tool will be discussed in terms of invocation, proper application, and interpretation of results.

FFT

The FFT (Fast Fourier Transform) is an algorithmically efficient Discrete Fourier Transform that produces a frequency domain waveform from a time-domain waveform. When the MRI is undergoing gradient switching, the induced pulsations can have a frequency spread that may complicate the selection of the fundamental frequency as needed by the CBSF. The frequency spread effect results from slight variations in timing between gradient switching points. Applying the FFT to the ECG waveform and examining the 10 harmonic, f_{10} , of the MRI signal will assist the user in selecting the proper fundamental. Referring to Figure 2, there is residual ripple after hardware filtering of the MRI signal. To apply the FFT to this waveform, invoke as follows:

Analysis > FFT, from which the FFT dialog box will be generated, as shown in Figure 4.

Select the default parameters then click “OK.” A new window will be generated and the resulting transform should be as shown in Figure 5:

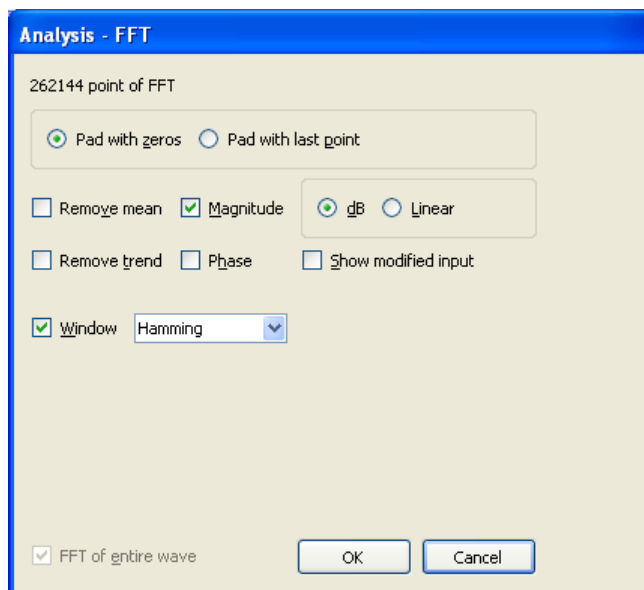


Figure 4: FFT dialog box with the required parameters selected

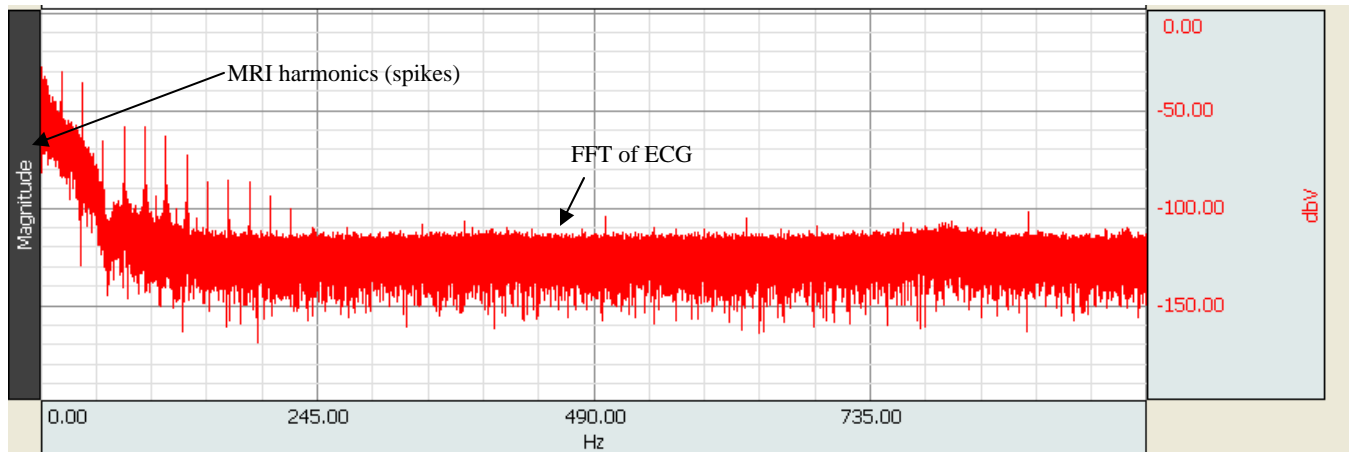


Figure 5: FFT of the waveform in Figure 2.

Note the MRI induced harmonics that appear as spikes on the FFT waveform. Expanding the waveform around the 6th harmonic shows the MRI frequency spread (Figure 6a). Expand the waveform around the 10th harmonic of the spikes. The expanded waveform should appear as shown in Figure 6b.

The center peak in Figure 6b is at 184.997 Hz which can be rounded to 185 Hz. This number divided by 10 can be used by the CBSF.

See **Application Note 259** for further discussions on identifying MRI spectral components on ECG waveforms.

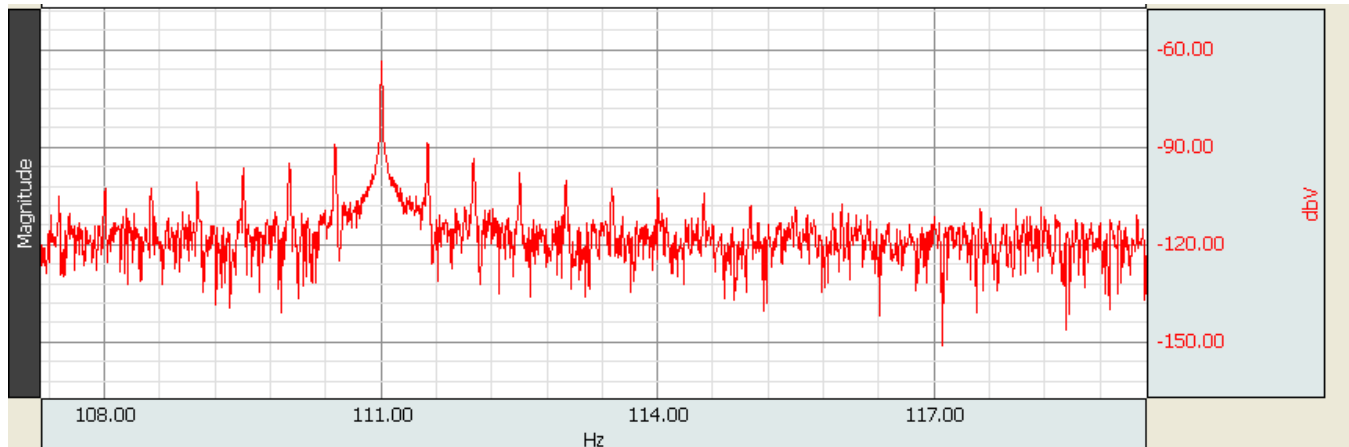


Figure 6a Expansion of the waveform in Figure 5. Note the MRI frequency spread around the 6th harmonic.

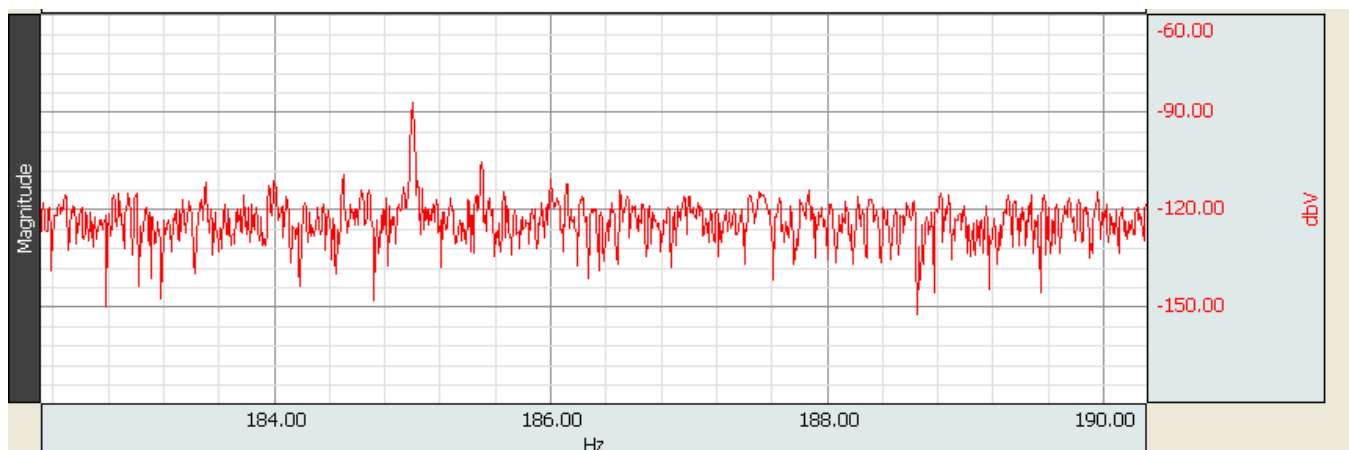


Figure 6b Expansion of the waveform in Figure 5. Note the MRI frequency spread around the 10th harmonic. Center spike is at 184.997 Hz.

Comb Band Stop Filters

AcqKnowledge implements a Comb Band Stop Filter by cascading a series of IIR Band Stop filters that will remove the fundamental and harmonics of an undesired signal. Invoking the filter is done as follows:

Transform > Digital Filters > Comb Band Stop...

A dialog box, as seen in Figure 7, shows the necessary filter parameters. The base frequency, as derived from the FFT exercise, is inserted into the “Fixed at” text box. The radio button should be enabled as well. The Q value is important to specify. A Q too high will not filter out the MRI induced harmonics, when there is a frequency spread due to variations in gradient switching timing. Typically, a Q = 2 provides wide enough coverage to help suppress the harmonics, harmonic spread, as well as the fundamental. Ensure that the “all up to Nyquist” option button is enabled. Applying the CBSF to the waveform of Figure 2 results in a cleaner waveform; see bottom waveform in Figure 8.

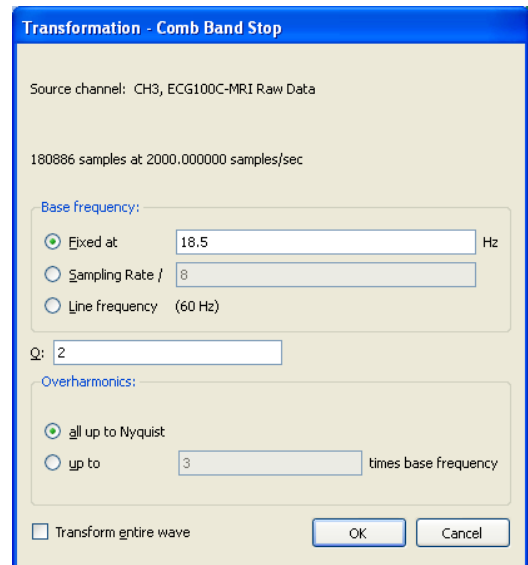


Figure 7: Comb Band Stop filter window

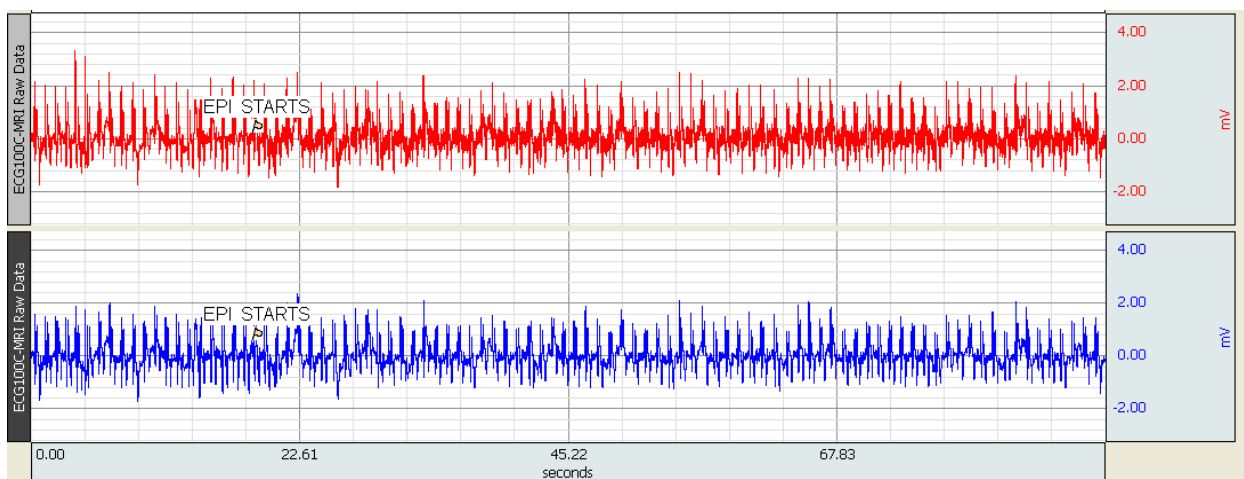


Figure 8: Top waveform is hardware-based filtered ECG signal (from ECG100C-MRI) with residual MRI induced ripple. Bottom waveform is same signal but passed through a CBSF. Note the reduction of the ripple in the bottom waveform.

Template Matching

The algorithms encompassing Template Matching are meant to extract certain waveform characteristics. They could be peak values, zero crossings, or derivative inflections. In this note, peak values over time are desired. For peaks, select a portion of the filtered waveform that is more or less representative of a cyclic peak. Expand the lower waveform of Figure 8 (the CBSF ECG signal), and highlight a representative ECG peak, as shown in Figure 9.

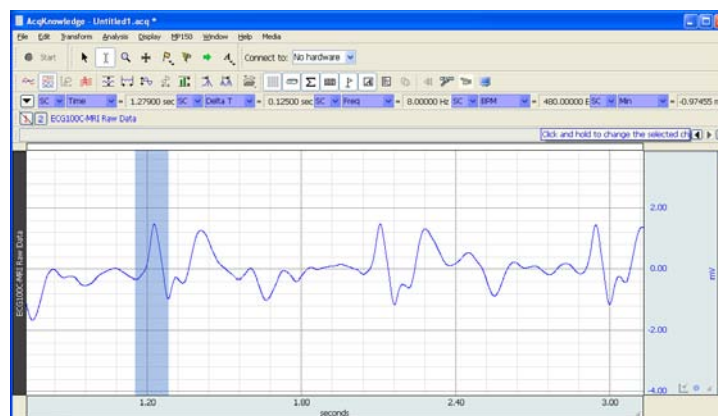


Figure 9: A representative peak is selected for use as a template for the correlation function.

To invoke the template, use the following menu sequence:

Transform > Template Functions > Set Template

This allows the user to set the criteria (as seen by the highlighted area) by which the algorithm will proceed through the waveform and look for matches to the template. To invoke the matching process, do the following:

1. *Edit > Select All*
2. *Transform > Template Functions > Correlation*

After these commands are executed, each ECG cycle with a match to the template is identified by a “spike”. The fidelity to the ECG profile is now gone only to be replaced by a sequence of spikes that denote the ECG template match which is usually based on the QRS complex. Figure 10 shows the resulting waveform.

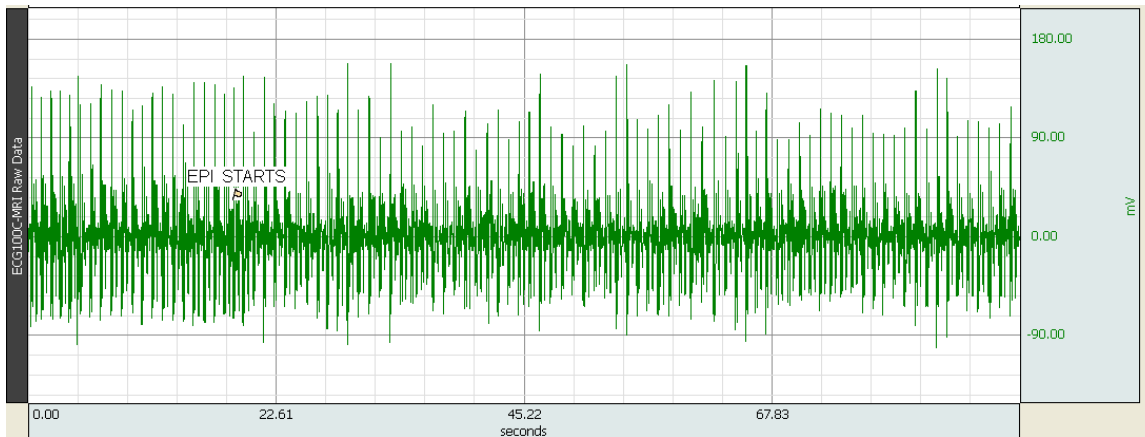


Figure 10: Waveform after correlation with the template (ECG- QRS complex peak)

Detect and Classify Heartbeats

As extracted from the AcqKnowledge[®] software guide:

“This robust QRS detector is tuned for human ECG Lead II signals. It attempts to locate QRS complexes and places an event marker near the center of each QRS complex to identify the type of heartbeat event.”

- Normal: The beat was recognizable as a valid heartbeat falling in a human heartbeat rate.
- PVC: The beat was shorter than the beats around it and may be a pre-ventricular contraction. These events can be found in the “Hemodynamic > Beats” submenu of the event type listing.
- Unknown: The beat wasn’t recognizable as a valid heartbeat. This may occur on the first beat prior to the QRS detector locking onto the signal. It may also occur if tracking is lost due to changes in signal quality.”

The Cycle/Peak detector may be used with these event markers to perform further cardiac analysis.

If the resulting ECG signal is not of the Lead II type, this type of event generator may have limited success in properly classifying the heart beats.

To invoke this tool, perform the following on the CBSF filtered ECG signal:

Analysis > Detect and Classify Heartbeats

The resulting waveform should have the following annotations as shown in Figure 11:

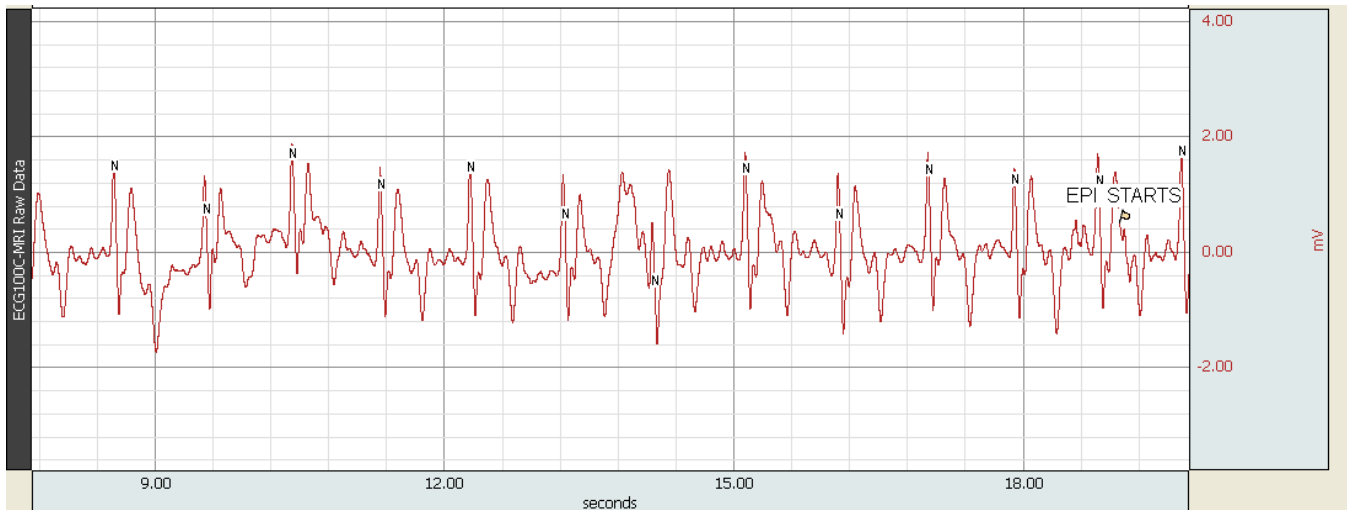


Figure 11: Filtered ECG signal with markers denoting heartbeat classification: N = normal. Cycle detectors can key off of this annotation to determine rate parameters.

Locate Complex ECG Boundaries

Again, this is another event marker tool. Paraphrasing from the manual:

“Locate ECG Complex Boundaries performs ECG waveform boundary detection for human ECG Lead II signals; ECG signals must be sampled at 5 kHz or below to be analyzed with this classifier. It will attempt to locate the boundaries of the QRS, T, and P wave and will define event markers for each individual complex. A listing of these complex boundary event markers can be found in the “Hemodynamic > ECG Complexes” submenu of the Event Type listing.

To invoke this tool on a filtered ECG signal, perform the following:

Analysis > Locate Complex ECG Boundaries

Performing this, the following should be seen as in Figure 12.

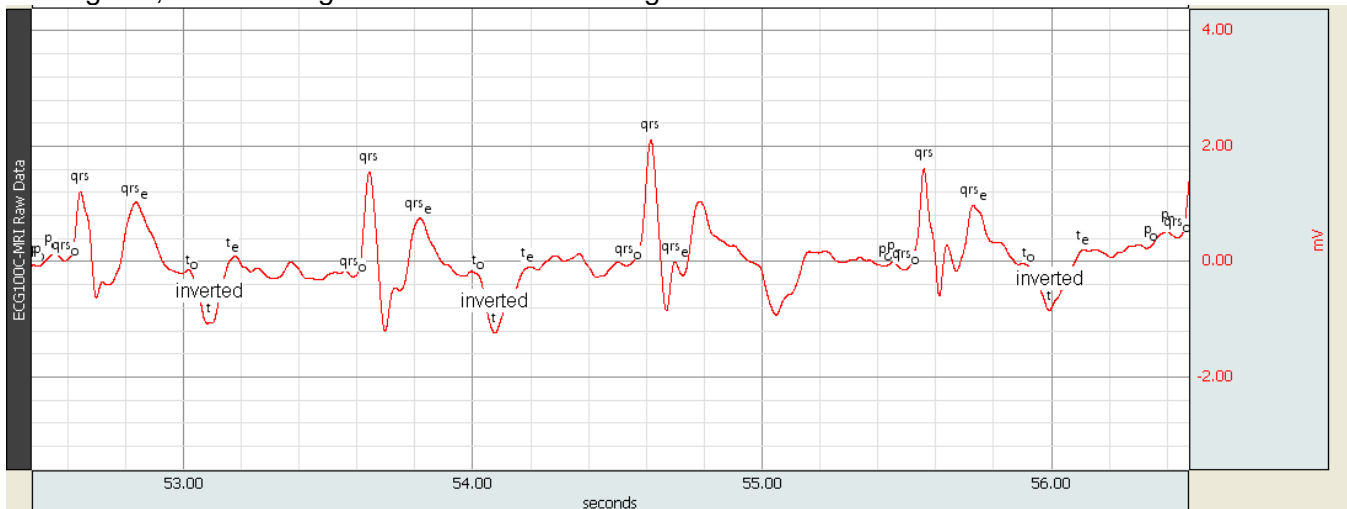


Figure 12: Annotations to the ECG signal using the Locate Complex ECG Boundaries tool. Cycle detectors can key off of this annotation to determine rate parameters.

Rate Detector

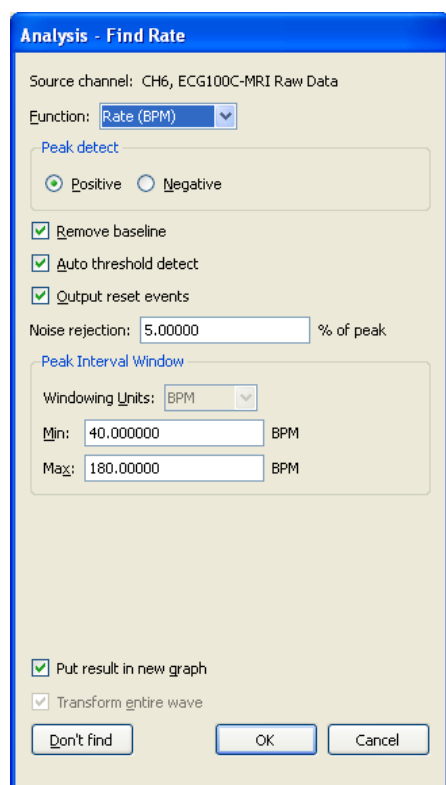


Figure 13: Rate Detector dialog box

The rate detector is a tool that extracts information from physiological data that has a degree of periodicity which includes but is not limited to: ECG, Blood Pressure, Respiration, and EMG. This tool allows the computing of rate (including BPM) for data that has already been collected.

Invoke the tool using the following:

Analysis > Find Rate

The associated dialog will be generated, as shown in Figure 13:

This tool is tuned for signals, such as ECG, that have well defined periodic peaks. Event markers such as those generated by *Detect and Classify Heartbeats* or *Locate Complex ECG Boundaries* are not used.

Using a waveform from a template match, such as one shown in Figure 10, with the Rate Detector output choice of BPM (Beats Per Minute), the following is obtained:

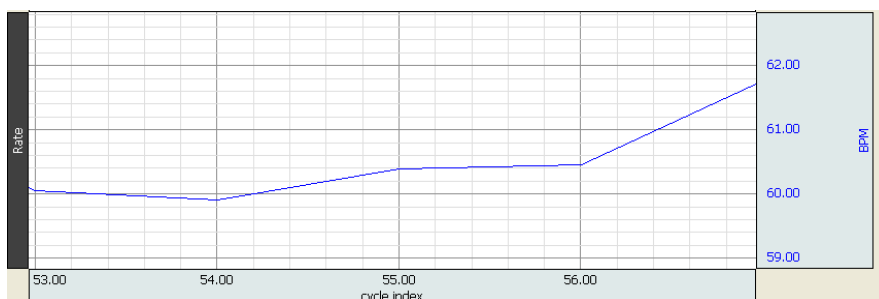


Figure 13: A portion of the Rate output using waveform of Figure 10 (Correlating a template matched to an ECG peak to the entire CBSF-filtered ECG waveform)

Find Cycle Detector

This tool is one of the most sophisticated for extracting cyclic information based on amplitude, time, or event-based measurements. This is the preferred tool to use for event labeled waveforms.

A cycle is defined as the interval between two events of user-specified types. The Cycles/Peaks tab offers three general methods for establishing cycle parameters:

- Peaks: Data driven maximum and minimum
- Events
- User-defined fixed time intervals

Selecting the waveform as shown in Figure 12, invoke this tool as follows:

Analysis > Find Cycle...

A dialog will be generated with three major tabs: Cycles/Peaks, Selection, Output as shown in Figure 14a. On the first tap, Cycles/Peaks, events can be specified and in this case, the QRS peak. The next tab, Selection (Figure 14b), shows how the cycles are partitioned based on the choices of the Cycles/Peak tab; they are delineated by alternating vertical colored strips. And the Output tab (Figure 14c,d) offers an option to output Measurement values, such as BPM, to a channel in a graph file.

After specifying the Find Cycle parameters, click OK. Then place the I-bar cursor to the beginning of the channel that contains the QRS annotated waveforms, and invoke the tool using:

Analysis > Find All Cycles

The lower waveform on Figure 14e should appear showing the BPM rate of the annotated ECG waveform, shown in the upper waveform.

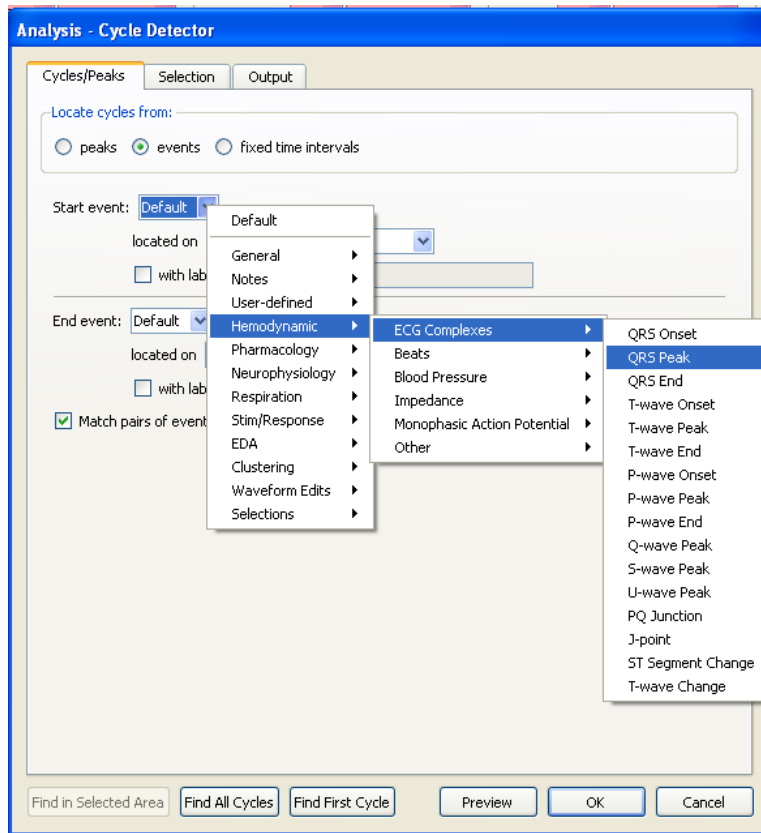


Figure 14a: Find Cycle dialog window.

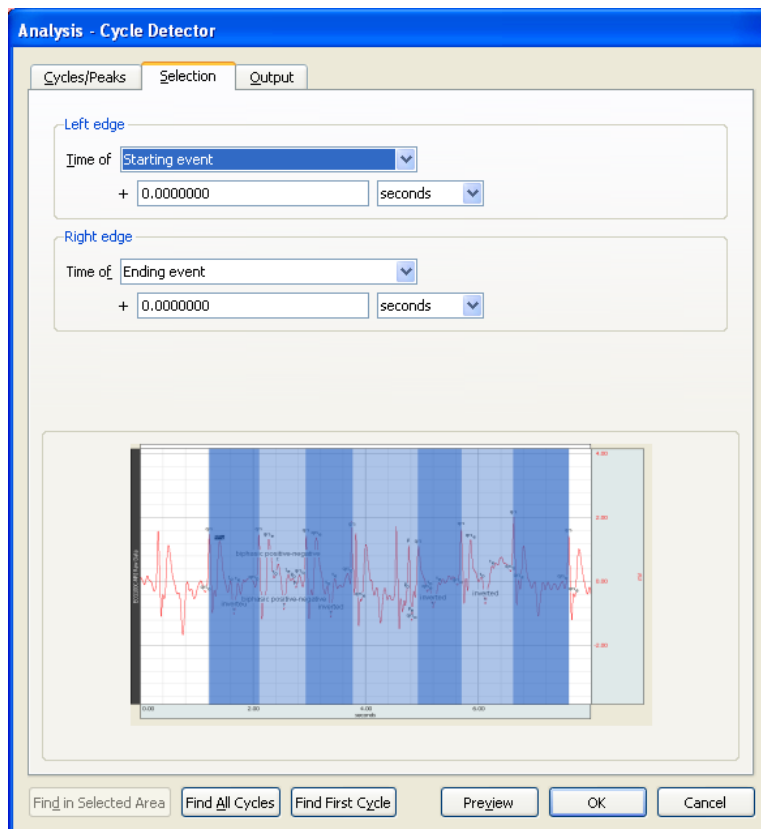


Figure 14b: Selection tab of the Find Cycle window

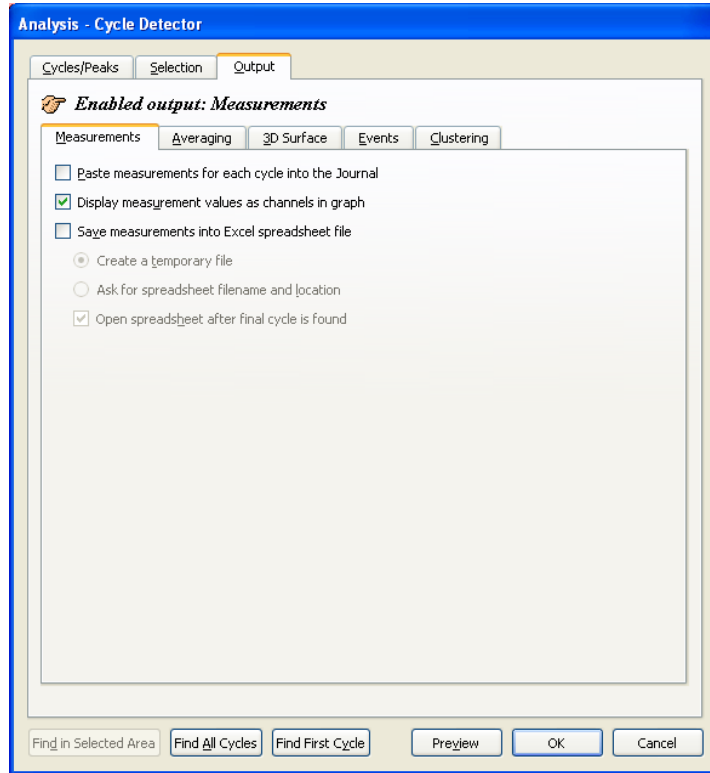


Figure 14c: Output tab of the Find Cycle window.

A selection is made to output values from the Measurement bars to a channel in the graph file



Figure 14d: Measurement value to plot to a channel

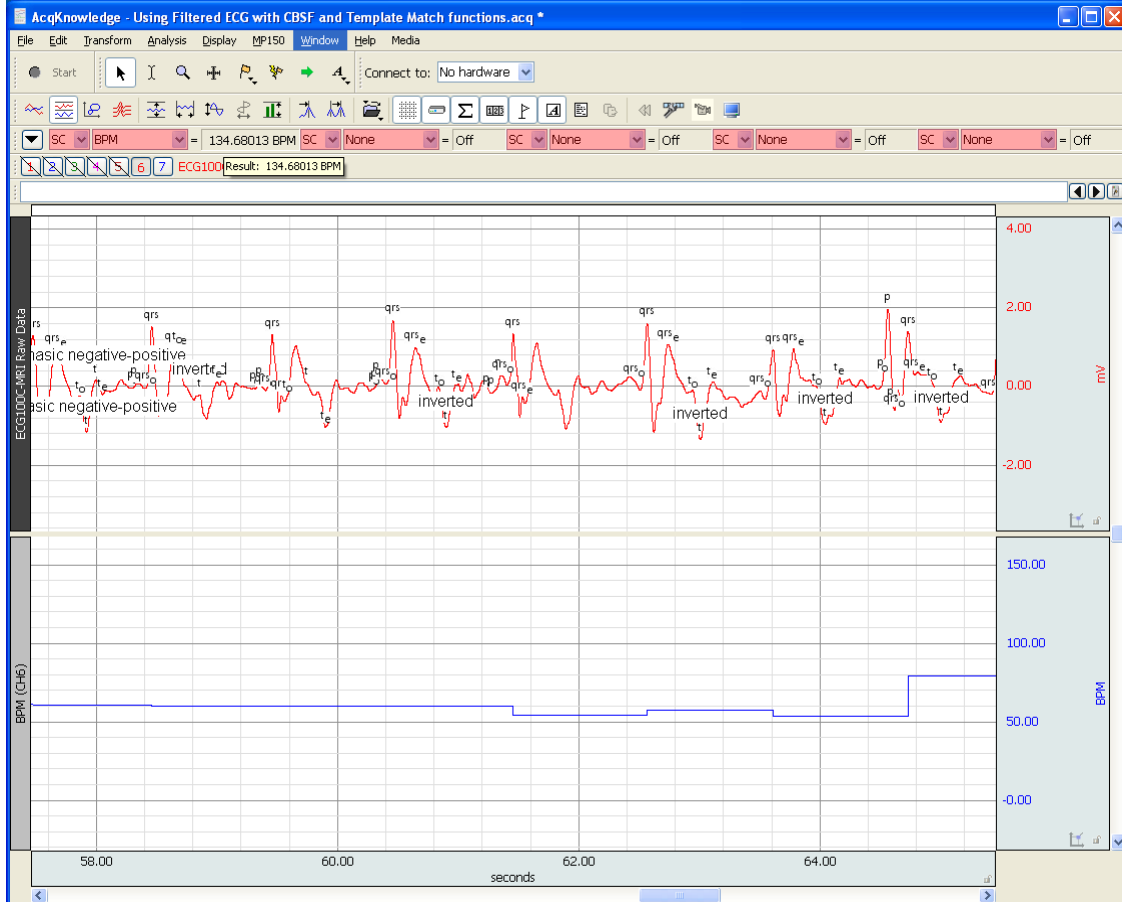


Figure 14e: Resultant graph (bottom) showing BPM rate from the annotated, filtered ECG waveform (top).

Example Waveform Analyses using Multiple Transforms

Figure 15 delineates the waveform analysis process starting with a raw ECG signal obtained from the ECG100C-MRI module then applying the appropriate transforms to obtain the BPM or other metric that illustrates a physiologic condition.

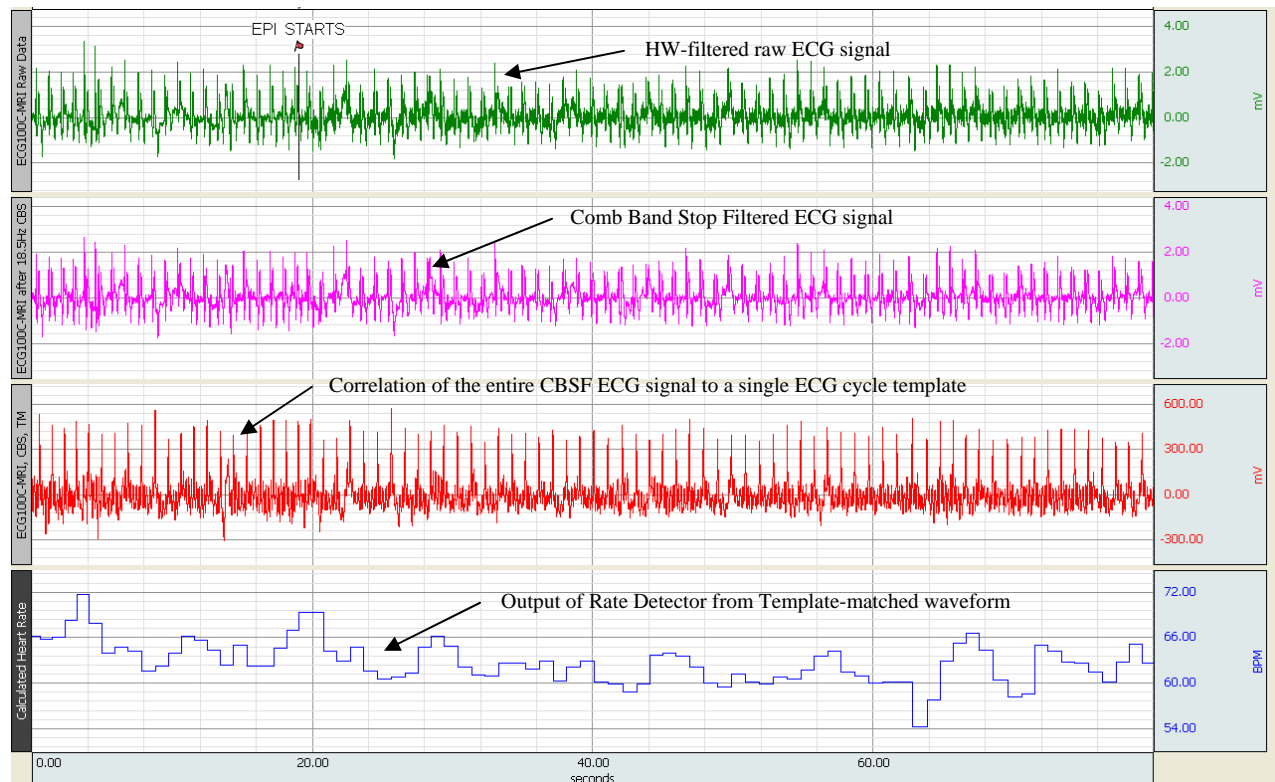


Figure 15: The process of extracting BPM metrics from the raw measured ECG signal.

- Top waveform: ECG signal derived from ECG100C-MRI module.
- Second waveform: Comb Band Stop Filtered ECG signal.
- Third waveform: Correlated output via template matching. Bottom waveform: Rate detector – BPM.

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 35 Hz 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 *AcqKnowledge* to further clean-up the data. In this case, the raw data was run through a Comb Band Stop Filter (CBSF) set to 18.5 Hz, including all harmonics out to the Nyquist. The reason 18.5 Hz was selected 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 18.5 Hz rate. The CBSF removes this synchronous artifact.

The third waveform (red) shows the result of a template match performed by *AcqKnowledge* during post-processing. The template chosen was a single ECG cycle within the CBSF ECG waveform (2nd from the top, Figure 15). This template was correlated with the entire CBSF ECG waveform and the result displayed in the waveform, third from the top. Note that each ECG cycle is now precisely identified by a “spike”.

The bottom waveform (blue) shows the result of applying a rate detector to 3rd waveform to calculate the BPM using simple threshold control. The subject’s BPM is displayed before and during EPI.

Alternate BPM derivations

Rather than proceed with the Comb-Band-Stop-Filter/Template approach to deriving BPM waveforms, a user can attempt this streamlined approach as shown in Figure 16a.

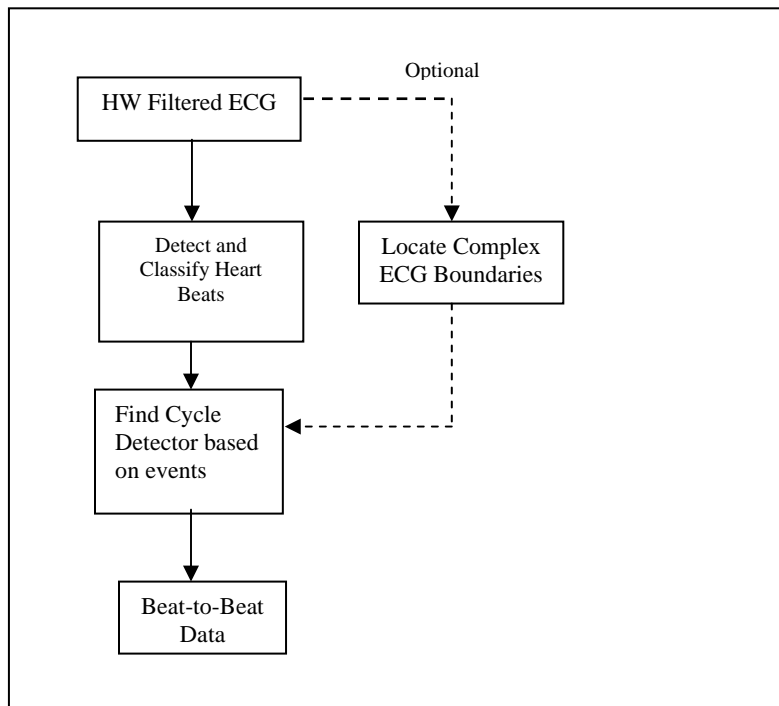


Figure 16a: Alternate path to deriving beat-to-beat data

Since the ECG signal has already been filtered using the ECG100C-MRI module, event classifiers then the Find Cycle tool can be invoked to determine BPM metrics. There are two basic hemodynamic classifiers that can be used. The first is invoked using:

Analysis > Detect and Classify Heartbeats

The classifier will impart annotations or markers to the waveform denoting types of heartbeats the algorithm deciphers (see Figure 16b).

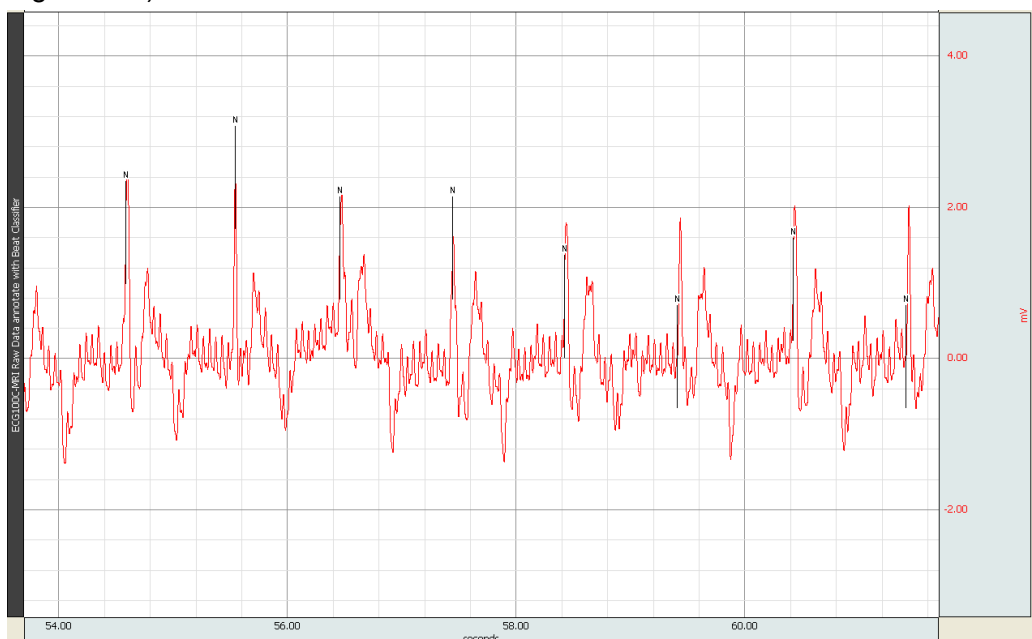


Figure 16b: Beat classifications on the ECG100C-MRI filtered data. "N" denotes a normal heartbeat

A second classifier is invoked using this menu selection:

Analysis > Locate ECG Complex Boundaries

Upon applying this tool, waveforms are annotated in the following manner as shown in Figure 16c.

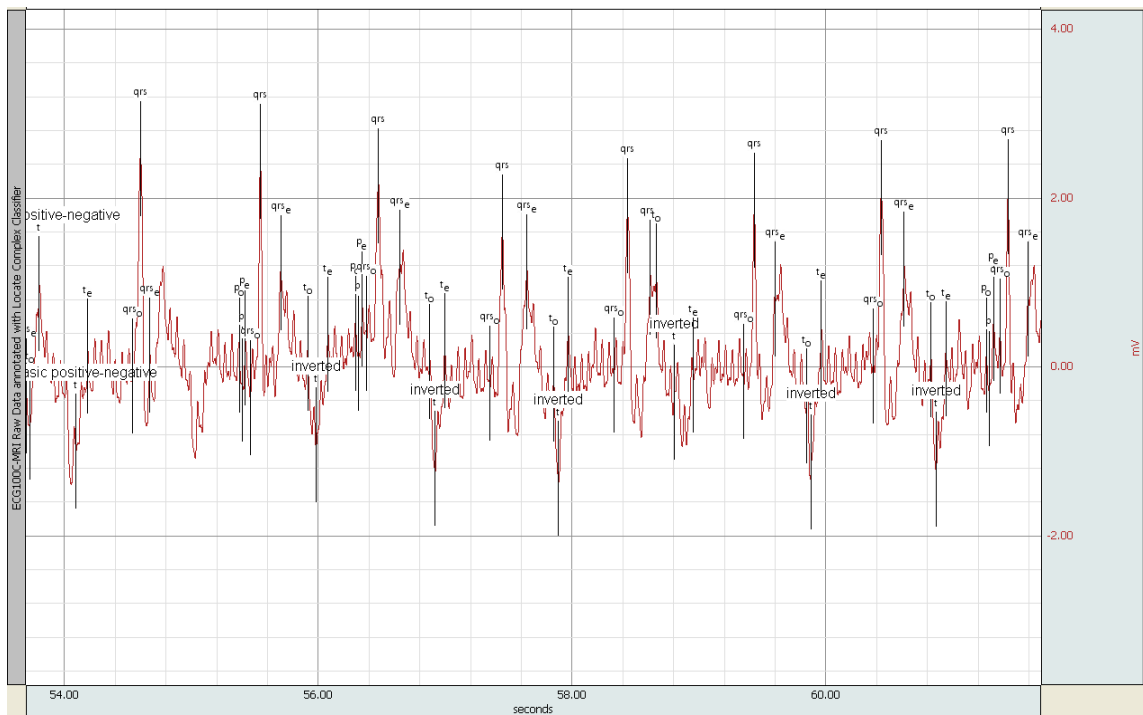


Figure 16c: ECG complex classifications on ECG100C-MRI filtered data. “qrs” denotes the QRS complex peak.

Upon classifying the waveforms, the Find Cycle detector can be invoked to determine BPM data. (see Section 3.7). The Find Cycle detector is applied to the waveforms of Figures 16b, c and the results are shown in Figure 17a along with the BPM data derived from using a template-match approach.

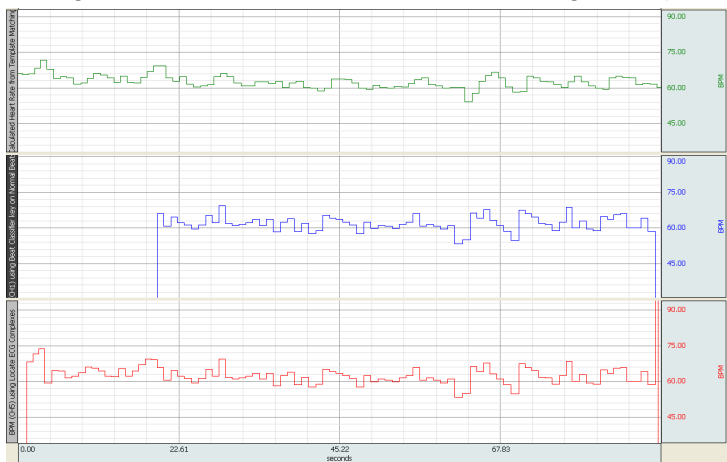


Figure 17a

- Top waveform: Template-Match
- Second waveform: Beat Classifier
- Bottom waveform: Locate ECG Complexes

Note that the BPM curves from the “Beat Classifier” and “Locate ECG Complex” methods give similar profiles, though the “Beat Classifier” appears to require a training period before valid beat detection commences.

Figure 17b shows an overlap view of the three BPM curves.

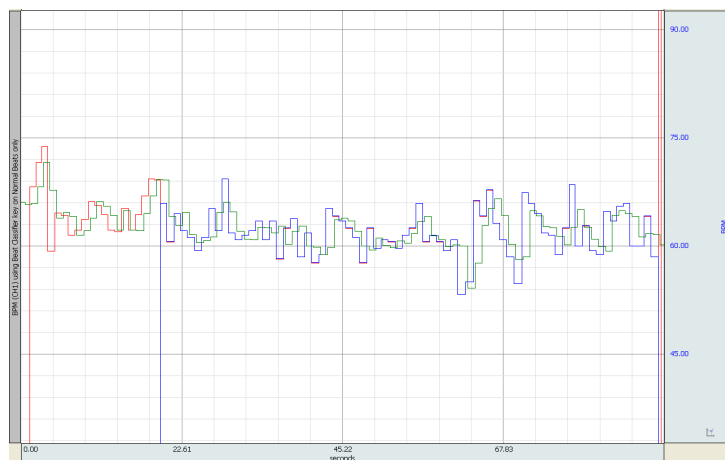


Figure 17b: Overlap view of Figure 17a