

BRAVEHEART: Open-Source Software for Automated Electrocardiographic and Vectorcardiographic Analysis

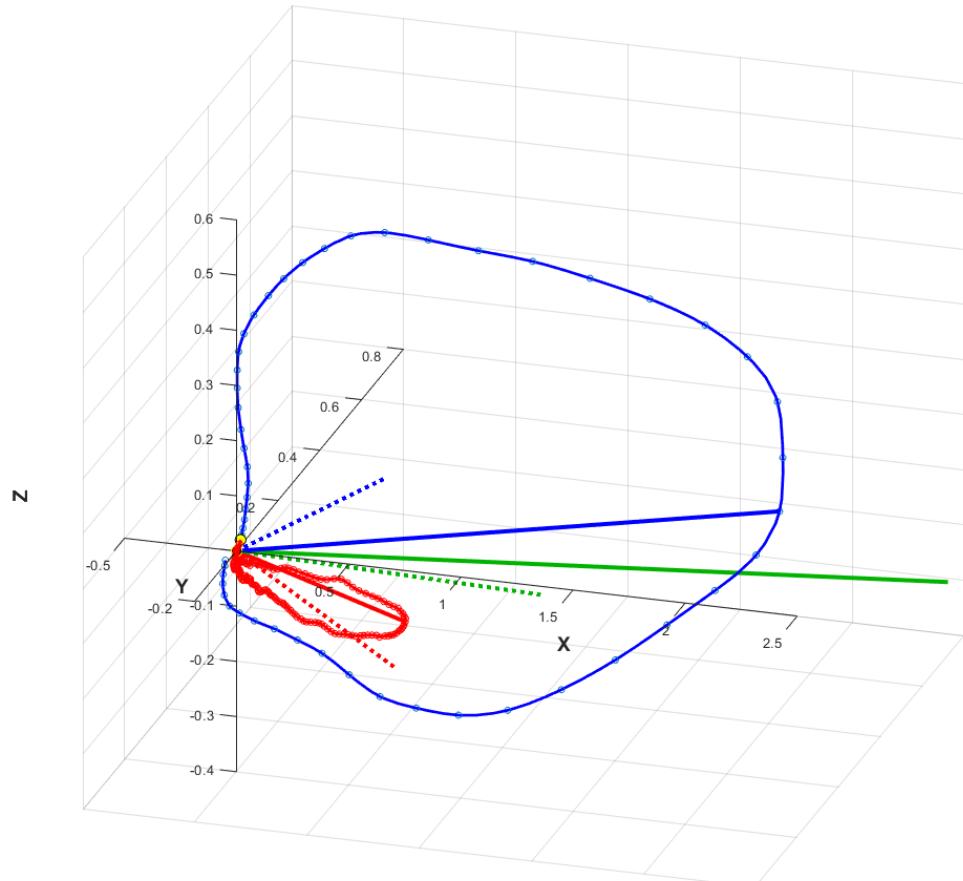
User Guide

Software Version 1.0.0

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<http://www.github.com/BIVectors/BRAVEHEART>



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1 Introduction

BRAVEHEART (**Beth Israel Analysis of Vectors of the Heart**) is a modular, customizable, open-source software package for processing electrocardiograms (ECGs) and vectorcardiograms (VCGs) for research purposes. BRAVEHEART was built using MATLAB and requires a version after R2022a (<http://www.mathworks.com>). The most up to date version of the software can be found on GitHub at <http://www.github.com/BIVectors/BRAVEHEART>, where the software, source code, and executables for Windows and Mac are available under version 3 of the General Public License (GPL) (<http://www.gnu.org/licenses/gpl-3.0.en.html>).

The following document contains information on how to use BRAVEHEART and how to efficiently edit select parts of the source code to allow addition of new ECG formats, transformation matrices, and ECG/VCG parameters. Information on the inner-workings of the software is also provided to facilitate understanding exactly what the software is doing at each step of ECG/VCG processing. This document is focused on use of the BRAVEHEART software. For additional, detailed information on the methodology behind various aspects of signal processing and annotation, please see our separate methods manuscript [1] which is also available on the BRAVEHEART GitHub repository as file `braveheart_methods.pdf`.

BRAVEHEART is available in different packages that will fit the needs of different types of users. `braveheart_batch.m` is a command line based program without any graphical user interface (GUI) that is able to rapidly process directories of ECGs by setting a few parameters. `braveheart_gui.m` is a GUI based version of BRAVEHEART that allows additional control over every aspect of ECG/VCG processing and additional types of signal processing and data visualizations. Both the command line version and GUI version of BRAVEHEART are also available as compiled executables for Windows and Mac computers that can be run without the need to have MATLAB installed.

We hope that BRAVEHEART will be helpful for your ECG/VCG research projects and welcome any feedback, bug reports, criticisms, or suggestions that you have while using BRAVEHEART. We can be contacted at braveheart.ecg@gmail.com with any questions, suggestions, or concerns.

2 Version History/Changelog

- v1.0.0 – 3/1/2023: Initial public release

3 Abbreviations

- BIDMC – Beth Israel Deaconess Medical Center
- BMI – body mass index
- bpm – beats per minute
- DC – direct current
- DICOM – Digital Imaging and Communications in Medicine
- ECG – electrocardiogram
- GPL – general public license
- GUI – graphical user interface
- HL7 – Health Level Seven
- HR – heart rate
- ISHNE – International Society for Holter and Noninvasive Electrocardiology
- LSTM – Long-Short Term Memory
- NN – neural network
- NCC – normalized cross correlation
- OS – operating system
- PVC – premature ventricular contraction
- Q_{on} – QRS complex onset
- Q_{off} – QRS complex end/offset
- RMSE – root mean square error
- SNR – signal to noise ratio
- SVG – spatial ventricular gradient
- T_{off} – T Wave end/offset
- VCG – vectorcardiogram
- VM – vector magnitude
- XML – extensible markup language

4 Installation

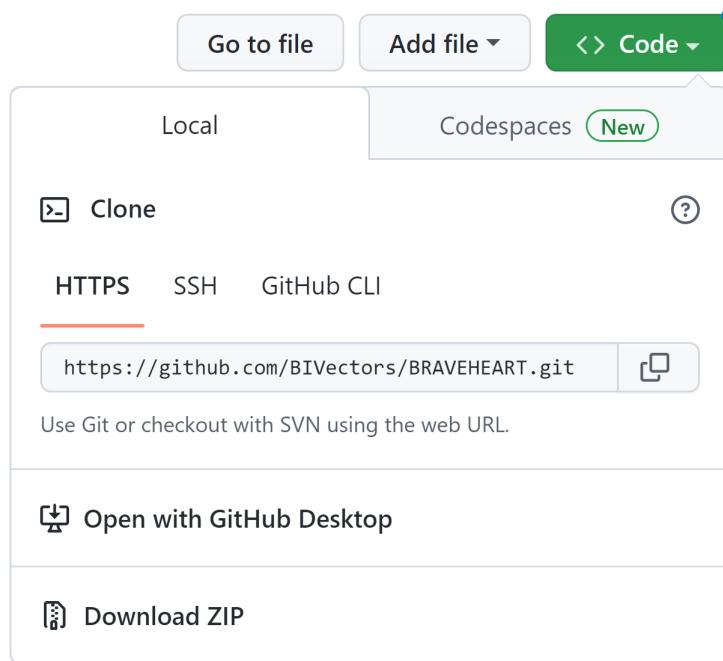
The most up to date MATLAB source code and executables for Windows and Mac operating systems can be found on the BRAVEHEART GitHub repository at
<http://www.github.com/BIVectors/BRAVEHEART>.

4.1 Using MATLAB Source Code (For Users With MATLAB)

Using BRAVEHEART via source code **requires MATLAB R2022a or later** and the following toolboxes (<https://www.mathworks.com/products.html>):

- Signal Processing
- Deep Learning
- Wavelet
- Parallel Computing (optional)
- Image Processing (optional – only for reading DICOM files – see **Chapter 21**)

Open the BRAVEHEART GitHub and click on the  button:



From here you can download a `.zip` file of all of the source code or clone the GitHub repository to your computer.

You can now view/edit/run the source code:

- To run the GUI version of BRAVEHEART run `braveheart_gui` from within MATLAB as described in detail in **Chapter 10**.
- To run the command line version of BRAVEHEART run `braveheart_batch()` from within MATLAB as described in detail in **Chapter 11**.

4.2 Using Executables (For Users Without MATLAB)

If you do not have access to MATLAB, or if you have MATLAB but do not have access to all of the required toolboxes, BRAVEHEART can be run via a compiled executable which contains the core MATLAB functions and all of the required and optional MATLAB toolboxes. Open the BRAVEHEART GitHub and navigate to the ‘Releases’ link on the right hand side, or go directly to <http://github.com/BIVectors/BRAVEHEART/releases>.

Releases 1

 **BRAVEHEART v1.0.0** Latest
3 days ago

3 days ago
 BIVectors
v1.0.0
2ffe86c
Compare ▾

BRAVEHEART v1.0.0 Latest

Initial public release

▼ Assets 6

 braveheart_mac_1.0.0.zip	48.9 MB	3 days ago
 braveheart_mac_1.0.0.zip.md5	32 Bytes	3 days ago
 braveheart_windows_1.0.0.zip	49.6 MB	3 days ago
 braveheart_windows_1.0.0.zip.md5	32 Bytes	3 days ago
 Source code (zip)		3 days ago
 Source code (tar.gz)		3 days ago

Note that the most current release may be after v1.0.0 and we suggest that you download the most recent version of the software. Download the `.zip` file that is appropriate for your operating system, unzip it, and then follow the instructions below. The files `braveheart_windows_x.x.x.zip.md5` and `braveheart_mac_x.x.x.zip.md5` contain the MD5

hashes for their respective `.zip` files (where `x.x.x` is the release version) if you would like to verify the contents of the `.zip` file before unzipping.

You must unzip/install the executable in a folder that has write access so that various files that are required for BRAVEHEART to function are editable.

4.2.1 Install the MATLAB Runtime

The MATLAB Runtime is a set of libraries that allow execution of compiled MATLAB code.

The **R2022a (9.12)** version of the Runtime must be installed to run any version of the compiled BRAVEHEART programs.

The MATLAB Runtime only needs to be installed once. To install there are 2 options:

1. Go to <https://www.mathworks.com/products/compiler/matlab-runtime.html> and download the **R2022a (9.12)** Runtime for Windows or Mac.
2. Within the downloaded `.zip` file there is a shortcut to directly download the appropriate (Windows or Mac) Runtime version.

After downloading, run the MATLAB Runtime installer and follow the instructions to complete the installation. Depending on the security settings of your computer you may need administrator rights to install the MATLAB Runtime.

4.2.2 Install BRAVHEART Executables on a Windows PC

After installing MATLAB Runtime R2022a (see above), unzip the `braveheart_windows.zip` file in a directory that has write access (on some systems, depending on security settings, the ‘Program Files’ folder may not work). You will see the 12 following files/folders:

- `braveheart_gui.exe` – BRAVEHEART GUI version (see **Chapter 10**).
- `braveheart_batch.exe` – BRAVEHEART Command line version (see **Chapter 11**).
- `Annoparams.csv` – File to edit annotation parameters (see **Chapter 6**).
- `ecg_formats.csv` – File to add new ECG formats (see **Chapter 7**).
- `transform_mats.csv` – File to add new transformation matrices (see **Chapter 8**).
- `batch_settings.csv` – File to edit command line batch parameters (see **Chapter 11**).
- `quality_presets.csv` – File to edit quality parameters (see **Chapter 14**).

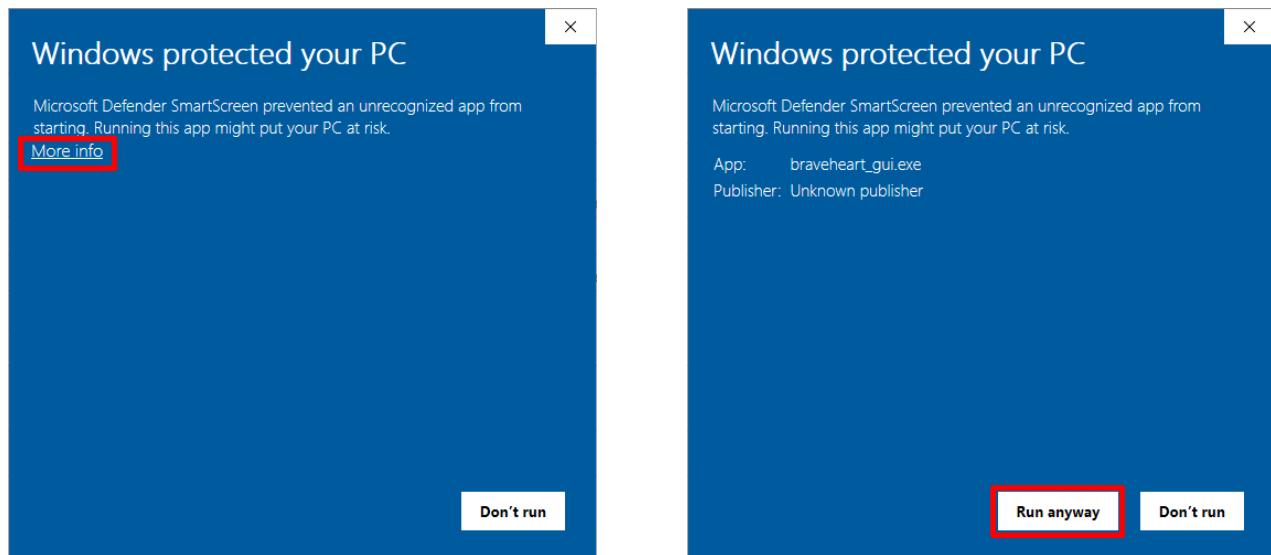
- `search_presents.csv` – File to edit annotation presets (see **Chapter 19**).
- `braveheart_userguide.pdf` – This file.
- `Example ECGs` – Directory containing 4 example ECG files (see **Chapter 5**).
- `Download MATLAB Runtime - Windows 64 bit` – Link to download MATLAB Runtime.
- `splash.png` – Image used while loading.

The external `.csv` files can be edited as needed and described in later sections of the user guide. If you are unable to edit the `.csv` files, unzip `braveheart_windows.zip` in a different directory with write access. The `.csv` files need to be in the same directory as the `.exe` files.

Double click on `braveheart_batch.exe` or `braveheart_gui.exe` to run the program.

Whitelist BRAVEHEART on Windows Runtime Protection

Depending on your version of windows and your anti-virus software, when you run `braveheart_gui.exe` or `braveheart_batch.exe` for the first time, a pop-up may block execution of the program. If the Windows Defender pop-up blocks execution of the program simply click “More Info” and then “Run anyway”:



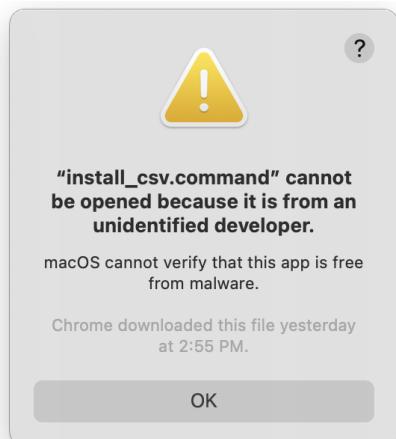
The exact appearance and text may vary depending on your version of Windows and specific security settings. If an alternative security program is in use, there will be a similar way of whitelisting the executable so that in the future, when you run it, the OS will not block it. This process will only have to be repeated if you install a new version of BRAVEHEART.

4.2.3 Install BRAVHEART Executables on a Mac

After installing MATLAB Runtime R2022a (see above), unzip the `braveheart_mac.zip` file in a directory that has write access. You will see the 15 following files/folders:

- `install_csv.command` – Script to copy `.csv` files to appropriate directory and to disable Mac OS runtime protection for relevant files (see next paragraphs in this section).
- `braveheart_gui.app` – BRAVEHEART GUI version (see **Chapter 10**)
- `braveheart_batch.app` – BRAVEHEART Command line version (see **Chapter 11**).
- `run_braveheart_gui.sh` – Script used by MATLAB
- `run_braveheart_batch.sh` – Script used by MATLAB
- `Annoparams.csv` – File to edit annotation parameters (see **Chapter 6**).
- `ecg_formats.csv` – File to add new ECG formats (see **Chapter 7**).
- `transform_mats.csv` – File to add new transformation matrices (see **Chapter 8**).
- `batch_settings.csv` – File to edit command line batch parameters (see **Chapter 11**).
- `quality_presets.csv` – File to edit quality parameters (see **Chapter 14**).
- `search_presets.csv` – File to edit annotation presets (see **Chapter 19**).
- `braveheart_userguide.pdf` – This file.
- `Example ECGs` – Directory containing 4 example ECG files (see **Chapter 5**).
- `Download MATLAB Runtime - Mac 64 bit` – Link to download MATLAB Runtime.
- `splash.png` – Image used while loading.

Double click `install_csv.command`. The first time that you run `install_csv.command`, Mac OS runtime protection may block it because it is from an “unidentified developer” and not signed:



To allow the script to run (this only has to be done once), **Control-click** `install_csv.command`, and choose “**Open**” from the menu. When the popup below appears, click `Open`:



This process will only have to be repeated if you install a new version of BRAVEHEART.

A script will run in Terminal. Enter your system password and press `return` on the keyboard.

This script moves the 6 necessary external `.csv` files noted above to the `home/users/<username>/braveheart` directory where they can be edited. The files are removed from the current directory after the script has run successfully. If you prefer, the files can also be moved to the folder manually.

Entering your system password is necessary because the script also whitelists `braveheart_gui.sh`, `run_braveheart_gui.sh`, `braveheart_batch.sh`, and `run_braveheart_batch.sh` for the Mac OS Gatekeeper runtime protection so the software can run without needing to manually whitelist each file. This is performed by removing the file attributes that blacklist an unsigned file from Gatekeeper and requires your system password:

```
sudo xattr -d com.apple.quarantine <filename>
```

If you prefer to not run the script, you will have to manually whitelist the `.app` and `.sh` files by **Control-clicking** on each file and choosing “**Open**” from the menu.

NOTE: Due restrictions with how compiled Matlab programs interact with the Mac OS, the above `.csv` files **must** be kept/edited in the `home/users/<username>/braveheart` directory. If

the files are placed/edited in another directory the program will not run and edits to the `.csv` files will not be recognized. This restriction on where the `.csv` files must be stored is unique to the Mac operating system. The executable `.app` files and their associated `.sh` files can be stored in any directory.

Double click on `braveheart_batch.app` or `braveheart_gui.app` to run the program.

5 Quick Start Using the BRAVEHEART GUI

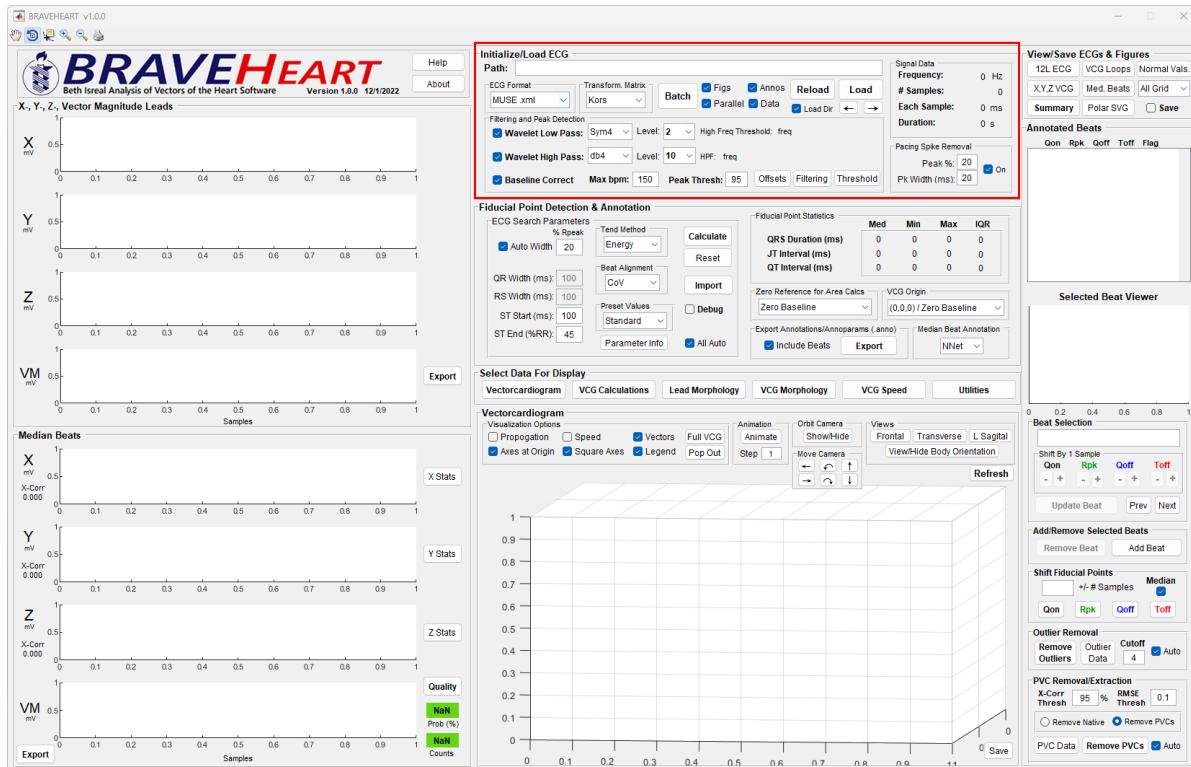
The following sections are provided as a way to “quick start” use of the BRAVEHEART GUI. Details on using BRAVEHEART in command line mode are provided in **Chapter 11**. Your understanding of the BRAVEHEART GUI will be better if you understand `Annoparams.m` (**Chapter 6**) and the specifics functions in each GUI section (**Chapter 10**), but this section is designed to get you using BRAVEHEART quickly, while showing you common functions.

This quick start guide uses 4 ECG files, (`example1.xml`, `example2.xml`, `example3.xml`, and `example4.xml`) which are available on the BRAVEHEART GitHub repository in GE MUSE XML format (see **Chapter 21**).

5.1 Example 1 - Good Quality ECG

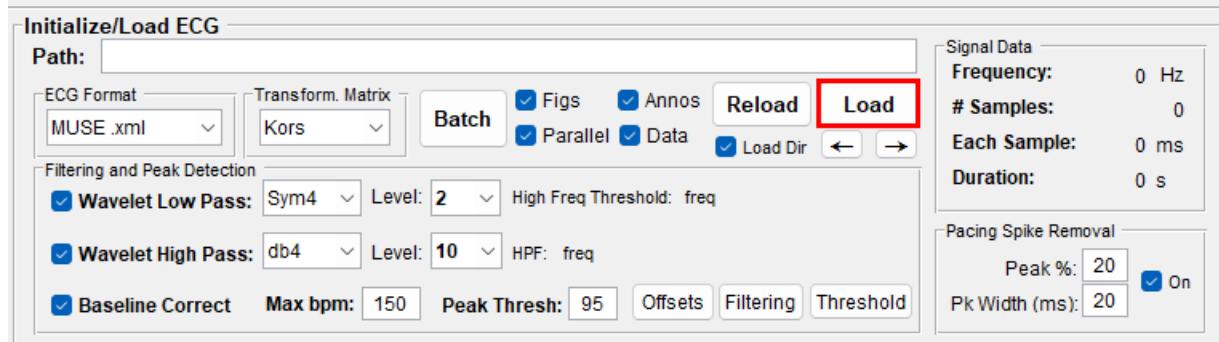
In this example we will load and process an ECG without any ectopy or significant noise/artifact using the standard filtering and annotation settings, and save the results to an external file.

Start at the highlighted ‘Initialize/Load ECG’ section:



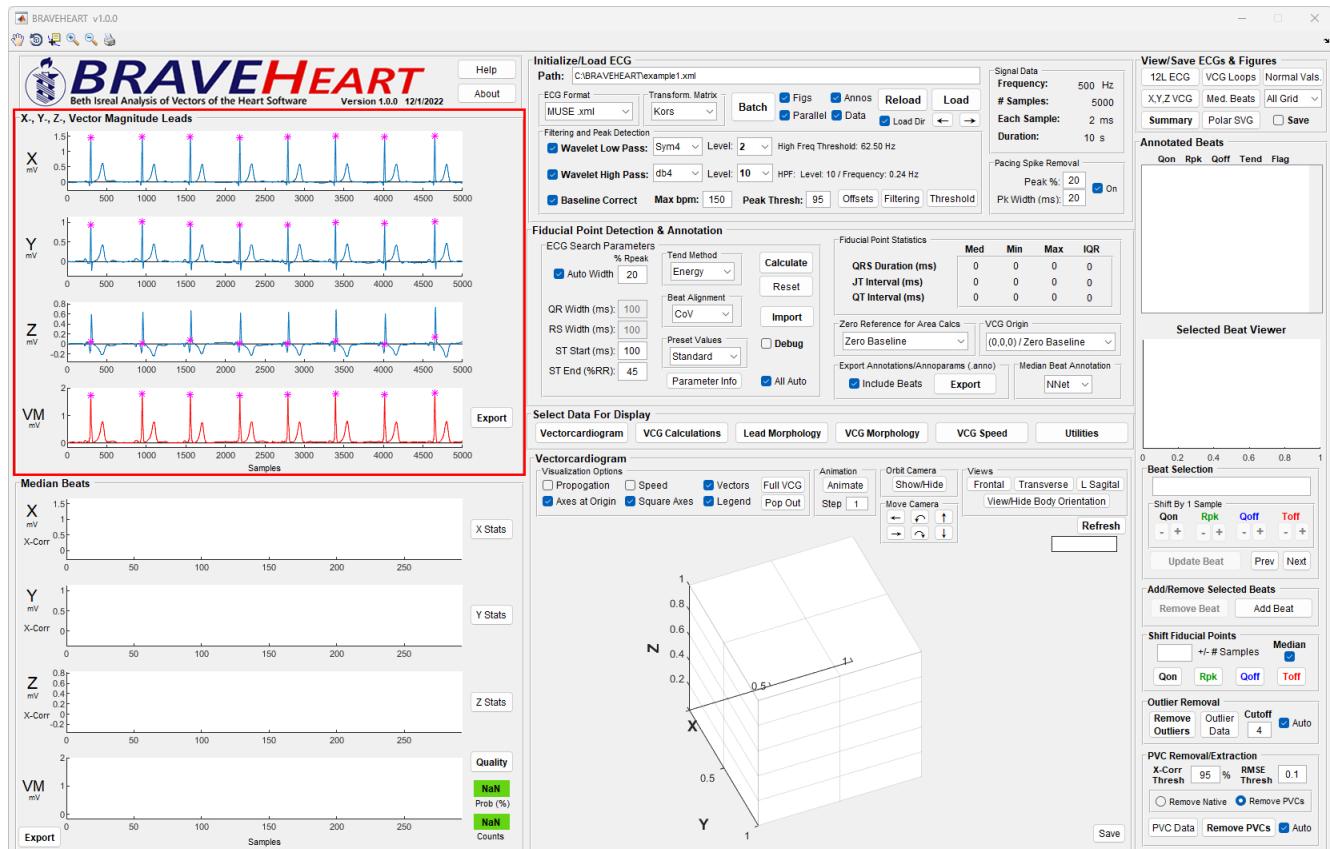
The ‘Initialize/Load ECG’ section of the GUI controls loading ECG files, filtering, baseline correction, and transformation into a VCG.

Click the **Load** button:



Select `example1.xml` from the appropriate directory and click ‘Open’ in the system dialogue box.

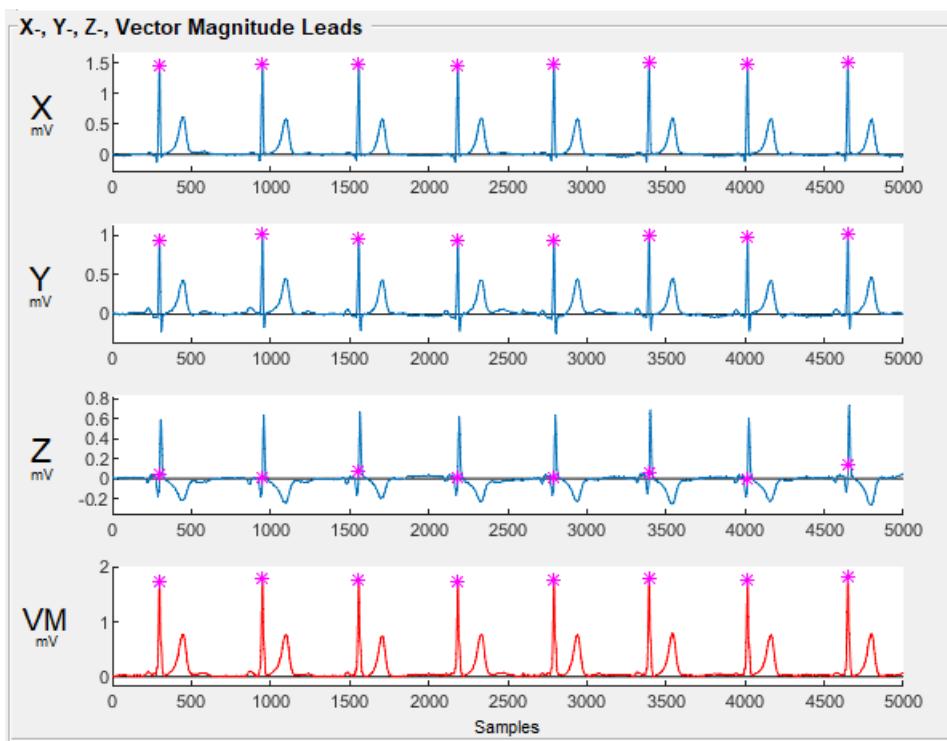
We see that the ECG has been loaded, converted into a VCG, and displayed in the upper left section of the GUI (‘X-, Y-, Z-, Vector Magnitude Leads’):



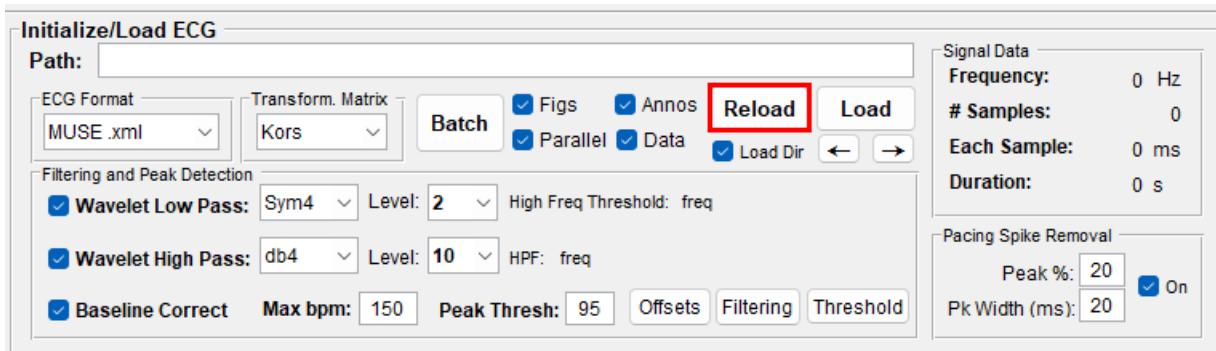
Once the ECG is loaded, we can view the standard 12-Lead ECG with 12 rhythm strips (**12L ECG**) and the VCG (**X,Y,Z VCG**) with rhythm strips by clicking on the appropriate buttons in the ‘View/Save ECG & Figures’ section in the upper right (see **Chapter 10.8** and **Chapter 18**):



In the upper left section of the GUI (‘**X-, Y-, Z-, Vector Magnitude Leads**’), note that each of the 8 R peaks has a magenta * which indicates the location of a detected R wave peak in the vector magnitude ($VM = \sqrt{X^2 + Y^2 + Z^2}$) lead. In this example we are able to visually confirm that QRST complexes were not missed or over counted:

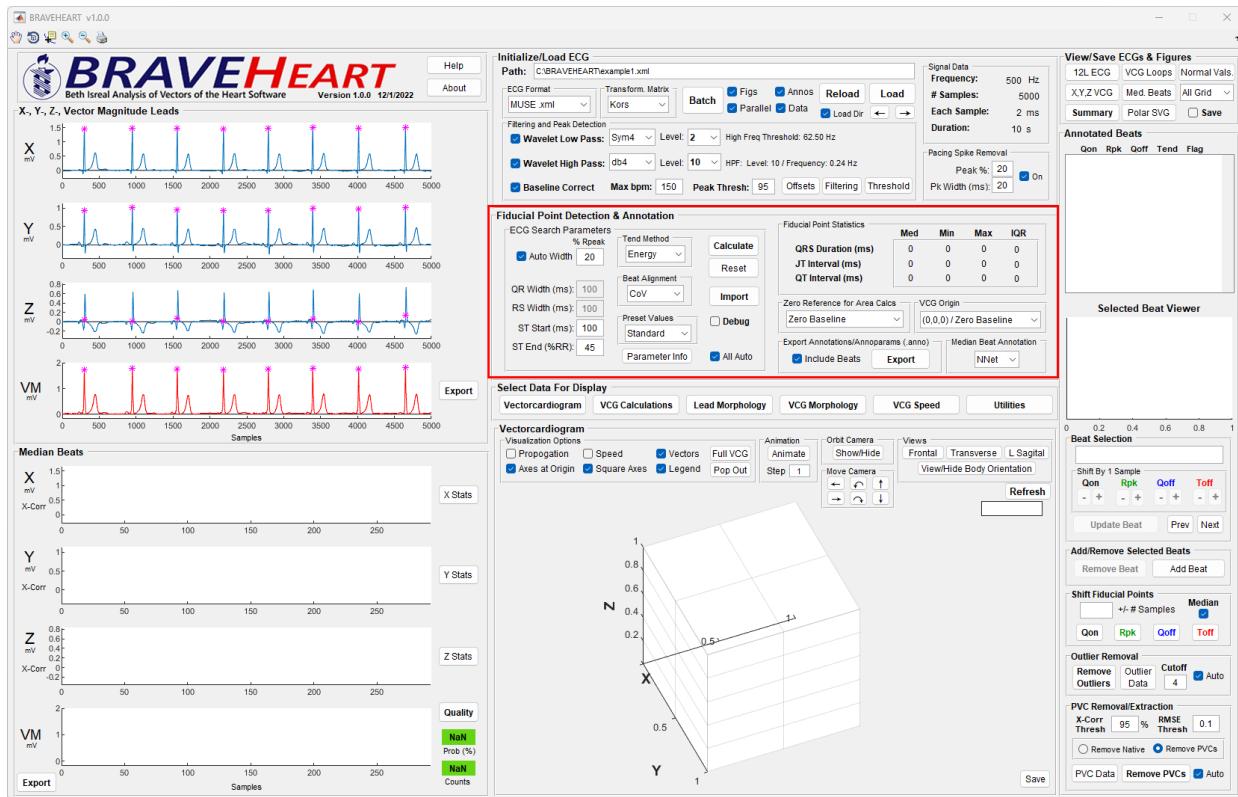


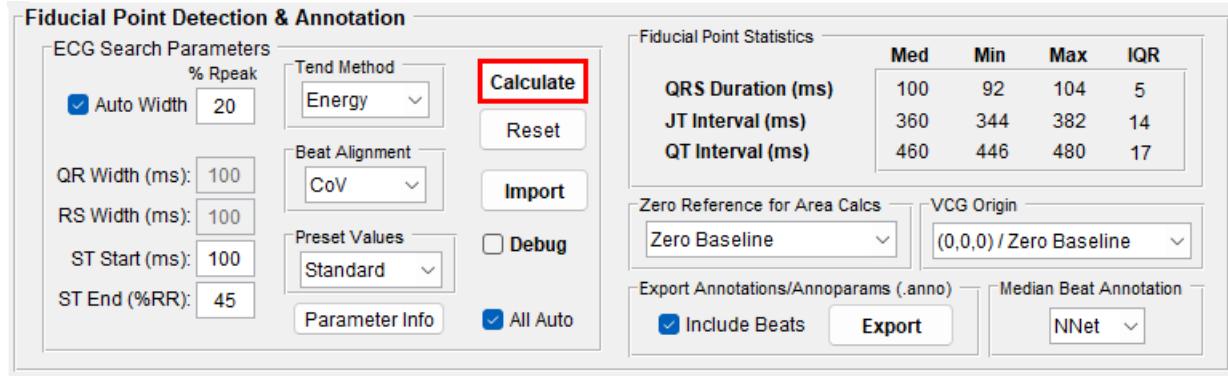
If we wanted to adjust ECG filtering parameters we would select the appropriate filtering parameters in the ‘**Initialize/Load ECG**’ section (see **Chapter 6.2** and **Chapter 10.2**) prior to clicking **Load**. Alternatively we could change the parameters after the ECG is loaded and then click **Reload** which is to the left of the **Load** button:



At this point the ECG has been loaded, filtered as appropriate, and converted into a VCG. We are now ready to further process the VCG with annotation, PVC/outlier beat removal, median beat construction, and calculations.

All of these processes can be performed by clicking the **Calculate** button in the 'Fiducial Point Detection & Annotation' Section:

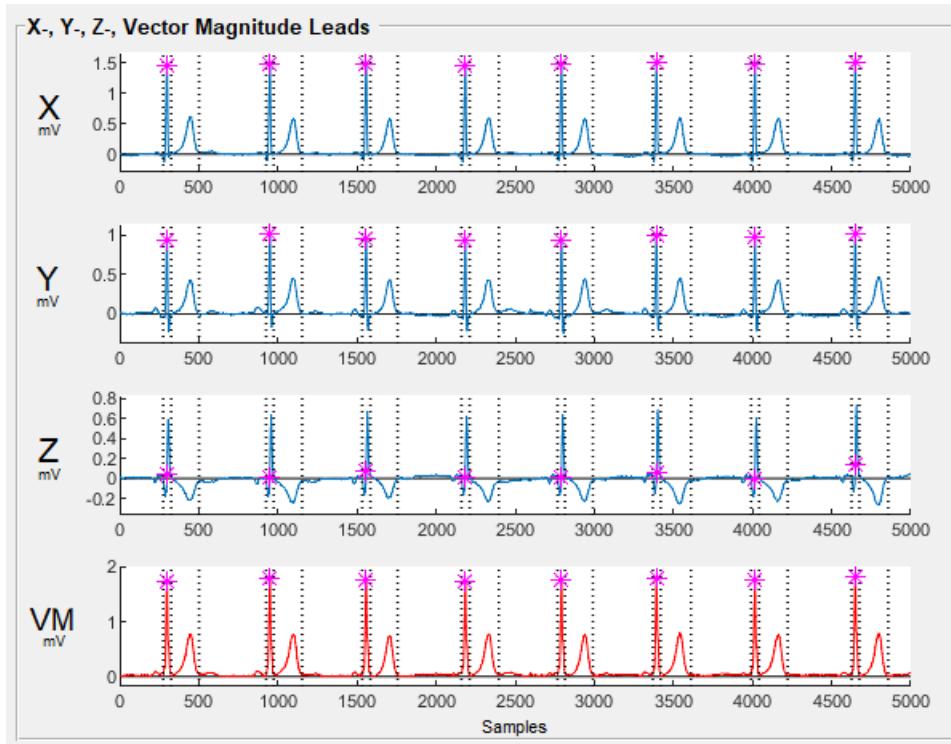




Click the **Calculate** button. The ECG is processed:



Note that after the ECG is processed using the **Calculate** button, new sections of the GUI have been filled in. For this ECG, no beats were detected as PVCs or outliers and removed (see **Chapter 13.3** and **Chapter 13.4**), and we see all beats continue to have a magenta *, indicating that they remain in the analysis. The ‘X-, Y-, Z-, Vector Magnitude Leads’ section in the upper left now also shows the QRS onset (Q_{on}), QRS offset (Q_{off}), and T wave offset (T_{off}) annotations for each beat as dashed vertical lines:

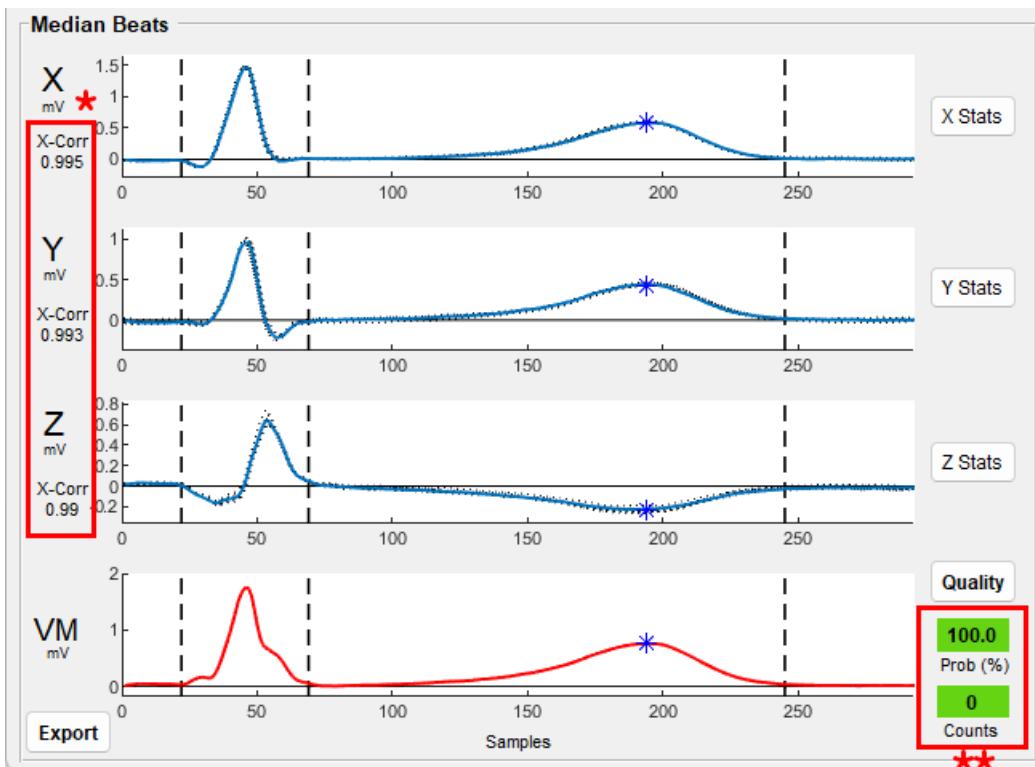


Since the ECG has been annotated, on the right of the GUI, in the ‘**Annotated Beats**’ section, we see the fiducial points (in samples – in the order of Q_{on} , R peak, Q_{off} , and T_{off}) which were used to segment out the 8 beats from the full ECG signals. These sample numbers correspond to the dashed lines and * in the ‘**X-, Y-, Z-, Vector Magnitude Leads**’ section noted above.

Annotated Beats (8)

Qon	Rpk	Qoff	Toff	Flag
275	299	326	502	
925	949	974	1153	
1533	1558	1585	1757	
2160	2184	2212	2396	
2768	2792	2814	2991	
3370	3393	3419	3610	
3991	4015	4042	4223	
4626	4650	4675	4858	

The median VCG beats (X, Y, and Z, and vector magnitude [VM]) are displayed in the lower left of the GUI in the ‘**Median Beats**’ section:



The individual beats that make up the X, Y, and Z median beats are displayed as black dotted plots, and the median beat fiducial points Q_{on} , Q_{off} , and T_{off} are denoted with vertical black dashed lines. This section also allows assessment of ECG processing quality. Note that the normalized cross correlation ('X-Corr') values for the X, Y, and Z leads on the left (red box with *) are all very close to 1, indicating that all of the beats that were used to construct the median beat are similar and aligned properly. The 'Prob (%)', in the lower right (red box with **), which is the predicted probability of the processed ECG being "good" quality, is 100%, and the number of poor quality flags ('Counts') is 0 indicating good quality processing. For further details of ECG quality assessment see **Chapter 14**.

Click on the **VCG Calculations** button in the middle of the GUI which displays calculations from the `VCG_Calc` results class (see **Chapter 22**):



This brings up the ‘VCG Calculations’ section which displays various VCG measurements and is also used for exporting all calculations (including parameters which are not displayed in the GUI). The controls for data export are shown in the bottom right:

Calculations		
Basic Parameters (ms) HR (bpm): 48 QT (ms): 446 QRS (ms): 94 QTc (Baz): 400 JT (ms): 352 QTc (Fr): 415 Tpeak: 344 Tpeak/QT: 0.771		
QRS Angle (°) Peak 3D QRST Ang: 19.97 Peak Front QRST Ang: 3.66 Area 3D QRST Ang: 40.85 Area Front QRST Ang: 12.33		
SVG Angles (°) Peak SVG-Peak QRS Ang: 5.98 Peak SVG-Peak T Ang: 13.99 Area SVG-Area QRS Ang: 29.31 Area SVG-Area T Ang: 11.54 Area SVG-Area SVG Ang: 7.83 Area SVG-Area QRS Ang: 13.77		
T Vector (mV-ms) & (*) Peak T Mag: 0.76 Area T Mag: 92.51 Peak T Az: -21.35 Area T Az: -27.65 Peak T El: 55.18 Area T El: 55.42		
Vector Ratios Peak QRST Ratio: 2.32 Area QRST Ratio: 0.41		
Vector Distances (mV) Area QRS & T: 68.54 Peak QRS & T: 1.08		
SVG Vector (mV-ms) & (*) Peak SVG Mag: 2.49 Area SVG Mag: 123.61 Peak SVG Az: -4.39 Area SVG Az: -13.78 Peak SVG El: 55.92 Area SVG El: 56.55		
VCG Path Length (mV) QRST Path Length: 6.33 T Path Length: 1.59 QRS Path Length: 4.73		
SVG Components (mV-ms) SVG x: 100.15↑ SVG y: 68.14↑ SVG z: -24.57		
SAI QRST (mV-ms) SAI x: 103.86 SAI QRST: 236.51↑ SAI y: 76.75 SAI vm: 148.49↑ SAI z: 55.89		
Data Export Dir.: C:\BRAVEHEART Select File: braveheart_output csv Note: <input type="button" value="Export Data (.csv)"/> <input type="button" value="Export Signals (.mat)"/>		

The default directory used to save files is the same directory from which the ECG was loaded. To change the directory for saving click **Select** and choose a new directory. The default file name for the saved data file is **braveheart_outut**; change this to what you want to name the output file.

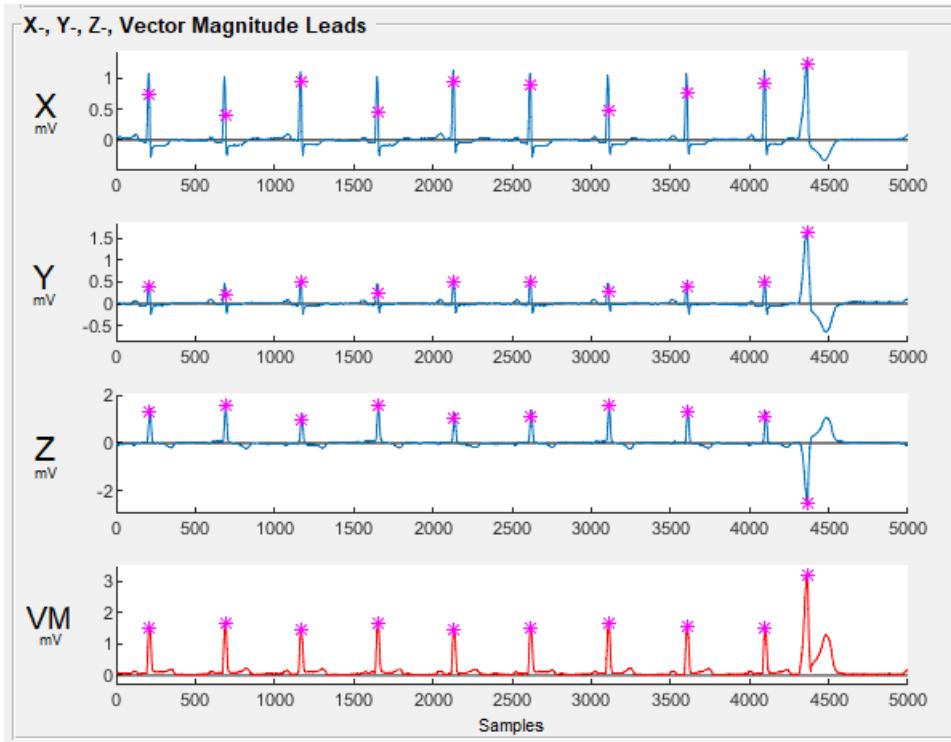
Once your file name and directory are set, click **Export Data (.csv)** to export the data to a **.csv** file located in the directory chosen above and with the specified file name. Once the file is successfully exported, **Success!** is displayed in green in the bottom right of the section.

5.2 Example 2 - ECG with PVCs

In this example we will load an ECG with a PVC, and show different ways of removing the PVC (see **Chapter 13.3** for additional information on PVC detection/removal).

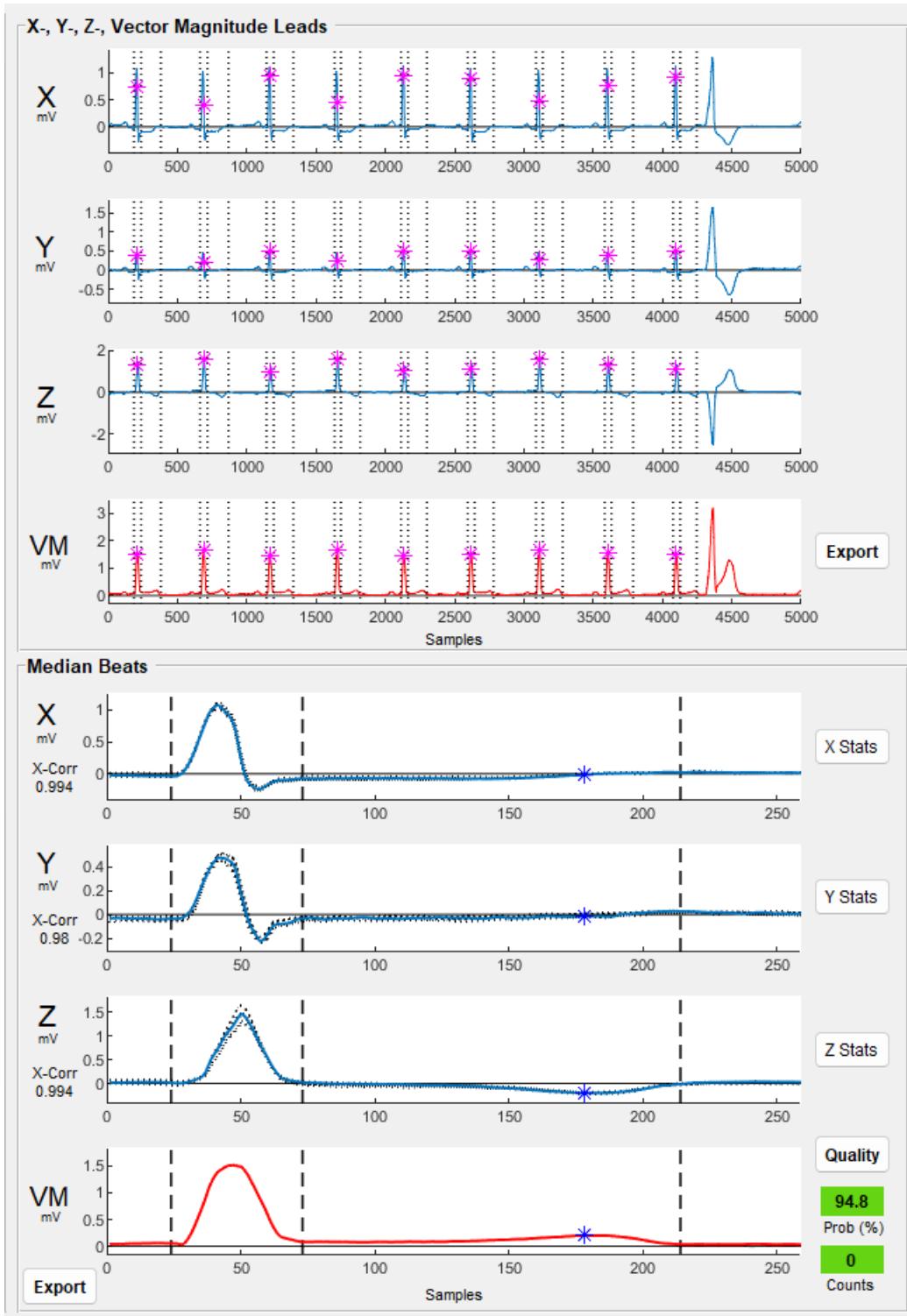
First load **example2.xml** using the **Load** button as noted above in Example 1 (**Chapter 5.1**).

By inspecting the ‘X-, Y-, Z-, Vector Magnitude Leads’ section, note that the last beat of this ECG is a PVC, and all beats/R peaks are correctly identified with a *****:



Click the **Calculate** button:

The ECG is processed, and because automatic PVC removal was turned on (this is enabled by default), the PVC is automatically removed. We can see the PVC has been removed by looking at the ‘X-, Y-, Z-, Vector Magnitude Leads’ section where we see that PVC does not have a * anymore, the fiducial points for the PVC are not present in the **Annotated Beats** section, and the PVC is not seen in the **Median Beats** section:



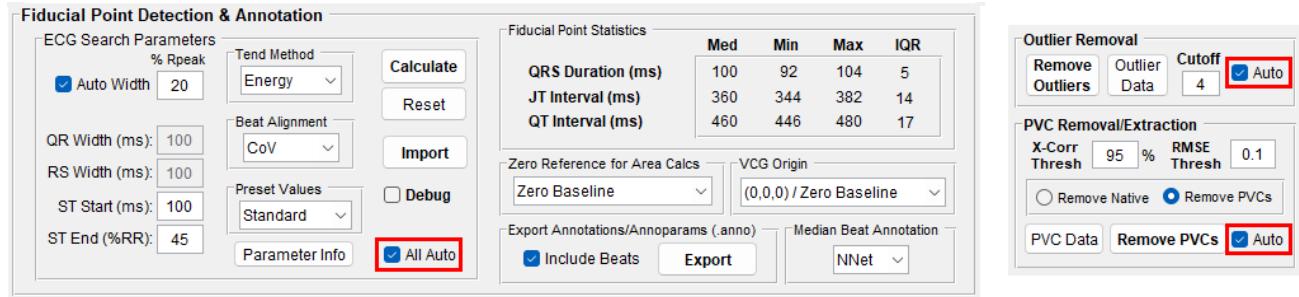
Also note that the Quality metrics (green text boxes in the lower right of the 'Median Beats' section show an excellent estimated quality ('Prob (%)') of approximately 95% (see **Chapter 14**).

Now click the **Reload** button:

The GUI is cleared and the ECG is reloaded without having to select the file again.

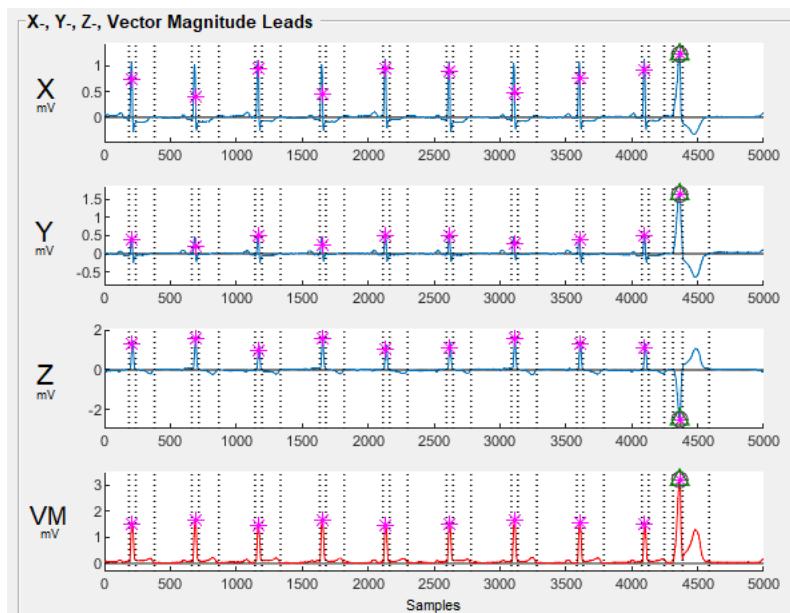
This time we will disable automatic PVC removal. We can do this by either unchecking

All Auto in the ‘Fiducial Point Detection & Annotation’ section which disables BOTH PVC and outlier removal, or by unchecking Auto in the PVC removal section in the bottom right of the GUI.



If you uncheck All Auto, the 2 Auto checkboxes in the PVC and outlier removal sections also become unchecked. Similarly, checking All Auto checks both Auto checkboxes.

Uncheck All Auto (and note that the 2 Auto checkboxes in the ‘PVC Removal/Extraction’ and ‘Outlier Removal’ sections also become unchecked), and then click **Calculate**. This time the PVC is not removed; note that in the ‘X-, Y-, Z-, Vector Magnitude Leads’ section, the PVC still has a * and annotations (dashed lines):

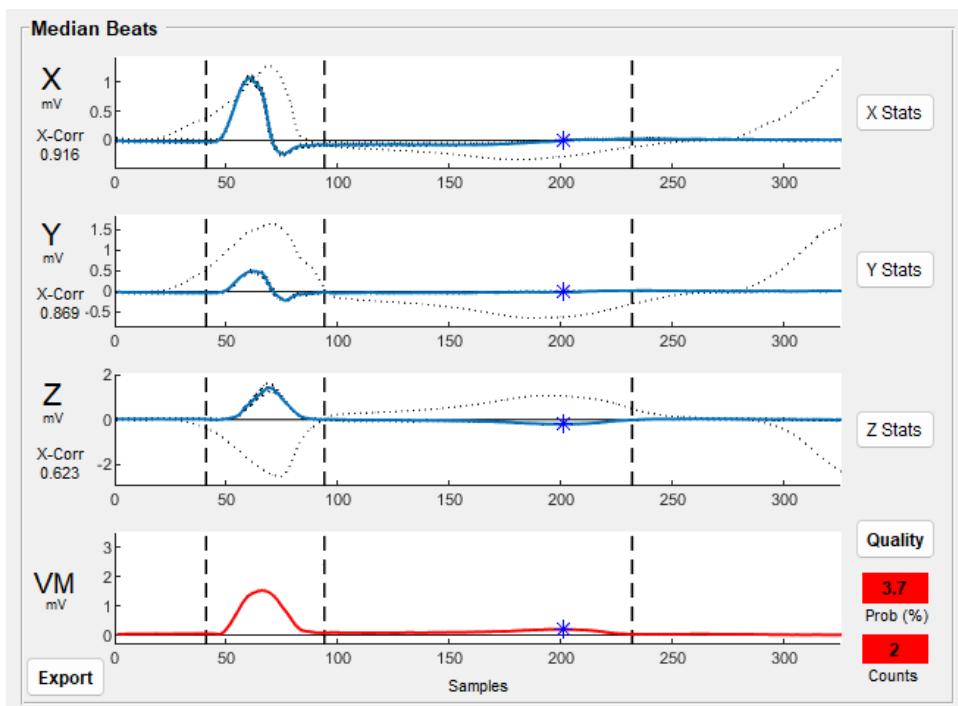


Also note that the PVC has a triangle around the * (Δ) which is how a beat that has been detected as a PVC is marked. In this case there is also a circle around the * because the PVC is additionally detected as an outlier (see Example 3 in **Chapter 5.3** and **Chapter 13.4**).

As the PVC is still present, the PVC fiducial points are also still present in the **Annotated Beats**' list where the PVC's fiducial points are followed by a '#', which is used to signify that the beat has been detected as a PVC by BRAVEHEART's PVC detection algorithm (the '**' denotes that this beat was classified as an outlier as well):

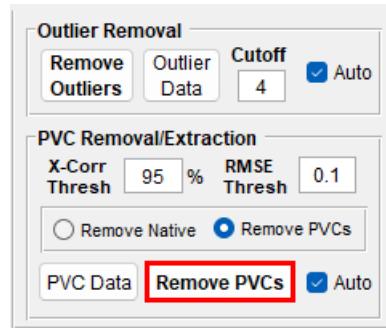
Annotated Beats (10)				
Qon	Rpk	Qoff	Toff	Flag
187	211	238	380	
663	691	716	867	
1143	1168	1195	1336	
1634	1655	1680	1818	
2112	2133	2163	2300	
2595	2618	2645	2780	
3087	3112	3136	3280	
3583	3607	3631	3789	
4076	4099	4128	4247	
4312	4363	4386	4587	** #

In the 'Median Beats' section the PVC is represented by a black dotted line that is different from the other beats:



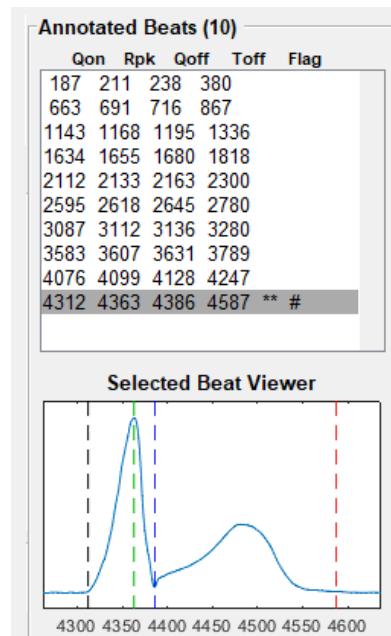
Also note that the quality metrics (red text boxes in the lower right of the ‘Median Beats’ section shows a low probability of “good” quality ‘Prob (%)’) of only 3.7% due to the PVC (see Chapter 14).

We will first remove the PVC using the PVC removal algorithm. In the ‘PVC Removal/Extraction’ section in the bottom right of the GUI, simply click **Remove PVCs**:

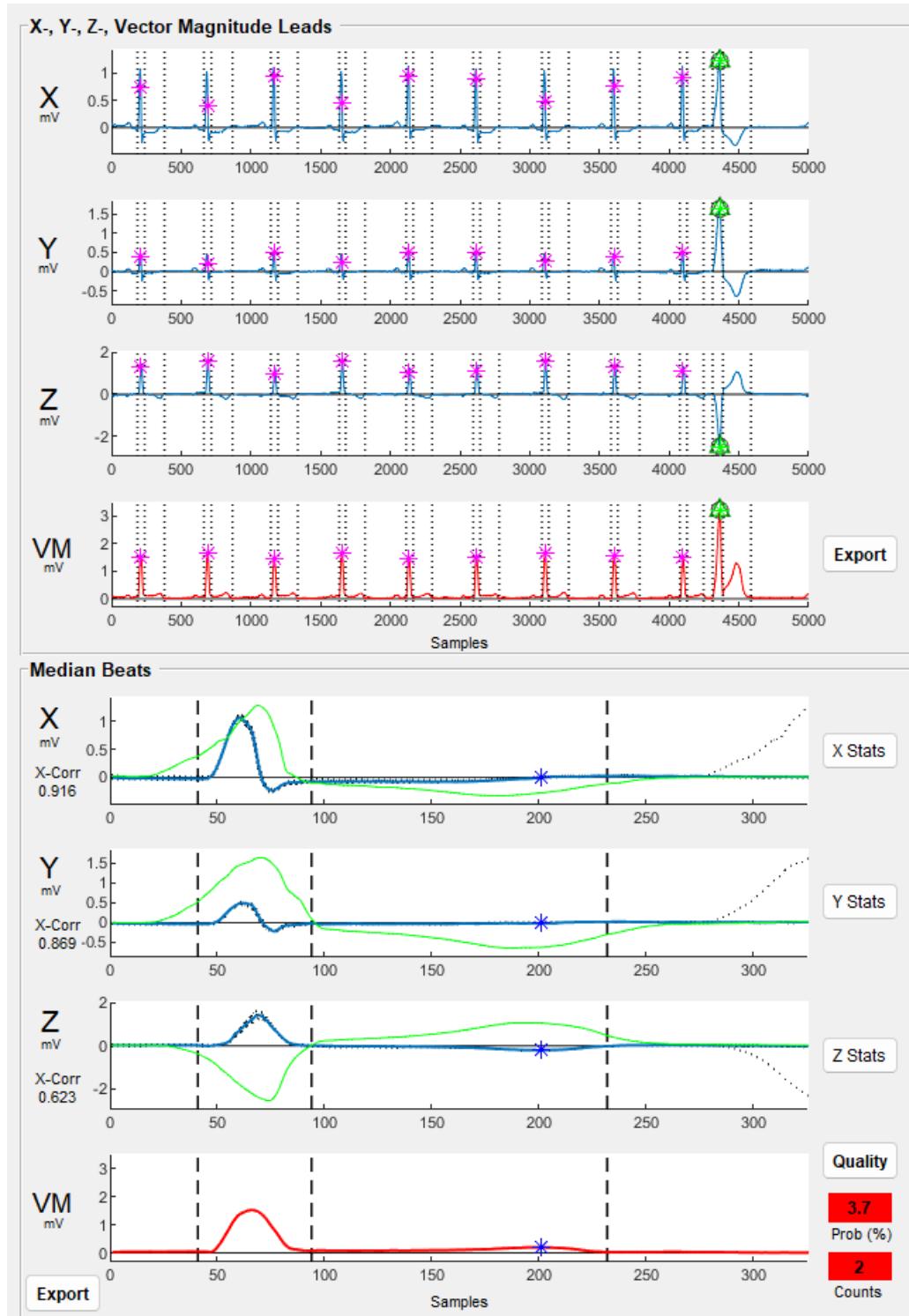


The ECG is reprocessed, the PVC is removed, and the median beat is recreated without the PVC.

Alternatively we could manually tell BRAVEHEART to remove the PVC. Reload the ECG with the **Reload** button. Click on the PVC beat in the ‘Annotated Beats’ list. The selected beat is highlighted in the list and appears in the ‘Selected Beat Viewer’ right below the ‘Annotated Beats’ list:



The selected beat is also highlighted with a green * in the ‘X-, Y-, Z-, Vector Magnitude Leads’ section, and the beat is highlighted in green in the ‘Median Beats’ section:



Click on the **Remove Beat** button in the ‘Add/Remove Selected Beats’ section:



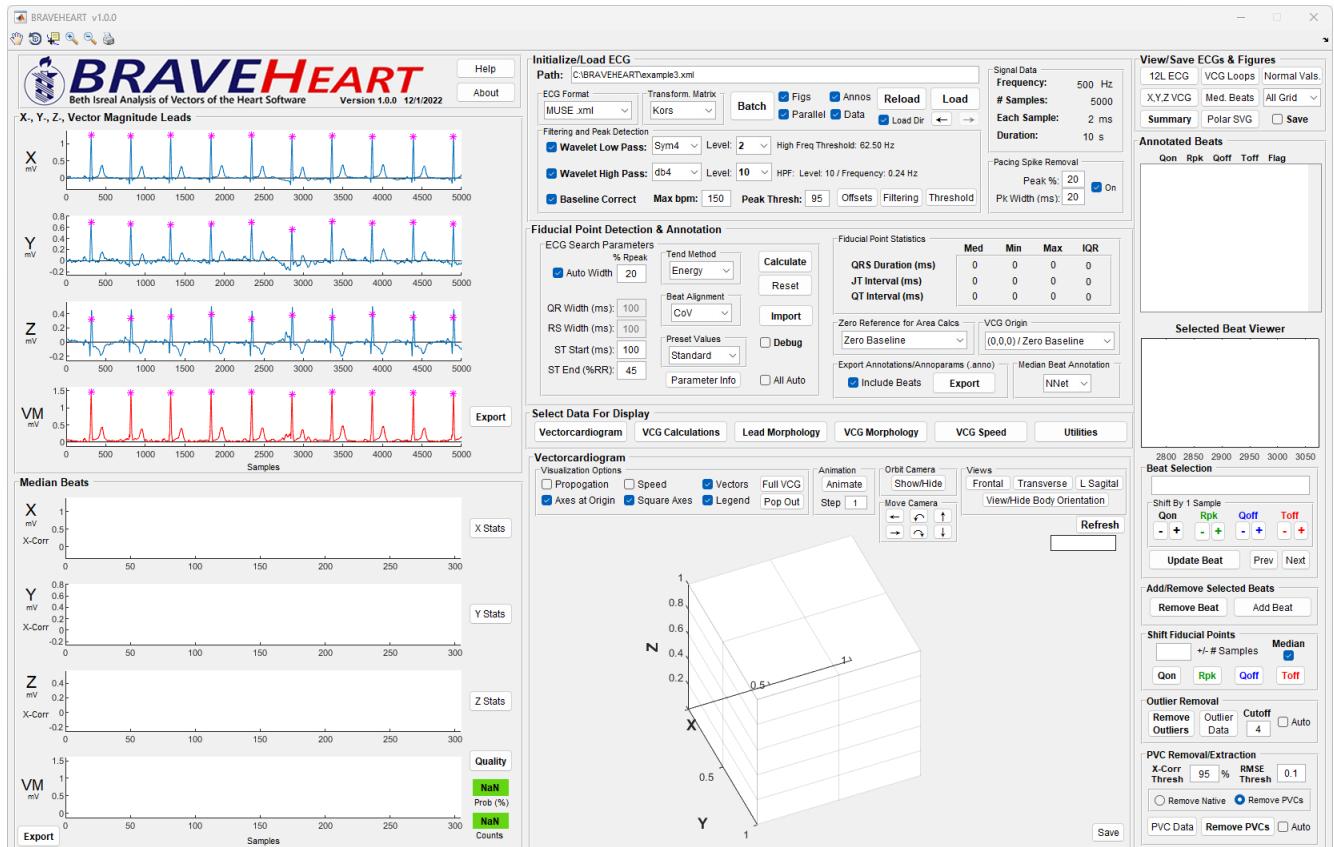
The ECG is reprocessed, the PVC is removed, and the median beat is recreated without the PVC. Once the PVC is removed, the estimated quality of the ECG is now high (94.8 % with green color background).

At this point, the data can be exported as noted above in Example 1 (**Chapter 5.1**).

5.3 Example 3 - ECG with Artifact

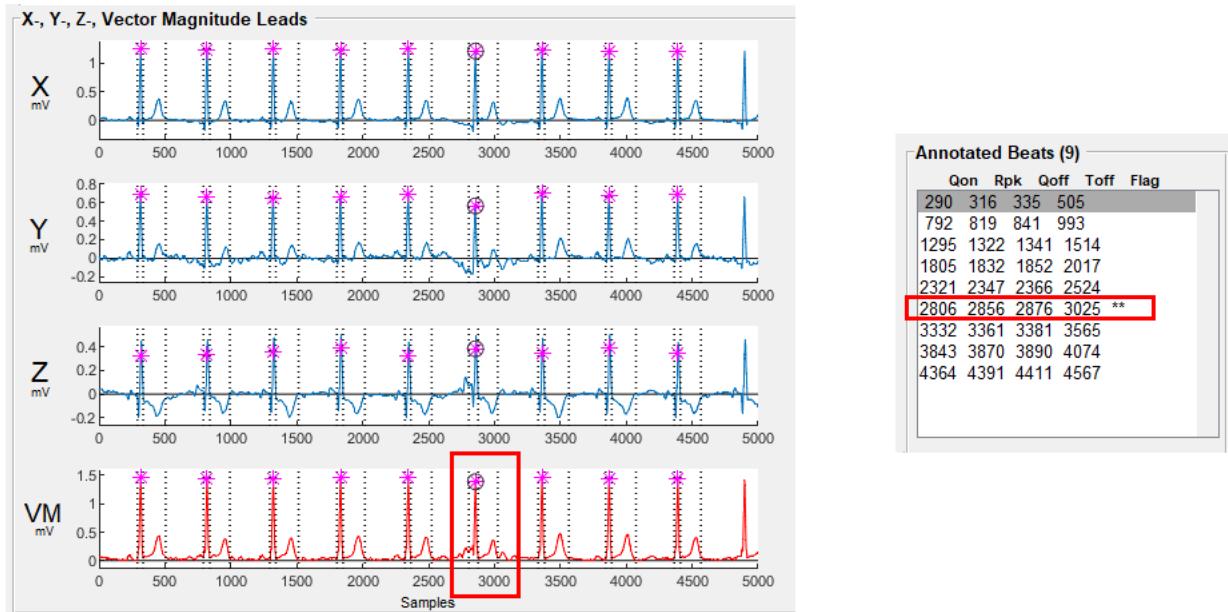
In this section we will load an ECG with focal noise that is removed with outlier detection and removal.

First load `example3.xml` and disable All Auto as noted above in Example 2 (**Chapter 5.2**).

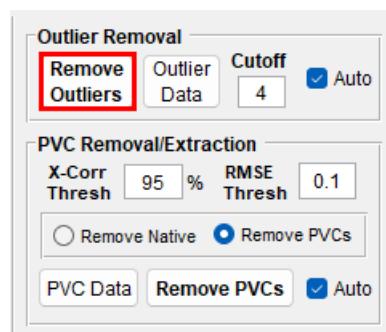


Note that the 6th beat has some focal noise.

Click the **Calculate** button. The 6th beat is identified as an “outlier” as noted by the circle around the * (✿), and the ‘**’ next to the beat in the ‘Annotated Beats’ section.



Had we had All Auto or the Auto in the ‘Outlier Removal’ section checked off, this beat, identified as an outlier, would have been automatically removed. In this case, however, because we disabled automatic outlier removal, we will have to manually remove the outliers similar to how PVCs are removed in Example 2 (Chapter 5.2). The outliers can be automatically removed by clicking the **Remove Outliers** button:

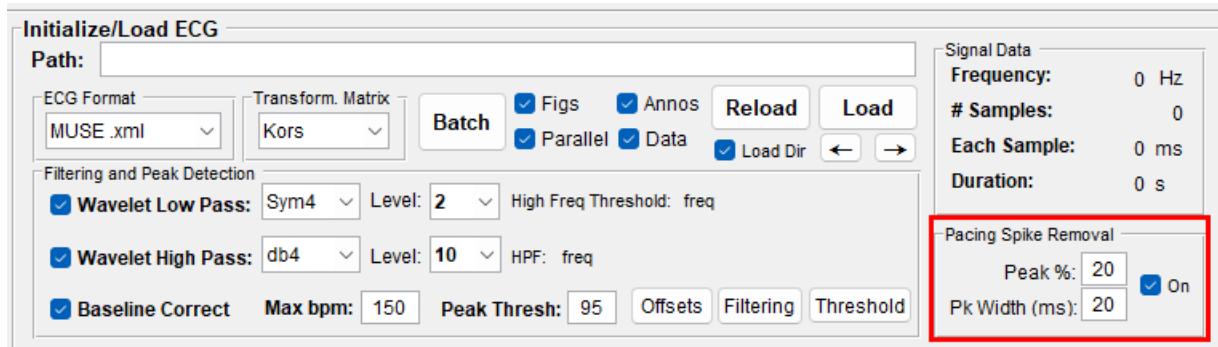


The outlier can also be removed by clicking on the beat in the ‘Annotated Beats’ section and then clicking the **Remove Beat** button in the ‘Add/Remove Selected Beats’ section as noted in Example 2 (Chapter 5.2).

5.4 Example 4 - Dealing with Pacing Artifact

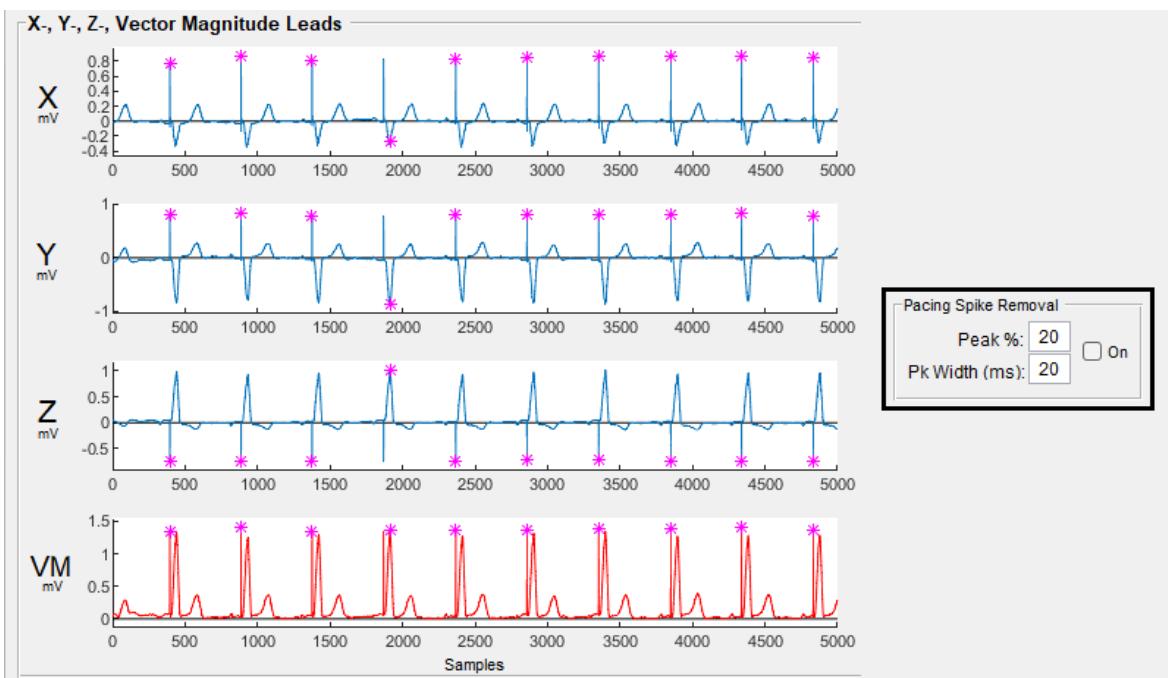
In this example we will see how BRAVEHEART deals with pacing artifact.

Pacemaker artifact detection and removal are controlled in the bottom right of the ‘Initialize/Load ECG’ section of the GUI:



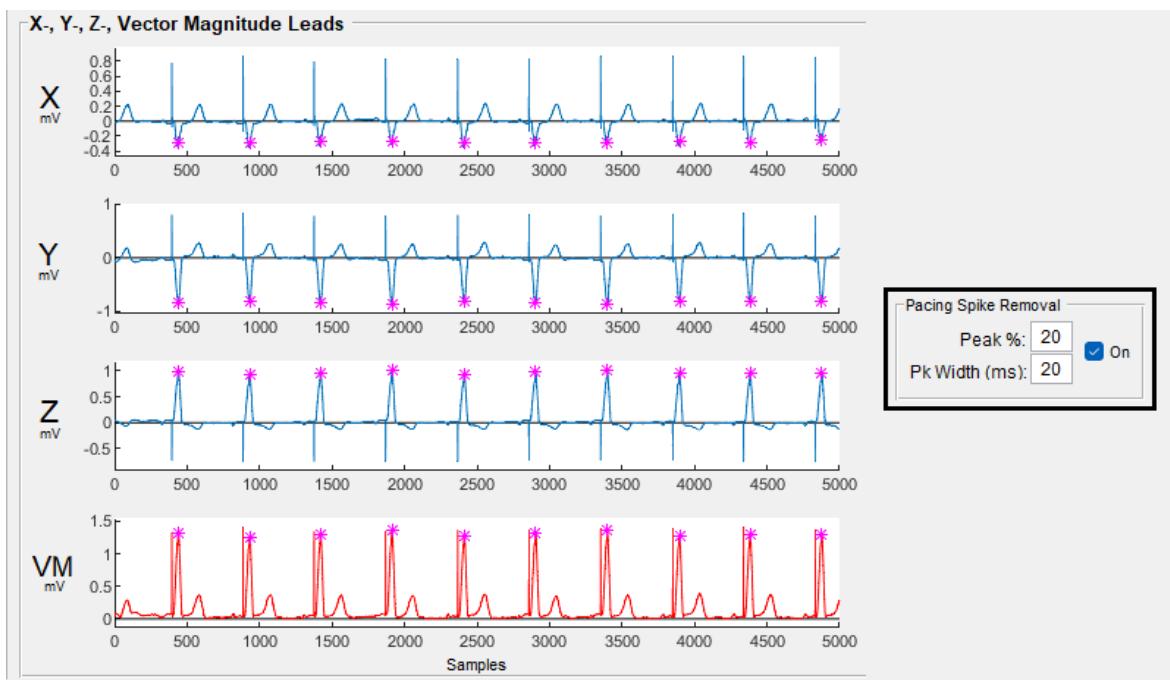
The ‘Peak %’ and ‘Pk Width (ms)’ textboxes usually can stay at their nominal values of ‘20’ and further details on these parameters are available in **Chapter 6.2**. We will focus on the On checkbox which enables/disables pacemaker artifact removal.

We will start by disabling pacemaker artifact removal by unchecking the On checkbox. Next, load `example4.xml` as noted in the above examples:



The ‘X-, Y-, Z-, Vector Magnitude Leads’ section shows that for almost all of the beats the R peak has been detected as the large pacing spike (see the location of the *) because in most beats the pacing artifact magnitude is larger than the QRS complex magnitude in the VM lead. This is very problematic, as if you press **Calculate** now you will see that the ECG does not process correctly and the results are unusable.

Re-enable pacemaker artifact removal by checking the **On** checkbox, and then reload the ECG with the **Reload** button:



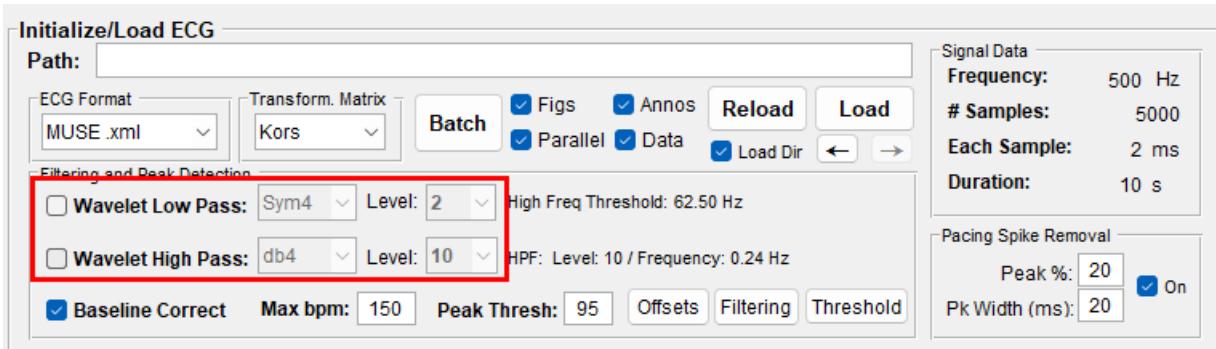
This time, as pacemaker artifact removal was enabled, the pacemaker spikes are ignored, and the true QRS peaks are detected as the R peaks. If you press **Calculate** the ECG will process correctly.

5.5 Example 5 - Using `.anno` Files

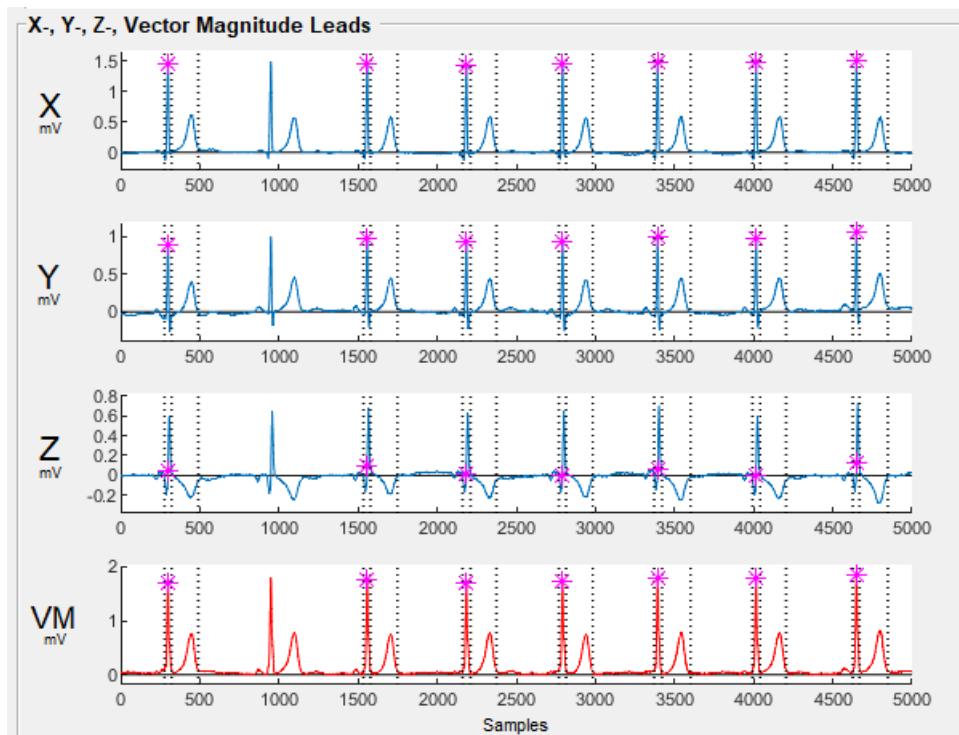
In this example we will load an ECG, process with non-nominal settings, remove some beats, and then use an `.anno` file to reproduce this workflow automatically the next time the ECG is loaded.

For illustrative purposes we will disable filtering and remove the second beat. Uncheck

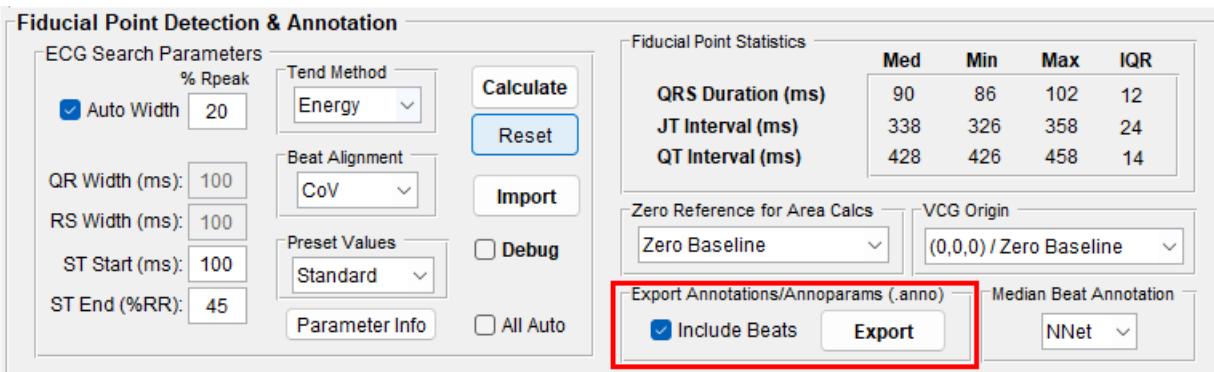
Wavelet Low Pass and **Wavelet High Pass** in the ‘Initialize/Load ECG’ section:



Next, load `example1.xml` and click **Calculate** as noted in the examples above. Click on the second beat in the ‘Annotated Beats’ listbox, and then delete the second beat using the **Remove Beat** button. The second beat is removed from the median beat and calculations:



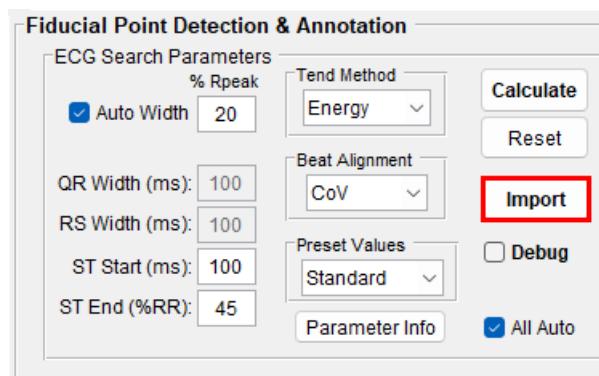
Note that the * is not present on the second beat indicating that the second beat is no longer included in the median beat. Now click on the **Export** button in the ‘Fiducial Point Detection & Annotations’ section of the GUI, making sure that the **Include Beats** checkbox is checked (this saves the beat annotations in addition to the annotation parameters).



A file named `example1.anno` appears in the same folder as `example1.xml`.

Reset all GUI parameters to nominal values with the **Reset** button which restores the default GUI/annotation parameters (see **Chapter 6**) and re-checks **Wavelet Low Pass** and **Wavelet High Pass**. Then reload the ECG from scratch with the **Reload** button.

This time, instead of clicking the **Calculate** button to process the ECG, we will reproduce what we did above by loading the `.anno` file: Click **Import** and choose `example1.anno`:



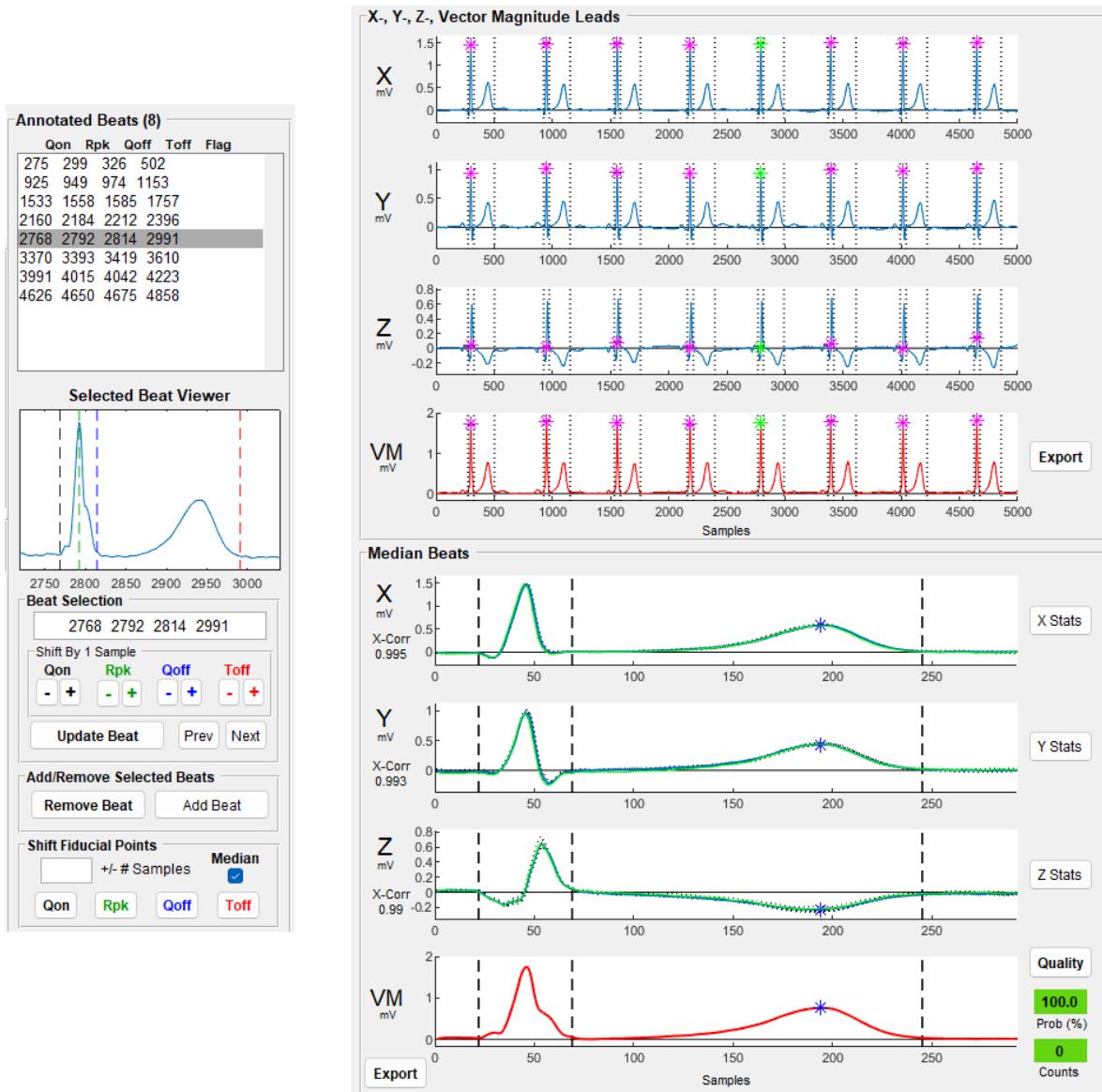
`example1.xml` is reloaded using the annotation/filtering parameters specified in the `.anno` file.

Note how **Wavelet Low Pass** and **Wavelet High Pass** are now unchecked, and beat 2, which was manually deleted before saving the `.anno` file, has been automatically deleted.

Using the **Import** button is equivalent to placing the file `example1.anno` in the same folder as the original ECG file `example1.xml` and then running batch ECG processing – the parameters/beats in the `.anno` file overwrite the default parameters and beat removal. Note that when using `.anno` files, after importing, automatic PVC and outlier removal are disabled.

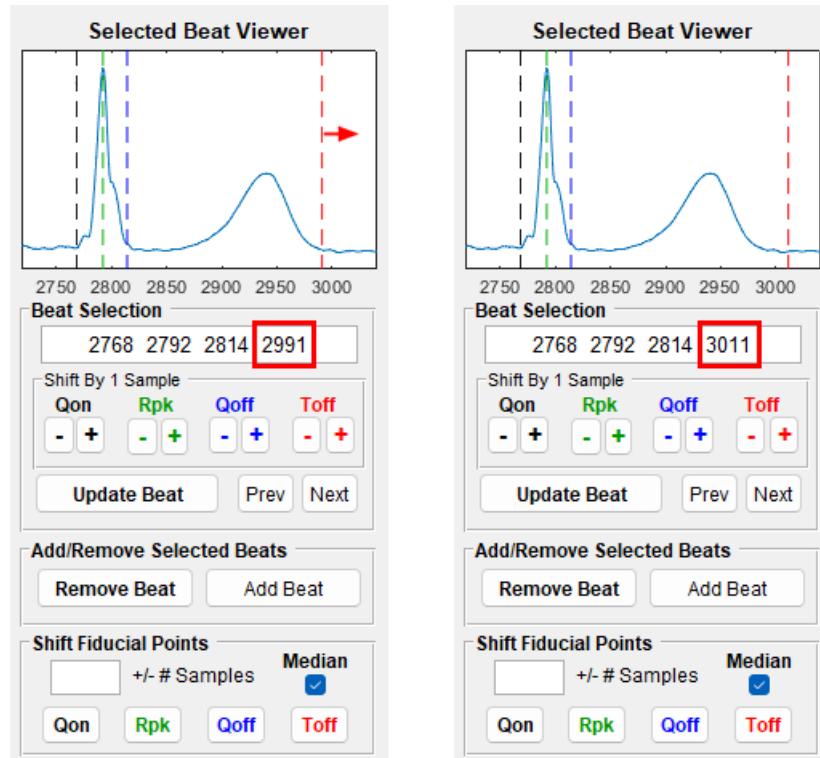
5.6 Editing Beats

The ‘**Annotated Beats**’ listbox contains fiducial point annotations for Q_{on}, R peak, Q_{off}, and T_{off} for each individual beat that was used to create the median beat. To edit a beat’s annotations, click on the row which corresponds to the beat in the listbox. The selected beat appears in the ‘**Selected Beat Viewer**’, the R peak of the selected beat is highlighted with a green * in the ‘**X-, Y-, Z-, Vector Magnitude Leads**’, and the selected beat is highlighted in green in the ‘**Median Beats**’ section. Below the ‘**Selected Beat Viewer**’ there is a ‘**Beat Selection**’ section that shows the fiducial points from the ‘**Annotated Beats**’ listbox. In the figure below the 5th beat has been selected:

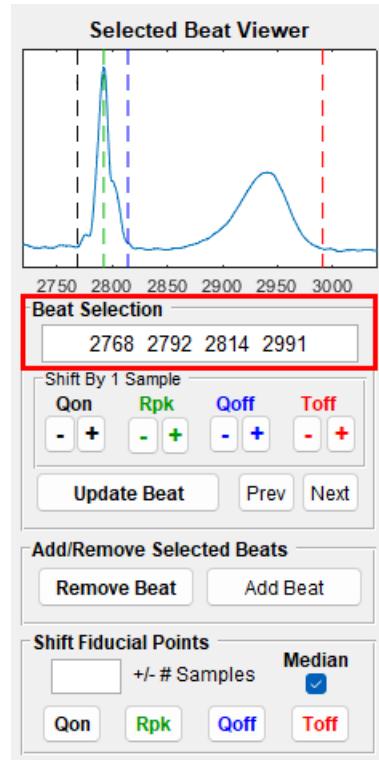


To edit the beats fiducial points there are a few options:

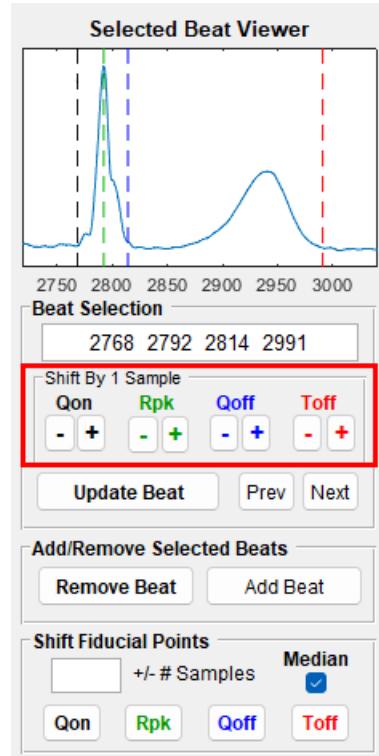
1. Drag the dashed lines on the ‘Selected Beat Viewer’ to their appropriate locations. Black is Q_{on}, green is R peak, blue is Q_{off}, and red is T_{off}. Once the mouse is released, the new location of the fiducial point is updated in the ‘Beat Selection’ textbox. In the figure below, as an example, the location of T_{off} for the beat is moved from sample 2991 to sample 3011 by dragging the red dashed line to the right:



2. Edit the values in the ‘Beat Selection’ textbox directly:



3. Click on the **[+]** and **[−]** buttons in the ‘Shift By 1 Sample’ section under the ‘Beat Selection’ textbox to increase or decrease the specified fiducial point value by 1 sample.:



After you use one of these three methods to set the appropriate values for the beat in the ‘**Beat Selection**’ textbox, click **Update Beat** to update the values and recalculate the new median beat and measurements.

Note: The **Next** and **Prev** buttons can be used to cycle through the beats in the ‘**Annotated Beats**’ listbox without clicking on each beat individually.

5.7 Removing Beats

To remove a beat, click on the beat to be removed in the ‘**Annotated Beats**’ listbox. The selected beat is shown in the ‘**Selected Beat Viewer**’ and highlighted in green in the ‘**X-, Y-, Z-, Vector Magnitude Leads**’ and ‘**Median Beat**’ sections as noted in the above examples. Once the beat to be removed is selected, click the **Remove Beat** button in the ‘**Add/Remove Selected Beats**’ section:



The selected beat is removed, a new median beat is created and annotated, and measurements are performed on the new median beat.

5.8 Adding Beats

It should be rare to have to add beats manually, but this can be done if needed. Enter the respective fiducial points in the ‘**Beat Selection**’ text box and then click **Add Beat** in the ‘**Add/Remove Selected Beats**’ section:



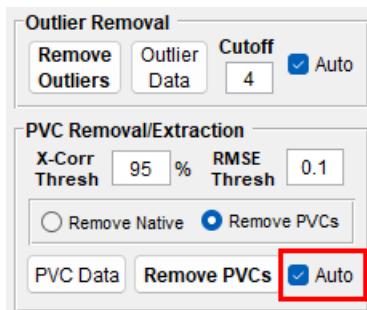
The new beat is added, a new median beat is created and annotated, and measurements are performed on the new median beat.

Note: Manually added beats are inserted at the end of the ‘**Annotated Beats**’ list and not in the temporal order in which they appear in the ECG. This has no effect on annotation or

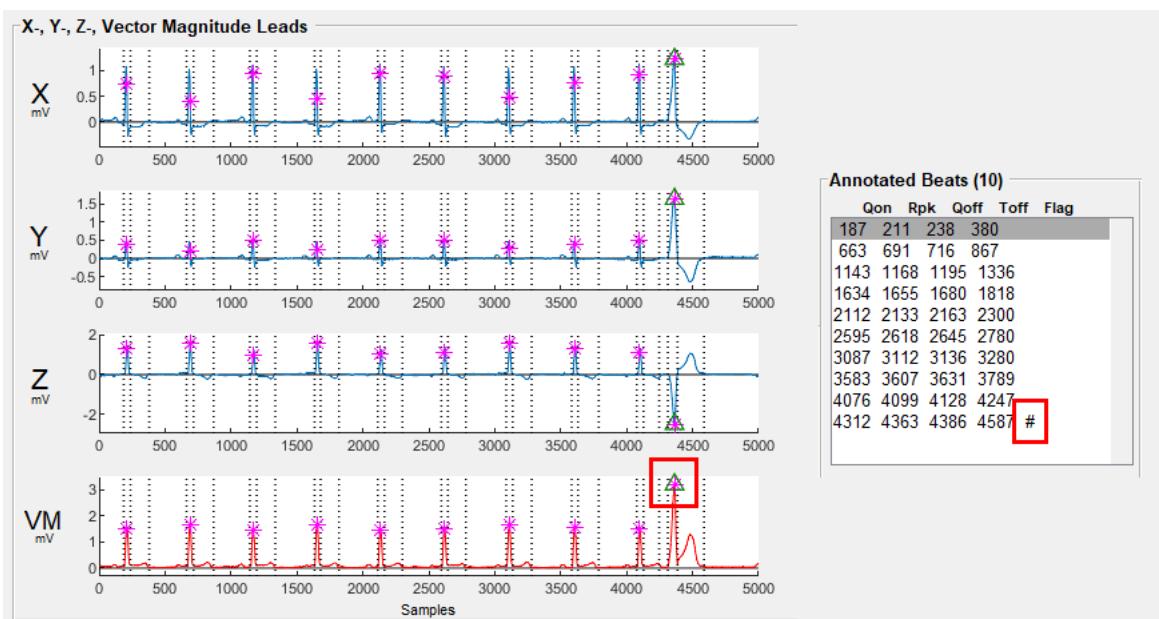
calculations.

5.9 Removing PVCs and other Non-Dominant Beats

A discussion of the PVC (or any non-dominant QRST morphology) detection and removal algorithm can be found in **Chapter 13.3** and/or the methods manuscript [1]. Additionally, Example 2 (**Chapter 5.2**) shows an example of PVC removal. If **Auto** is checked in the ‘**PVC Removal/Extraction**’ section, PVCs will be automatically detected and removed when the **Calculate** button is clicked. If PVC removal is disabled (**Auto**), PVCs will be detected but not removed as noted above in Example 2.



After the **Calculate** button is clicked, PVCs are noted in the ‘**X-, Y-, Z-, Vector Magnitude Leads**’ section with a \triangle , and in the ‘**Annotated Beat**’ list with a ‘#’ following the numbered fiducial points.

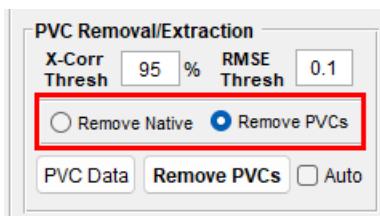


In the figure above, for illustrative purposes, outlier detection (see **Chapter 5.10** and **Chapter 13.4**) was disabled. In many cases, PVCs also get flagged as outliers, and the GUI will note the beat as both a PVC and outlier as shown in Example 2 (**Chapter 5.2**).

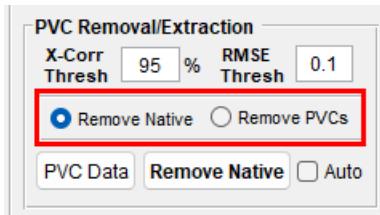
Data about how BRAVEHEART is classifying each beat for PVC detection can be displayed in the GUI by clicking the **PVC Data** button which displays a figure showing which beats are being detected as PVCs and why. Further details are available in **Chapter 18** and **Figure 26**.

PVCs that have been detected but not removed can be easily removed all at once by clicking the **Remove PVCs** button. Alternatively, PVCs can be manually removed one at a time by selecting each PVC in the ‘**Annotated Beat**’ list and then clicking the **Remove Beat** button as described in the previous examples.

If you wanted to analyze the PVC in the `example2.xml` rather than removing it, use the radio button which allows you to select if ‘PVC Removal’ will remove or keep PVCs. The default setting is to ‘Remove PVCs’:



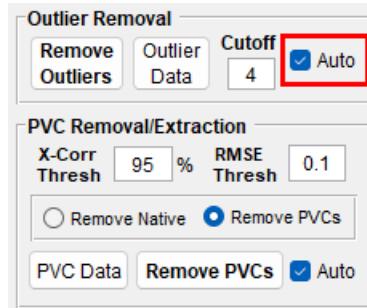
By choosing ‘Remove Native’ in the radio button, note how the **Remove PVCs** button changes to the **Remove Native** button:



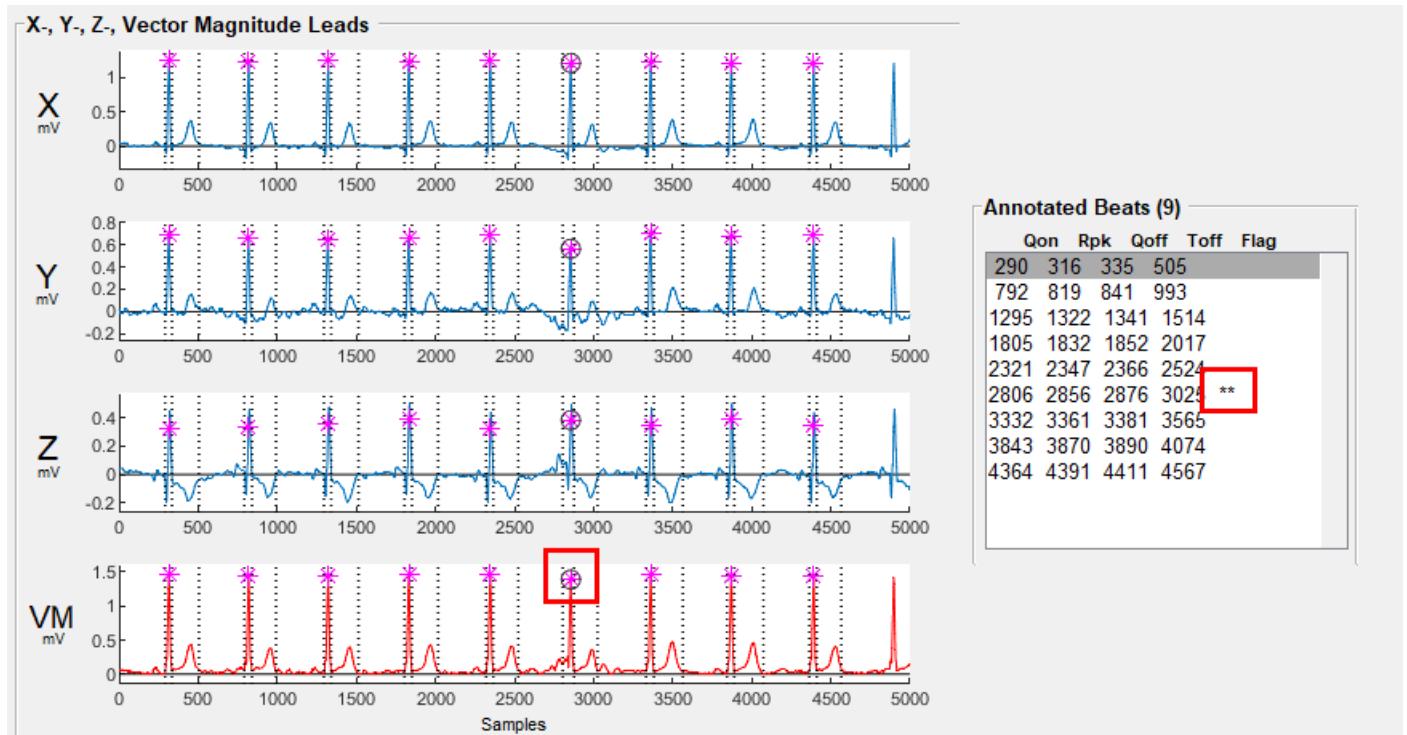
After an ECG is processed with the **Calculate** button, if ‘Remove Native’ is selected in the GUI radio button, automatic PVC removal and the **Remove Native** button will actually remove the non-PVC beats and keep the PVCs/non-dominant beats for analysis.

5.10 Removing Outlier Beats

A discussion of the outlier detection algorithm can be found in **Chapter 13.4** and/or the methods manuscript [1]. If **Auto** is checked in the ‘**Outlier Removal**’ section, outliers will be automatically detected and removed when **Calculate** is pressed. If outlier removal is disabled (**Auto**), outliers will be detected but not removed.



Outliers are noted in the ‘**X-, Y-, Z-, Vector Magnitude Leads**’ section with a \circledast , and in the ‘**Annotated Beat**’ list with a ‘**’ following the numbered fiducial points:



Data about how BRAVEHEART is classifying each beat for outlier detection can be displayed in the GUI by clicking on the **Outlier Data** button. The QR and RT intervals are used for outlier detection, and beats that are considered as outliers will have their QR and/or RT interval

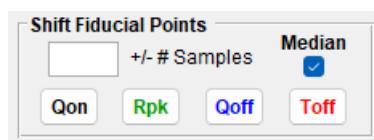
displayed with a red background. The other measures that are displayed, such as the RS, JT, and QT intervals and area under the QRST complex are displayed for the users information but are not used to actually flag a beat as an outlier, and are displayed with a black background. See **Chapter 13.4** and **Figure 27** for further details.

Outliers that have been detected but not removed can be easily removed all at once by clicking the **Remove Outliers** button. Alternatively, outliers can be manually removed one at a time by selecting each beat in the ‘**Annotated Beat**’ list and then clicking the **Remove Beat** button. Note that outliers and PVCs are reassessed after each beat is removed, so it is possible that a beat which is classified as an outlier prior to another beat being removal may no longer be classified as an outlier after the other beat is removed. Additionally, some outliers may also be marked as PVCs, and PVC removal may remove them.

5.11 Manually Adjusting Median Beat Annotations

Median beat fiducial point annotation nominally utilizes a custom neural network (NN) developed specifically for median beat annotation (see the methods manuscript [1] and **Chapter 17** for details). We have demonstrated that the NN has very high accuracy, but rarely annotations may be inaccurate. There is some subjectivity in annotating QRST fiducial points, especially the T_{off} , so we would recommend not manually editing the median beat fiducial points unless the provided points are significantly abnormal to maintain consistency and reproducibility of the results. In cases where the NN provided fiducial points are significantly abnormal, or in niche cases where manual annotation is required, the median beat fiducial points Q_{on} , Q_{off} , and T_{off} can be manually adjusted as described below.

In the ‘**Shift Fiducial Points**’ section below the ‘**Selected Beat Viewer**’, make sure **Median** is checked. Enter a number of *samples* (positive numbers shift towards the right/later, and negative numbers shift towards the left/earlier) in the textbox. Then press the button for the fiducial point you want to shift:



For example, to shift the median beat T_{off} later by 3 samples, enter '3' in the textbox and click the **Toff** button. To shift the median beat Q_{on} earlier by 2 samples enter '-2' in the textbox and click the **Qon** button. The fiducial points of the median beat are adjusted and calculations are updated.

5.12 Exporting Measurements to a Text File

BRAVEHEART can output results to a text file for analysis. After you have processed the ECG and made any manual edits, click the **VCG Calculations** button in the middle of the GUI as shown in Example 1 (Chapter 5.1).

This brings up the 'VCG Calculations' section which displays various VCG measurements and is used for exporting all calculations. The controls for data export are shown in the bottom right:

Calculations

Basic Parameters (ms)		QRST Angle (°)	
HR (bpm): 48	QT (ms): 446	Peak 3D QRST Ang: 19.97	Peak Front QRST Ang: 3.66
QRS (ms): 94	QTc (Baz): 400	Area 3D QRST Ang: 40.85	Area Front QRST Ang: 12.33
JT (ms): 352	QTc (Fr): 415		
Tpeak: 344	Tpeak/QT: 0.771		
QRS Vector (mV-ms) & (°)		SVG Angles (°)	
Peak QRS Mag: 1.76	Area QRS Mag: 37.79	Peak SVG-Peak QRS Ang: 5.98	
Peak QRS Az: 2.69	Area QRS Az: 18.25	Peak SVG-Peak T Ang: 13.99	
Peak QRS El: 56.94	Area QRS El: 65.57	Area SVG-Area QRS Ang: 29.31	
T Vector (mV-ms) & (°)		Area SVG-Tang: 11.54	
Peak T Mag: 0.76	Area T Mag: 92.51	Area SVG-Area SVG Ang: 7.83	
Peak T Az: -21.35	Area T Az: -27.65	Area SVG-Area QRS Ang: 13.77	
Peak T El: 55.18	Area T El: 55.42		
SVG Vector (mV-ms) & (°)		Vector Ratios	
Peak SVG Mag: 2.49	Area SVG Mag: 123.61	Peak QRST Ratio: 2.32	Area QRS & T: 68.54
Peak SVG Az: -4.39	Area SVG Az: -13.78	Area QRST Ratio: 0.41	Peak QRS & T: 1.08
Peak SVG El: 55.92	Area SVG El: 56.55		
SVG Components (mV-ms)		Vector Distances (mV)	
SVG x: 100.15↑	SVG y: 68.14↑	QRST Path Length (mV): 6.33	T Path Length: 1.59
SVG z: -24.57		QRS Path Length: 4.73	
SAI QRST (mV-ms)			
SAI x: 103.86	SAI QRST: 236.51↑		
SAI y: 76.75	SAI vm: 148.49↑		
SAI z: 55.89			
Data Export			
Dir.: C:\BRAVEHEART	Select		
File: braveheart_output	.csv		
Note:			
Export Data (.csv)		Export Signals (.mat)	

The default directory used to save files is the same directory from which the ECG was loaded. To change the directory for saving click **Select** and choose a new directory. The default file name for the saved data file is **braveheart_output**; change this to what you want to name the output file.

Once your file name and directory are set, click **Export Data (.csv)** to export the data to a **.csv** file located in the directory chosen above and with the specified file name. Once the file is successfully exported, **Success!** is displayed in green in the bottom right of the section.

5.13 Exporting Signals

Chapter 5.12 describes how to export calculations into a text file for further analysis. BRAVEHEART can also export these calculation data, and all ECG, VCG, median beat signals, and annotation data, in a MATLAB **.mat** file which contains a data structure with all results/signals. In the ‘VCG Calculations’ section, click the **Export Signals (.mat)** button. A file with the same name as the ECG and with extension **.mat** is created in the directory specified for data export.

5.14 Exporting Figures

A variety of figures can be generated and saved by the BRAVEHEART GUI. See Chapter 18 for additional information.

6 Annotation Parameters (`Annoparams.m`)

`Annoparams.m` contains parameters which control the behavior of BRAVEHEART's ECG/VCG signal processing and annotation algorithms. These parameters can be set globally by editing the `Annoparams.m` file. In cases where BRAVEHEART is being run via executable and `Annoparams.m` cannot be edited, the parameters can be set by editing `Annoparams.csv` which is an external file with name/value pairs separated by commas. When the program is run via executable, calls to pull data from `Annoparams.m` will instead pull data from `Annoparams.csv`. Note that when editing `Annoparams.csv`, unlike when editing `Annoparams.m`, strings should not be enclosed in quotes.

When using the GUI it should be rare to have to edit the `Annoparams.m` file because almost all of the important parameters that would be set in `Annoparams.m` can be set via dropdowns, checkboxes, or textboxes in the GUI. The correspondence between GUI elements and specific properties of `Annoparams.m` is described in [Chapter 10](#) and [Chapter 23](#).

When using the GUI, values are pulled from `Annoparams.m` (or `Annoparams.csv`) when the GUI is loaded-initialized for the first time and when GUI parameters are reset with the `Reset` button (see [Chapter 10](#)). The actual GUI settings at the time an ECG is processed or a calculation is run will override any settings within `Annoparams.m` (or `Annoparams.csv`).

The following sections describe the properties within the `Annoparams.m` class that can be set by the user (either via editing files or the GUI) to change the behavior of BRAVEHEART.

6.1 Annoparams Properties (`Annoparams.m`)

`Annoparams.m` properties are listed here and descriptions of their use follows in [Chapter 6.2](#).

Note: some comments used as headings for groups of similar properties have been omitted.

```
maxBPM = 150; % Sets window for detecting R peaks
pkthresh = 95; % Percentile of ECG signal above which a peak can be found
lowpass = 1; % Low pass wavelet filter on/off
highpass = 1; % High pass wavelet filter on/off
wavelet_level_lowpass = 2; % Lvl 2 at 500 Hz and Lvl 3 at 997 Hz is 62.5 Hz low-pass filter
wavelet_level_highpass = 10; % Lvl 10 is 0.24 Hz at 500 Hz
wavelet_name_lowpass = 'Sym4'; % Low-pass wavelet (Sym4, Sym5, Sym6, db4, db8)
wavelet_name_highpass = 'db4'; % High-pass wavelet (Sym4, Sym5, Sym6, db4, db8)
baseline_correct_flag = 1; % Corrects baseline offset

transform_matrix_str = 'Kors'; % Kors or Dower transformation matrix

baseline_flag = 'zero_baseline'; % Zero reference for area calculations
origin_flag = 'zero_origin'; % Origin for VCG plotting

autoMF = 1; % Auto estimate QRS width
autoMF_thresh = 20; % Percent Rpeak threshold if autoMF = true
MF_width = 40; % Length of median filter (in ms) used when autoMF = true

QRwidth = 100; % Width of QR search window in ms
RSwidth = 100; % Width of RS search window in ms
STstart = 100; % Distance between Qoff and start of Tend search window in ms
STend = 45; % Length of Tend search window as a percent of RR interval

spike_removal = 1; % Remove pacemaker spikes
pacer_spike_width = 20; % Max width of pacing spike (in ms)
pacer_mf = 4; % Pacer spike detection median filter (in ms)
pacer_thresh = 20; % Percent peak of pacer spike used for spike removal

align_flag = 'CoV'; % Beat alignment method ('CoV' or 'Rpeak')
cov_mf = 40; % width of CoV median filter (in ms)
cov_thresh = 30; % CoV median filter threshold %
shiftq = -40; % Q window expand when calculating median beat (in ms)
shifttt = 60; % T window expand when calculating median beat (in ms)

Tendstr = 'Energy'; % Tend detection method ('Energy', 'Tangent', or 'Baseline')

median_reanno_method = 'NNNet'; % 'NNNet' for neural network and 'Std' for standard annotations

outlier_removal = 1; % Remove outliers
modz_cutoff = 4; % Cutoff for mod Z-score to flag an outlier (higher less sensitive)
pvc_removal = 1; % Remove PVCs
pvcthresh = 0.95; % Cross correlation threshold for PVC removal
rmse_pvcthresh = 0.1; % Normalized RMSE threshold for PVC removal
keep_pvc = 0; % Set = 1 if PVC removal removes native QRS instead of PVCs

blanking_samples = 0; % Blanking window (in samples) to ignore in speed calculations

debug = 0; % Debug mode (generates debug annotation figures)
```

6.2 Annoparams Property Descriptions

`property` | *acceptable values*

property description

`pkthresh` | Numeric values between `0` and `100`

Cutoff percentile above which an R peak can be detected in the vector magnitude (VM) signal as part of initial R peak detection. This is nominally set to `95`. Higher values may miss some R peaks, while lower values may inappropriately identify peaked T waves or other parts of the ECG signal. However, because the R peak detection algorithm also takes into account a rate related blanking period around each R peak defined by `maxBPM` (see below) where only a single R peak can be detected, as long as the `maxBPM` parameter is set to a reasonable rate, it is rare to over count R peaks unless `pkthresh` and `maxBPM` are both set very low. In cases where the magnitude of PVCs or paced beats in the VM lead is significantly different than the magnitude of the dominant QRST morphology, `pkthresh` may have to be reduced to detect both the dominant and non-dominant R peaks.

Additional information can be found in **Chapter 13.1** and **Figure 22** which illustrates R peak detection using the `pkthresh` and `maxBPM` parameters.

`maxBPM` | Positive numeric values

Length of the blanking window in beats per min (bpm) centered around each dominant R peak in the VM signal where a second R peak will not be found. This is also the lower limit of the heart rate (HR) that can be detected by the R peak detector; `maxBPM` must be set to a value above the HR on the ECG to avoid missing QRS complexes. The blanking window in ms (w) given as $w = 60000/\text{maxBPM}$. The nominal value of `150` bpm corresponds to a 400 ms window centered on the highest peaks detected in the VM signal. Additional information can be found in **Chapter 13.1** and **Figure 22** which illustrates R peak detection using the `pkthresh` and `maxBPM` parameters.

`lowpass` | Integer `0` or `1`

Sets if low-pass wavelet-based filtering is activated (`1`) or deactivated (`0`). Low-pass filtering removes frequencies above a cutoff frequency and helps remove high-frequency noise.

`highpass` | Integer `0` or `1`

Sets if high-pass wavelet-based filtering is activated (`1`) or deactivated (`0`). High-pass filtering removes frequencies below a cutoff frequency and helps remove low-frequency baseline wander and DC offset.

`wavelet_level_lowpass` | Integer values ≥ 1

Corresponds to the low-pass filtering cutoff frequency level. The low-pass cutoff filtering frequency (F) is given by $F = (f/2)/(2^n)$, where f is the ECG sampling frequency and n is the value of `wavelet_level_lowpass`. As can be seen, the same wavelet level will correspond to a different low-pass filtering cutoff frequency for signals with different sampling frequencies. In general, `wavelet_level_lowpass` should be a low value ≤ 3 for most applications (depending on signal sampling frequency) to avoid removing frequencies contained within the QRST complex (0.5-40 Hz)[2]. The maximum n (maximum value of `wavelet_level_lowpass`) depends on the length of the ECG signal in samples (L) and is given as $n_{max} = \text{floor}(\log_2 L)$. The BRAVEHEART GUI nominally sets `wavelet_level_lowpass = 2` for signals sampled at 500 Hz, and `wavelet_level_lowpass = 3` for signals sampled at 1000 Hz when ECG formats are changed; this corresponds to a nominal low-pass filtering cutoff of 62.5 Hz.

`wavelet_level_highpass` | Integer values ≥ 1

Corresponds to the high-pass filtering cutoff frequency level. The high-pass cutoff filtering frequency (F) is given by $F = (f/2)/(2^n)$, where f is the ECG sampling frequency and n is the value of `wavelet_level_highpass`. As can be seen, the same wavelet level will correspond to a different high-pass filtering cutoff frequency for signals with different sampling frequencies. In general, `wavelet_level_highpass` should be a high value ≥ 9 to avoid removing frequencies contained within the QRST complex (0.5-40 Hz)[2]. The maximum n (maximum value of `wavelet_level_highpass`) depends on the length of the ECG signal in samples (L) and is given as $n_{max} = \text{floor}(\log_2 L)$. The BRAVEHEART GUI nominally sets `wavelet_level_lowpass = 10` for signals sampled at 500 Hz, and `wavelet_level_lowpass = 11` for signals sampled at 1000 Hz when ECG formats are changed; this corresponds to a nominal high-pass filtering cutoff frequency of 0.24 Hz.

`wavelet_name_lowpass` | `string` values corresponding to MATLAB wavelet names

Corresponds to the specific wavelet used for low-pass filtering. Nominal settings use '`'sym4'`', which corresponds to the Symlets 4 wavelet, and which should be adequate for most ECG signals. A full list of MATLAB wavelets and their associated strings can be found in the MATLAB documentation or by typing `waveinfo` in the MATLAB Command Window.

`wavelet_name_highpass` | `string` values corresponding to MATLAB wavelet names

Corresponds to the specific wavelet used for high-pass filtering. Nominal settings use '`'db4'`', which corresponds to the Daubechies 4 wavelet, and which should be adequate for most ECG signals. A full list of MATLAB wavelets and their associated strings can be found in

the MATLAB documentation or by typing `waveinfo` in the MATLAB Command Window.

`baseline_correct_flag` | Integer `0` or `1`

Sets if physiological baseline correction is activated (`1`) or deactivated (`0`). This provides additional baseline correction after high-pass filtering to set the isoelectric TP segment (the physiological zero voltage reference) as the approximate zero voltage reference for calculations. Further information can be found in **Chapter 13.2** and **Figure 24**.

`transform_matrix_str` | `'Kors'` or `'Dower'`

Sets the transformation matrix used to transform the ECG into a VCG. The nominal transformation matrix is the Kors transformation matrix [3] which is set by the string `'Kors'`. The inverse Dower transformation [4] can be used with the string `'Dower'`.

Additional transformation matrices can be added as shown in **Chapter 8**.

`baseline_flag` | `'zero_baseline'`, `'Tend'`, `'QRS Onset'`, or `'Avg'`

Sets how the zero baseline is defined for area calculations. The nominal setting of `'zero_baseline'` takes 0 mV as the reference line and should be used assuming the signals are zeroed appropriately using filtering and baseline correction. Other options include `'Tend'` which sets the end of the T wave, `'QRS Onset'` which sets the start of the QRS complex, and `'Avg'` which sets the mean of the QRS onset and T wave end as the zero reference for area calculations, respectively. In general, the nominal setting `'zero_baseline'` should be used (See **Chapter 13.2** and **Figure 23**).

`origin_flag` | `'zero_origin'`, `'Tend'`, or `'Avg'`

Sets the location of the VCG origin. The nominal setting of `'zero_origin'` takes the point (0,0,0) as the origin and should always be used assuming the signals are zeroed appropriately using filtering and baseline correction. `'Tend'` shifts (0,0,0) to the location of the end of the 3D T wave loop, and `'Avg'` shifts (0,0,0) to the point in space equidistant between the onset of the 3D QRS loop and the end of the 3D T wave loop.

`autoMF` | Integer `0` or `1`

Sets if median filtering is used to estimate QRS width as part of heuristic first pass QRS detection/annotation. If `autoMF = 0`, the values of `QRwidth` and `QSwidth` (see below) are used to set the QRS fiducial point detection window. Setting `autoMF = 1` allows BRAVHEART to dynamically adjust the QRS fiducial point search window for each beat individually rather than relying on a fixed window for all beats, and is recommended for most ECGs. In cases where heuristic first pass annotation fails (usually due to atypical

QRST morphology), setting `autoMF = 0` and manually adjusting `QRwidth` and `QSwidth` may be useful. See **Chapter 16** for further details.

`autoMF_thresh` | Integers between `0` and `100`

Sets the percentage of each beat's VM QRS peak voltage that is used to estimate each QRS peak width as part of first pass heuristic annotation. If the value of `autoMF_thresh` is set too high, the QRS search window will be too short and the true onset/offset of the QRS complex may be missed. If the value of `autoMF_thresh` is set too low, parts of the T wave may be captured in the QRS search window and inaccuracies in the location of QRS onset/offset may result. The nominal value of `20` works for the majority of ECGs. Modest increases or decreases in this value may occasionally be needed based on QRS/T wave morphologies. See **Chapter 16** for further details.

`MF_width` | Positive integer values

Sets the width of the median filter (in ms) used when `autoMF = 1`. The nominal value of `40` should be used for most applications and rarely requires change. Note: This property cannot be set via the GUI.

`QRwidth` | Positive integer values

Manually sets the width of the heuristic first pass annotation QRS search window (in ms) **before** the R peak if `autoMF = 0`. This search window is used to locate the QRS onset (Q_{on}). A description of the windows used for heuristic first pass annotation is detailed in **Chapter 16** and **Figure 30**. If `autoMF = 1` this has value no effect on annotation.

`RSwidth` | Positive integer values

Manually sets the width of the heuristic first pass annotation QRS search window (in ms) **after** the R peak if `autoMF = 0`. This search window is used to locate the QRS offset (Q_{off}). A description of the windows used for heuristic first pass annotation is detailed in **Chapter 16** and **Figure 30**. If `autoMF = 1` this value has no effect on annotation.

`STstart` | Positive integer values

Sets the distance (in ms) between the end of the QRS complex and the start of the T wave end search window. A description of the windows used for heuristic first pass annotation is detailed in **Chapter 16** and **Figure 30**.

`STend` | Positive values between `0` and `100`

Sets the width of the T wave end search window starting at `STstart` and going forward by

`STend` % of the mean RR interval across the full ECG. `STend` is set as a percentage rather than as absolute value in ms because the QT interval is highly influenced by heart rate, and this reduces the need for frequent adjustment of this parameter. A description of the windows used for heuristic first pass annotation is detailed in **Chapter 16** and **Figure 30**.

`spike_removal` | Integer `0` or `1`

Sets if automatic pacemaker spike/artifact removal is on (`1`) or off (`0`). In general, even if pacing is not present, this should be left on as the signals and subsequent annotation will not be affected if pacing is not present. In rare cases, disabling pacemaker spike removal by setting `spike_removal = 0` may resolve errors during ECG loading or annotation and can assist with trouble shooting ECGs that won't load, usually due to very wide or atypical pacing spikes/artifact.

`pacer_spike_width` | Positive integer values

Sets the maximum width of a high-frequency deflection (in ms) in the VM lead that can be defined as a pacing spike. The nominal value of `20` should work in most cases. If there are issues removing very large/wide pacing spikes, adjusting this value may be useful.

`pacer_mf` | Integer `0` or `1`

Sets the width of the median filter (in ms) used when `spike_removal = 1`. The nominal value of `4` should be used for most applications and rarely requires change. Note: This property cannot be set via the GUI.

`pacer_thresh` | Numeric values between `0` and `100`

Sets the percentage of the pacemaker spike amplitude that is used to determine if a high frequency spike is a pacing artifact. In most cases, the nominal value of `20` works well, but if there are issues removing very large pacing spikes, adjusting this value may be useful.

`align_flag` | `'CoV'` or `'Rpeak'`

Sets how individual beats are aligned to create a median beat using either the filtered center of voltage (`'CoV'`) or R wave peak (`'Rpeak'`), respectively. The nominal value of `'CoV'` generally performs better than `'Rpeak'` as it is less influenced by noise or by variations in QRS morphology such as are sometimes seen in bundle branch blocks, and should be used for most applications. If median beat alignment is poor when using `'CoV'`, trying `'Rpeak'` may possibly improve beat alignment.

`cov_mf` | Positive integer values

Sets the width of the median filter (in ms) used to determine the center of voltage. In general this should remain at the nominal value of **40** and rarely requires change. Note: This property cannot be set via the GUI and rarely requires editing.

`cov_thresh` | Numeric values between **0** and **100**

Sets the percentage of the VM QRS peak used for aligning QRST complexes via center of voltage. Note: This property cannot be set via the GUI and rarely requires editing.

`shiftq` | Negative integer values

Sets the value in ms by which the window around the median beat is expanded prior to the onset of the QRS complex. This ensures that the location of the QRS onset is not cut short. The nominal value of **-40** should be used for almost all applications. Making this value more negative will increase the amount of signal that is included in the median beat before the onset of the QRS complex, and making this value less negative will decrease the amount of signal that is included in the median beat before the onset of the QRS complex. Note: This property cannot be set via the GUI.

`shiftt` | Poitive integer values

Sets the value in ms by which the window around the median beat is expanded after the end of the T wave. This ensures that the location of the T wave end is not cut short. The nominal value of **60** should be used for almost all applications. Making this value larger will increase the amount of signal that is included in the median beat after the end of the T wave, while making this value smaller will decrease the amount of signal that is included in the median beat after the end of the T wave. Note: This property cannot be set via the GUI.

`Tendstr` | **'Energy'**, **'Tangent'**, or **'Baseline'**

Sets the method for T wave end detection (T_{off}) when using the heuristic T wave end detector. If set to **'Energy'** it utilizes a validated method that assesses T wave energy towards the end of the T wave that is better able to deal with low amplitude or abnormal T waves than other methods [5]. Setting `Tendstr` to **'Tangent'** utilizes the tangent method, and setting as **'Baseline'** uses baseline crossing. In general, the best results are obtained with **'Energy'**. See **Chapter 16** for further details.

`median_reanno_method` | **'NNNet'** or **'Std'**

Once a median beat is created, median beat fiducial points are obtained by annotating the median beat QRST complex. `median_reanno_method` sets how median beats are annotated,

using either the standard heuristic annotater (`'Std'`) or a custom neural network (`'NNet'`). In almost all cases the nominal value of `'NNet'` should be used as it is the most accurate way to annotate median beats. In rare cases where the neural network fails to accurately annotate a median beat, switching to `'Std'` may work, although usually ECGs that fail neural network annotation are ECGs with significant noise and artifact that are difficult to annotate regardless of method. Details of neural network development and annotation performance are available in the methods manuscript [1] and **Chapter 17**.

`outlier_removal` | Integer `0` or `1`

Sets if automatic outlier beat removal is activated (`1`) or deactivated (`0`). When using the GUI, if `outlier_removal = 0` outlier beats will be identified and marked but not removed. See **Chapter 13.4** for additional details.

`modz_cutoff` | Integer `0` or `1`

Sets the threshold for the modified Z-score that is used to define a beat as an “outlier”. If the modified Z-score for the QR and/or RT interval of an individual beat is above the `modz_cutoff` value, the beat is flagged as an outlier. Higher values may be needed when there are few beats; if there are > 15 beats a cut off value of `3.5` is reasonable, although if there are < 10 beats a cut off value of approximately `4` may be needed [6]. See **Chapter 13.4** for additional details.

`pvc_removal` | Integer `0` or `1`

Sets if automatic PVC/non-dominant beat removal is activated (`1`) or deactivated (`0`). When using the BRAVEHEART GUI, if `pvc_removal = 0` PVCs/non-dominant beats will be identified and marked but not removed. The `keep_pvc` parameter (see below) controls whether the dominant or non-dominant beats are kept for analysis. See **Chapter 13.3** for further details.

`pvcthresh` | Numeric values

Sets the cutoff (as a percentage) for normalized cross correlation (NCC) as used for PVC/non-dominant beat detection. The nominal value of `95` works well for most applications. The contribution of NCC to PVC/non-dominant beat detection can be disabled by setting `pvcthresh = 0`. See **Chapter 13.3** for further details.

`rmse_pvcthresh` | Numeric values

Sets the cutoff for root-mean square error (RMSE) as used for PVC/non-dominant beat detection. The nominal value of `0.1` works well for most applications. The contribution of

RMSE to PVC/non-dominant beat detection can be disabled by setting `rmse_pvcthresh = -1`. See **Chapter 13.3** for further details.

`keep_pvc` | Integer `0` or `1`

Sets if PVCs/non-dominant beats are removed (`0`) or if dominant beats are removed to allow analysis of the PVCs/non-dominant beats (`1`).

`blanking_samples` | Positive integers

Sets the window (in samples) after QRS onset which is not included in calculations of VCG loop speed (See **Chapter 10.7**). In general this can be left at the nominal value of `0`, but in certain paced ECGs where there is some contamination of the start of the QRS complex with a high amplitude/frequency pacing spike, increasing this value may be useful. In certain situations it may be desirable to also look at speed at specific parts of the QRST complex, and increasing the blanking window can also assist with this by excluding the signal contained within the blanking window from any speed calculations.

`debug` | Integer `0` or `1`

Sets if BRAVEHEART generates debug figures during ECG signal annotation. This can be useful for troubleshooting. Further details can be found in **Chapter 25.6**, **Figure 30**, and **Figure 49**.

7 Adding New ECG Formats

BRAVEHEART can read a variety of ECG data formats (see [Chapter 21](#)). However, if you are using an ECG file format which cannot be read by BRAVEHEART currently, you will have to supply your own load module and modify the relevant part of the `ECG12` constructor in the file `ECG12.m`. Fortunately, adding new ECG formats to BRAVEHEART is straightforward, and only 2 files (`ECG12.m` and `ecg_format.csv`) need to be edited as described in the following sections:

7.1 The `ECG12` Object

12-lead ECG data is stored in an `ECG12` object which contains the following 14 properties:

- `hz` – the ECG sampling frequency in Hz
- `units` – an optional `string` describing ECG voltage units (usually '`mV`')
- `I` – voltage data for ECG lead I
- `II` – voltage data for ECG lead II
- ... `III`, `avR`, `avL`, `aVF`, `V1`, `V2`, `V3`, `V4`, `V5`, `V6` – voltage data for these leads

Note that only 2 of the 6 frontal leads (`I`, `II`, `III`, `avR`, `avL`, `aVF`) contain unique information.

The data within an `ECG12` object is accessed by querying its properties as if it were a normal data structure in MATLAB; for example, if you have an `ECG12` object named `ecg`, lead II would be accessed as `ecg.II`, and the sampling frequency would be accessed as `ecg.hz`.

7.2 Editing `ECG12.m`

We will start by adding a new format (called “New Format”) to BRAVEHEART. At line 66 of `ECG12.m` you will see a `switch` statement which constructs `ECG12` objects based on a source format string (`format`), such as `'bidmc_format'` or `'muse_xml'`, and a function to load the ECG data from a file:

```
% ADD NEW ECG FORMATS TO THIS SWITCH STATEMENT
switch format

case 'bidmc_format'
    obj.hz=500;
    unitspermv=200;
    [obj.I, obj.II, obj.III, obj.avR, obj.avF, obj.avL, ...
     obj.V1, obj.V2, obj.V3, obj.V4, obj.V5, obj.V6] = load_ecg(filename, unitspermv, format);

case 'muse_xml'
    [obj.hz, obj.I, obj.II, ...
     obj.V1, obj.V2, obj.V3, obj.V4, obj.V5, obj.V6] = load_musexml(filename);
    obj.III = -obj.I + obj.II;
    obj.avF = obj.II - 0.5*obj.I;
    obj.avR = -0.5*obj.I - 0.5*obj.II;
    obj.avL = obj.I - 0.5*obj.II;

...
end
```

We will add a new `case` statement with a function that generates all of the parts of an `ECG12` object (the `units` property is optional).

For example, if you have a function `load_new_format.m` which loads an ECG in `'new_format'` format from a `.txt` file (input variable name `filename`), the outputs of the function should include the frequency (`obj.hz`) and the 12 ECG leads (`obj.<lead>`). Note that you can supply all 12 leads as the output of the load function (see `'bidmc_format'` in the code block above), or you can supply the 8 independent leads in the load function and then reconstruct the 4 additional frontal plane leads in `ECG12.m` itself (see `'muse_xml'` in the code block above).

After this addition, you will have something that looks like this

```
% ADD NEW ECG FORMATS TO THIS SWITCH STATEMENT
switch format

case 'bidmc_format'
obj.hz=500;
unitspermv=200;
[obj.I, obj.II, obj.III, obj.avR, obj.avF, obj.avL, ...
obj.V1, obj.V2, obj.V3, obj.V4, obj.V5, obj.V6] = load_ecg(filename, unitspermv, format);

case 'muse_xml'
[obj.hz, obj.I, obj.II, ...
obj.V1, obj.V2, obj.V3, obj.V4, obj.V5, obj.V6] = load_musexml(filename);
obj.III = -obj.I + obj.II;
obj.avF = obj.II - 0.5*obj.I;
obj.avR = -0.5*obj.I - 0.5*obj.II;
obj.avL = obj.I - 0.5*obj.II;

case 'new_format'
[obj.hz, obj.I, obj.II, obj.III, obj.avR, obj.avF, obj.avL, ...
obj.V1, obj.V2, obj.V3, obj.V4, obj.V5, obj.V6, obj.avL] = load_new_format(filename);

...
end
```

Editing of `ECG12.m` is now complete.

7.3 Editing `ecg_formats.csv`

In addition to the ECG constructor, you will need to modify `ecg_formats.csv` to use your new format. `ecg_formats.csv` is an external, comma delimited, editable file that links the ECG `format` with associated file extensions and labels. `ecg_formats.csv` is also the way that new ECG formats are added to the BRAVEHEART GUI without the hassle of needing to edit the GUI figure.

MUSE .xml,	muse_xml,	.xml,	500
BIDMC .txt,	bidmc_format,	.txt,	500
Prucka .txt,	prucka_format,	.txt,	997
Philips .xml,	philips_xml,	.xml,	500
ISHNE .ecg,	ISHNE,	.ecg,	1000
GE .mrq,	mrq_ascii,	.mrq,	500
DICOM .dcm,	DICOM,	.dcm,	500
HL7 .xml,	hl7_xml,	.xml,	500
Unformatted .txt,	unformatted,	.txt,	500

The first column in `ecg_formats.csv` is the text that shows up in the GUI when selecting the

ECG format (New Format .txt). This can be a string with punctuation or spaces. Column 2 is the ECG format string (`format`) which was added to the `switch` statement above (`'new_format'`), column 3 is the new ECG format file extension (`.txt`), and column 4 is the sampling frequency of the ECG signals which is used by the GUI to select the nominal wavelet levels for filtering. The actual frequency used in calculations is determined when the ECG is actually loaded from the file (see section **Chapter 7.1** describing the `ECG12` class which includes sampling frequency (`hz`) as a property), and the frequency in column 4 of `ecg_formats.csv` is only used to update the nominal filtering settings in the GUI when a different format is chosen from the ‘ECG format’ dropdown. The frequency in column 4 has no effect when BRAVEHEART is being run from `braveheart_batch.m` where all filtering is set in `Annoparams.m` (or `Annoparams.csv` if the program is compiled).

For example, if ECGs of the format (`'new_format'`) are sampled at 1000 Hz, but the `ecg_formats.csv` file column 4 lists the sampling frequency for this format at 500 Hz, the low-pass filtering wavelet level will be set to 2 (nominal for 500 Hz) instead of 3 (nominal for 1000 Hz) when you choose the (`'new_format'`) format in the GUI dropdown. The difference in wavelet filtering settings will slightly change the filtered ECG/VCG signals and therefore slightly change subsequent calculations, but all calculations will use the correct sampling frequency of 1000 Hz, because the correct sampling frequency would be pulled from the `ECG12` object `hz` property when the file is loaded (note that some file formats have the sampling frequency hard coded when they are loaded by `ECG12` if that information is not part of the ECG data file). As the command line version of BRAVEHEART does not utilize any part of the GUI, the frequencies in column 4 of `ecg_formats.csv` are ignored when using `braveheart_batch.m`.

To add the `'new_format'` ECG format as shown above to `ecg_formats.csv`, you would add a new line to `ecg_formats.csv` including a name for the GUI, format name, format file extension, and sampling frequency as shown here:

MUSE .xml,	muse_xml,	.xml,	500
BIDMC .txt,	bidmc_format,	.txt,	500
Prucka .txt,	prucka_format,	.txt,	997
Philips .xml,	philips_xml,	.xml,	500
ISHNE .ecg,	ISHNE,	.ecg,	1000
GE .mrq,	mrq_ascii,	.mrq,	500
DICOM .dcm,	DICOM,	.dcm,	500
HL7 .xml,	hl7_xml,	.xml,	500
Unformatted .txt,	unformatted,	.txt,	500
New Format .txt,	new_format,	.txt,	500

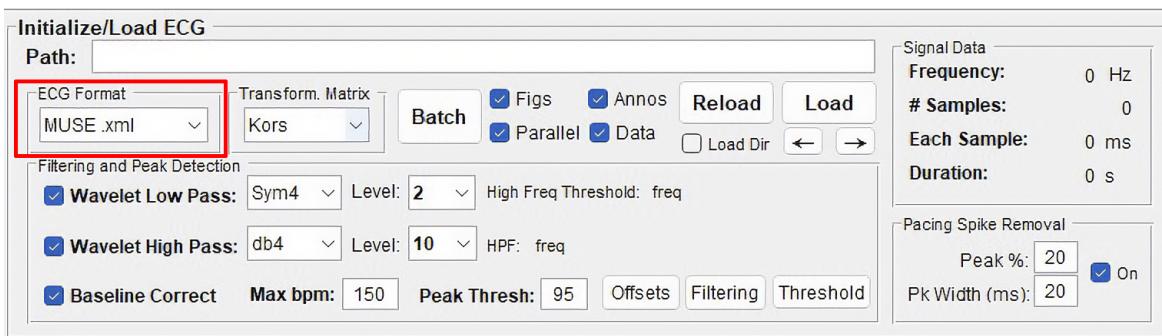
This will now link the format `'new_format'` to the file extension `.txt`. When the GUI is used

the string “**New Format .txt**” will show up in the ECG format dropdown, and choosing this format in the dropdown will automatically choose nominal filtering settings for an ECG sampled at 500 Hz.

7.4 Using Newly Added ECG File Formats

If you are using the command line version of BRAVEHEART (see **Chapter 11**), simply use your new `format` string (in the above example `'new_format'`) in the header of `BRAVEHEART_batch.m` or `batch_settings.csv` if you are using the compiled version (remember that when editing `batch_settings.csv` that strings should NOT be surrounded by quotes).

If you are using the GUI version of BRAVEHEART, simply choose the new format from the ‘ECG format’ dropdown (see GUI item **1.1** in **Chapter 10**).



8 Adding New Transformation Matrices

BRAVEHEART includes the Kors [3] and inverse Dower [4] transformation matrices to convert the 12-lead ECG into a VCG using 8 independent ECG leads. In certain situations, alternative transformation matrices may be needed. This section will illustrate how it is straightforward to add a new transformation matrix to BRAVEHEART. For illustrative purposes we will add a new transformation matrix called the “NewMatrix” transformation.

8.1 Create a Function for The New Transformation Matrix

We will start by creating a function `newmatrix()` in a file `newmatrix.m` which simply contains the coefficients for the new transformation matrix. This should be a 3×8 matrix with rows corresponding to X, Y, and Z, and columns ordered as V1, V2, V3, V4, V5, V6, I, and II:

```
function M = newmatrix()
    % Note: These are random numbers
    %
    %      V1      V2      V3      V4      V5      V6      I      II
    M = [ -0.23   0.15  -0.02   0.13   0.10   0.62   0.44  -0.09 ;  % X
          0.10  -0.12  -0.12   0.10  -0.11   0.13  -0.11   0.98 ;  % Y
         -0.32  -0.36   0.12  -0.23  -0.05   0.22   0.21  -0.14 ]; % Z
end
```

8.2 Editing `ecgtransform.m`

The actual transformation between ECG to VCG is performed by the function `ecg_transform.m`. The new transformation matrix will have to be added to this file.

Start by opening `ecg_transform.m`:

```
function [X, Y, Z, VM] = ecgtransform(L1, L2, V1, V2, V3, V4, V5, V6, transform_matrix)

% Create matrix of leads V1, V2, V3, V4, V5, V6, I, II = Matrix E
E = [ V1, V2, V3, V4, V5, V6, L1, L2 ];

% Choose transformation matrix

switch transform_matrix
    case 'Dower'
        M = dowermatrix();
    case 'Kors'
        M = korsmatrix();
    otherwise
        error('Unknown transform_matrix: %s', transform_matrix);
end

...
```

Add a new `case` statement to the `switch` statement with a string that is the name of the transformation matrix (`'NewMatrix'`) and which assigns `M = newmatrix()`.

```
switch transform_matrix
    case 'Dower'
        M = dowermatrix();
    case 'Kors'
        M = korsmatrix();
    case 'NewMatrix'
        M = newmatrix();
    otherwise
        error('Unknown transform_matrix: %s', transform_matrix);
end
```

8.3 Editing `transform_mat.csv`

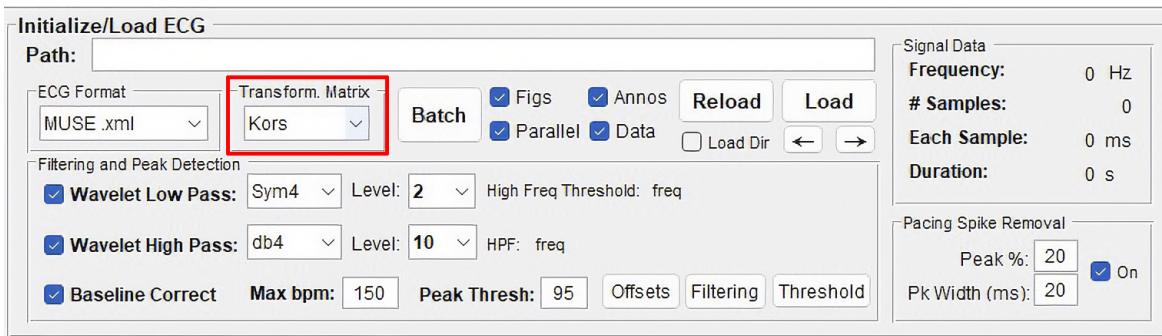
Finally, to add the new transformation matrix to the GUI dropdown, edit `transform_mat.csv` to include the new string used in the switch statement (in this example `NewMatrix`). Strings in `transform_mat.csv` need to be in the order they appear in the switch statement. As with editing the contents of all BRAVEHEART `.csv` files, do not include quotes around strings.

Kors
Dower
NewMatrix

8.4 Using Newly Added Transformation Matrices

If using the command line version of BRAVHEART (see [Chapter 11](#)), open `Annoparams.m` (or `Annoparams.csv` if you are using the compiled version) and assign the newly created transformation matrix string to the parameter `transformation_matrix_str` (e.g. `transformation_matrix_str = 'NewMatrix'`).

If you are using the GUI version of BRAVEHEART, simply choose the new format from the ‘Transform. Matrix’ dropdown (see GUI item [1.2](#) in [Chapter 10](#)).



9 Adding New ECG/VCG Parameters

New ECG/VCG measurements or parameters can easily be added to BRAVEHEART. To illustrate the process we will add a new measurement called `newvar` to BRAVEHEART. Note that although this parameter will be automatically added to BRAVEHEART's output files, adding new measurements to the GUI output panels requires more extensive editing of the GUI figure and other functions that are beyond the scope of this guide.

9.1 Result Classes

BRAVEHEART currently has 3 results classes which are used to store different ECG/VCG measurements. These classes automatically update the output files at the time of data export, so minimal coding is required to add a new measurement. The 3 existing results class objects are somewhat arbitrarily divided into `VCG_Calc.m` which contains mostly ECG and VCG measurements such as ECG intervals, and vector measurements, `Lead_Morphology.m` which contains mostly ECG/VCG QRST complex measurements, and `VCG_Morphology.m` which contains mostly VCG loop morphology measurements. We suggest that you add your new measurement to one of these existing results classes to minimize the need for coding. Each of these 3 results classes takes slightly different inputs, so make sure the class you add to has the required inputs for your new measurement. If your new function is extremely complicated and requires more than the ECG/VCG median beat signals, ECG median beat fiducial point annotations, or annotation parameters (which are the inputs to the existing results classes), addition of your parameter might require more extensive coding which is beyond the scope of this guide. Descriptions of the different calculations that are performed by each result class and the variable names which store the results internally and in output files are shown in **Chapter 22**. All results classes operate on median beats.

We review the 3 results classes in the following sections:

9.1.1 VCG_Calc.m

VCG_Calc.m takes the following inputs:

- A `Beats` class object
- A `VCG` class object
- An `Annoparams` class object

A `Beats` class objects is used to describe individual beat annotations after first pass heuristic ECG annotation or median beat annotation. The `Beats` class object contains the following 7 properties which describe the locations of fiducial points and other features:

- `Q` – location (in samples) of QRS onset (Q_{on}) for the median beat
- `QRS` – location (in samples) of the R wave peak for the median beat
- `S` – location (in samples) of QRS offset (Q_{off}) for the median beat
- `T` – location (in samples) of T wave peak for the median beat
- `Tend` – location (in samples) of T wave offset (T_{off}) for the median beat
- `outlier` – index of outlier beats (not applicable for median beats)
- `pvc` – index of PVCs/non-dominant beats (not applicable for median beats)

The data within a `Beats` object is accessed by querying its properties as if it were a normal data structure in MATLAB; for example, if you have an `Beats` object named `median_beat`, the location of the T wave end would be accessed as `median_beat.Tend`. This is critically important for any new functions that are added to the results classes, because the location of the fiducial points on the median beat signal need to be accounted for in all calculations; the median beat signals have variable amounts of signal before and after the QRST complex which should NOT be included in calculations.

A `VCG` class object is analogous to the `ECG12` class object (see [Chapter 7.1](#)) and contains the following 7 properties:

- `hz` – the VCG sampling frequency in Hz
- `units` – an optional `string` describing VCG voltage units (usually '`mV`')
- `X` – voltage data for VCG lead X
- `Y` – voltage data for VCG lead Y
- `Z` – voltage data for VCG lead Z

- `VM` – voltage data for the VM VCG lead ($VM = \sqrt{X^2 + Y^2 + Z^2}$).
- `endspikes` – data on location of pacemaker spikes (if present)

The data within a `VCG` object is accessed by querying its properties as if it were a normal data structure in MATLAB; for example, if you have an `VCG` object named `vcg`, lead X would be accessed as `vcg.X`.

An `Annoparams` class object is described in detail in [Chapter 6](#). The data within an `Annoparams` object is accessed by querying its properties as if it were a normal data structure in MATLAB; for example, if you have an `Annoparams` object named `aps`, the parameter `lowpass` would be accessed as `aps.lowpass`.

In `VCG_Calc.m` the `VCG` class object is a variable named `v_uncropped`, the `Beats` class object is a variable named `medianbeat`, and the `Annoparams` class object is a variable named `aps`. `VCG_Calc` contains a function called `crop` which cuts out the median QRST complex from the full median VCG signal. The variable `v_cropped` is the `VCG` class object which only contains the actual QRST complex. `v_cropped.X` is equivalent to `v_uncropped.X(medianbeat.Q:medianbeat.Tend)` (and the same for leads Y, Z, and VM).

9.1.2 `Lead_Morphology.m`

`Lead_Morphology.m` includes the following inputs:

1. An `ECG12` class object
2. A `VCG` class object
3. A `Beats` class object
4. An `Annoparams` class object

The parameters in each of these class objects have been previously described above.

In `Lead_Morphology.m` the `ECG12` class object is a variable named `ecg`, the `VCG` class object is a variable named `vcg`, and the `Annoparams` class object is a variable named `aps`. When the `Lead_Morphology` class is called, the median beat `Beats` class object input is converted to a 1×4 vector named `fidpts`, which contains the values of `[beats.Q, beats.QRS, beats.S, beats.Tend]` in that order which is analogous to the values of

$[Q_{on}, R \text{ peak}, Q_{off}, T_{off}]$. The location of Q_{on} can therefore be called as `fidpts(1)`, the location of the R peak can be called as `fidpts(2)`, the location of Q_{off} can be called as `fidpts(3)`, and the location of T_{off} can be called as `fidpts(4)`. As another example, the QRS complex in lead X would be obtained as `vcg.X(fidpts(1):fidpts(3))`, and the full QRST complex in lead Y would be obtained as `vcg.Y(fidpts(1):fidpts(4))`. There is no `crop` function in `Lead_Morphology.m`, although it could be added if needed.

9.1.3 `VCG_Morphology.m`

`VCG_Morphology.m` includes the following inputs:

1. An `ECG12` class object
2. A `VCG` class object
3. A `Beats` class object

The parameters in each of these class objects have been previously described above.

In `VCG_Morphology.m` the `ECG12` class object is a variable named `ecg`, and the `VCG` class object is a variable named `vcg`. Similar to the `Lead_Morphology` class, when the `VCG_Morphology` class is called, the median beat `Beats` class object input is converted to a 1×4 vector named `fidpts` which contains the values of `[beats.Q, beats.QRS, beats.S, beats.Tend]` in that order (see Chapter 9.1.2 above).

9.2 Adding a New Calculation

We will add our new measurement to `VCG_Calc.m`. We start by opening `VCG_Calc.m` and finding the `properties` section at the top.

```
classdef VCG_Calc
%
properties (SetAccess=private)
    % SVG
    svg_x
    svg_y
    svg_z

    % SAI
    sai_x
    sai_y
    sai_z

    ...
    % QRS/QT intervals (in ms)
    qrs_int
    qt_int
end
```

Further down in the `methods` section of `VCG_Calc.m` you will see a busy chunk of code starting around line 184 with the comment `% ADD NEW MEASUREMENTS IN THIS SECTION` assigning various values to the members of the `VCG_Calc` class:

```
% ADD NEW MEASUREMENTS IN THIS SECTION
...
obj.vcg_length_qrs = curve_length(v_cropped.X, v_cropped.Y, v_cropped.Z, 1, qend);
obj.vcg_length_t = curve_length(v_cropped.X, v_cropped.Y, v_cropped.Z, qend, length(v_cropped.X));
obj.vcg_length_qrst = curve_length(v_cropped.X, v_cropped.Y, v_cropped.Z, 1, length(v_cropped.X));
...
...
```

In this code snippet (which is a small part of the `VCG_Calc` class property assignments), the values of `vcg_length_qrs`, `vcg_length_t`, and `vcg_length_qrst` (see [Chapter 22](#)) are assigned their respective properties in the class, `obj.vcg_length_qrs`, `obj.vcg_length_t`, and `obj.vcg_length_qrst`, respectively. Again, note how the calculations use the cropped VCG lead signals (just the QRST complex) (`v_cropped.X`, `v_cropped.Y`, and `v_cropped.Z`) rather than `v_uncropped` which is the QRST complex with additional signal before Q_{on} and additional signal after T_{off} .

Our new measurement `newvar` is calculated from a function called `calc_newvar(x,y,z,beats)` which is saved in a file `calc_newvar.m`:

```
newvar = calc_newvar(x,y,z,beats)
```

This function takes in median X, Y, and Z QRST complexes and a `Beats` object and outputs the value of `newvar`. We start by adding `newvar` to the `properties` section of `VCG_Calc.m`:

```
classdef VCG_Calc
%
properties (SetAccess=private)
    % SVG
    svg_x
    svg_y
    svg_z

    % SAI
    sai_x
    sai_y
    sai_z

    % New Measurement
    newvar
    ...

    % QRS/QT intervals (in ms)
    qrs_int
    qt_int
end
```

We then insert the function which is used to calculate `newvar` into the `methods` section of `VCG_Calc.m`, assigning its output to `obj.newvar`:

```
% ADD NEW MEASUREMENTS IN THIS SECTION
...
obj.vcg_length_qrs = curve_length(v_cropped.X, v_cropped.Y, v_cropped.Z, 1, qend);
obj.vcg_length_t = curve_length(v_cropped.X, v_cropped.Y, v_cropped.Z, qend, length(v_cropped.X));
obj.vcg_length_qrst = curve_length(v_cropped.X, v_cropped.Y, v_cropped.Z, 1, length(v_cropped.X));

obj.newvar = calc_newvar(v_cropped.X, v_cropped.Y, v_cropped.Z, beats);
...
...
```

Once the new variable is added to a result class, no further files require editing. The functions for exporting data will now automatically include a variable called `newvar` and assign it the value calculated by the `calc_newvar` function.

Chapter 22 lists the different parameters that are included in each of the results classes.

10 Using the BRAVEHEART GUI

10.1 GUI Overview

In addition to batch processing of ECGs via `braveheart_batch.m` (see [Chapter 11](#)), the BRAVEHEART GUI facilitates control over each step of ECG/VCG processing and can generate additional figures and data visualizations. In this chapter we provide an overview of the different functions of the GUI and how to process ECGs from files to measurements saved for further processing.

To run the BRAEHEART GUI, type `braveheart_gui` in the MATLAB Command Window if the program is being run via source code within MATLAB, or open the executable if running via a compiled version of the GUI.

The BRAVEHEART window immediately after opening is shown below in [Figure 1](#). The appearance on your computer may vary slightly based on your operating system. A screen resolution of at least 1920 x 1080 is recommended.

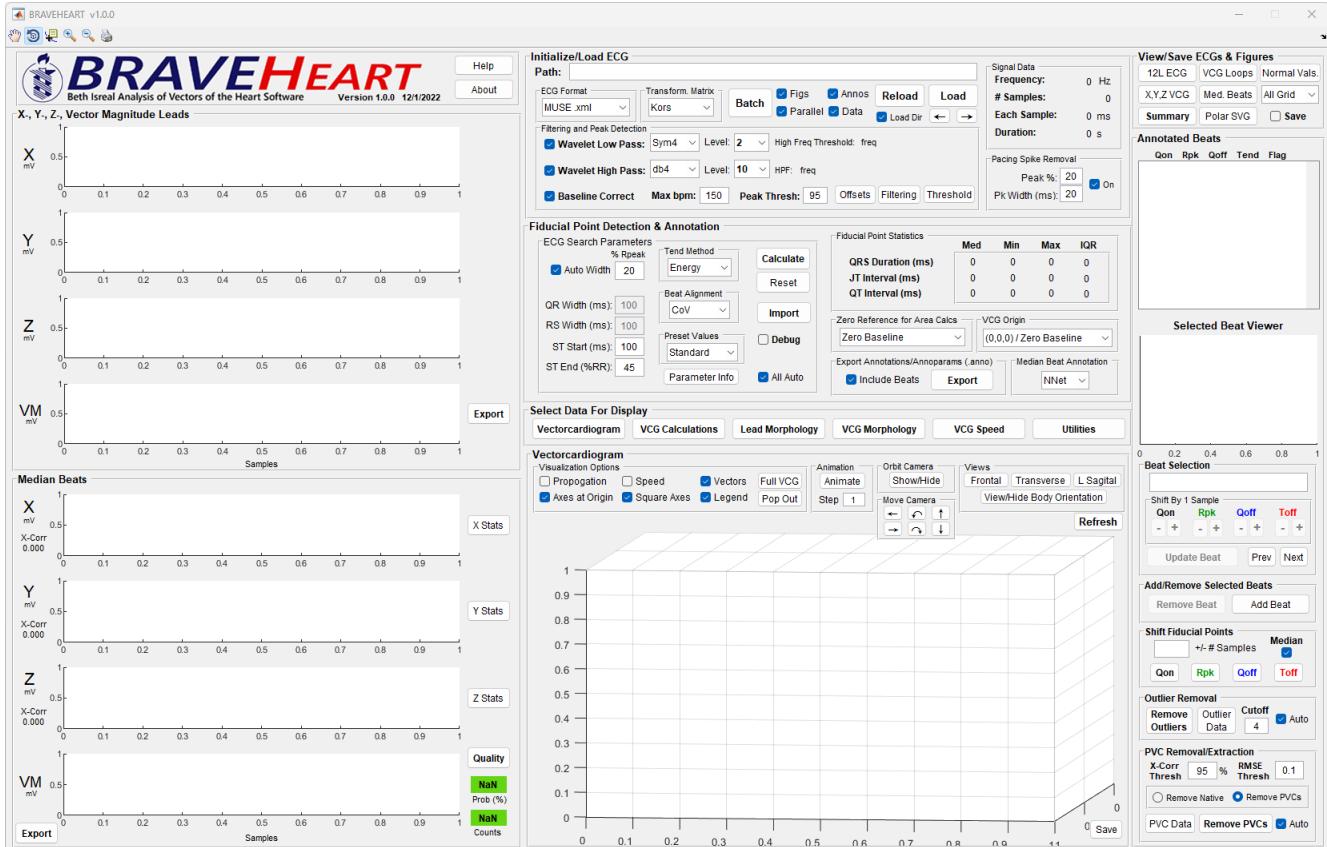


Figure 1: GUI when BRAVEHEART is first loaded.

The GUI is organized into 10 different sections which, in general, have different functions. The

different sections of the GUI are shown below in **Figure 2**; a general description of each section is provided followed by detailed descriptions of GUI items within each section.

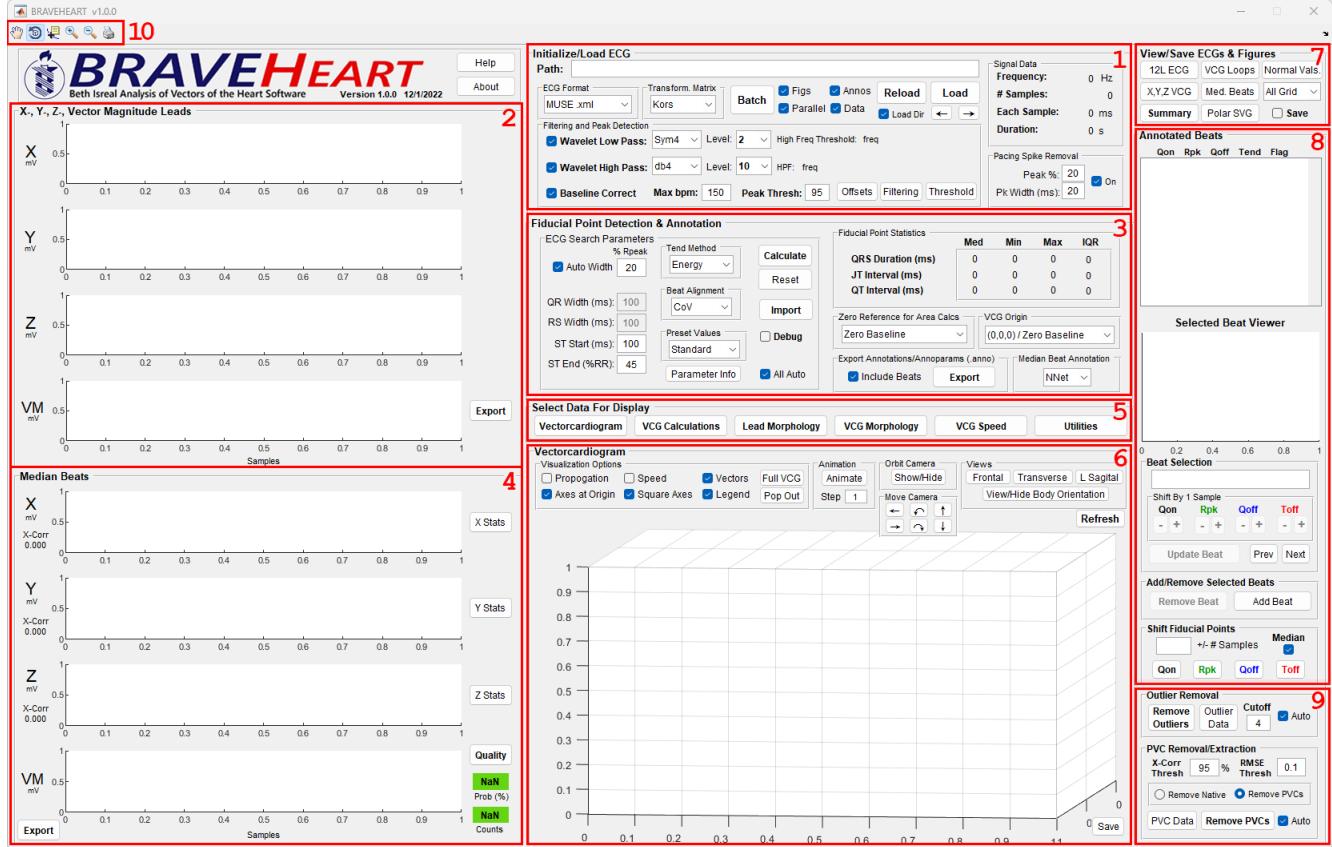


Figure 2: GUI Sections 1–10.

Many of the parameters that are set using the GUI correspond to the properties in the `Annoparams.m` class, and users are referred to **Chapter 6** for further details of each property. A summary of the link between `Annoparams.m` and sections of the GUI is provided in **Chapter 23**. The GUI also contains other functions and visualization that are unique to the GUI and which allow fine control and/or visualization of different steps in ECG/VCG processing.

Throughout the guide, to denote a specific section/item within the GUI, the term ‘GUI item **N.M**’ with numbers in red text will be used; **N** refers to the GUI section (1–10) as noted in **Figure 2** above, and **M** refers to the numbered item within the section as detailed in the subsequent sections. For example, the **Load** button would be denoted as GUI item **1.9** as it is item **9** in GUI section **1**, and the **Calculate** button would be similarly denoted as GUI item **3.6**.

Section 6 is unique in that what is displayed depends on what button is selected in Section 5. For Section 6 alone, there is an extra number to denote the specific part of the GUI that is being shown. For example, the **Vectorcardiogram** button (GUI item **5.1**) loads GUI section 6.1, and the first item in this section is noted as GUI item **6.1.1**, while the **VCG Morphology** button

loads GUI section 6.4 and the first item in this section is noted as GUI item **6.4.1**.

10.2 GUI Section 1 – ECG Loading, Filtering, R Peak Detection, and Baseline Correction

Section 1:

Choose an ECG file and load (or reload) the ECG data. Choose options for transformation of the ECG into a VCG, QRS peak detection, signal filtering, and pacemaker spike removal.

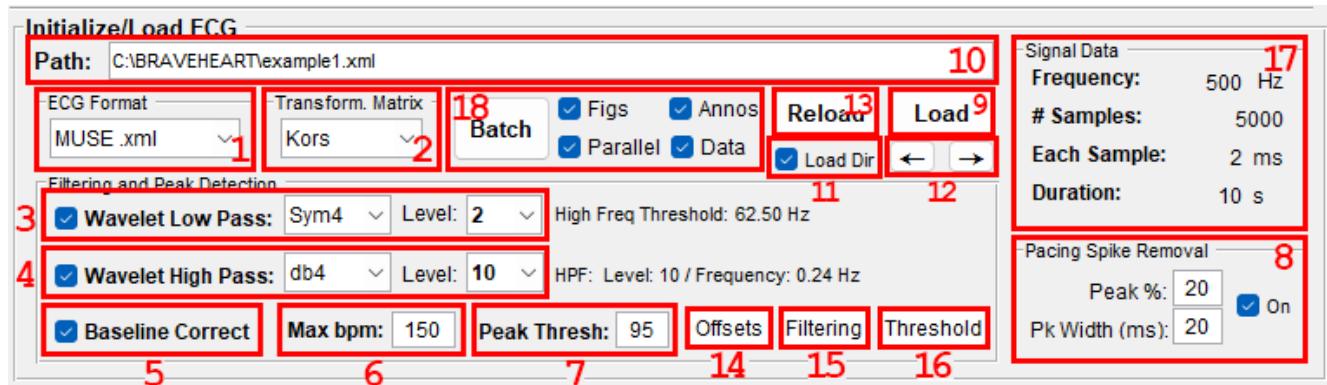


Figure 3: GUI Section 1

1. Dropdown to select the format of the ECG to be loaded. Sets the value of `format` in the ECG constructor `ECG12.m`. The link between the text shown in the dropdown and the actual `format` that is utilized by the GUI is contained in the external file `ecg_formats.csv` (see **Chapter 7**). Additional information on ECG formats that can be read by BRAVEHEART and how to add new formats can be found in **Chapter 21** and **Chapter 7**, respectively.

2. Dropdown to select the VCG transformation matrix used to transform the ECG into a VCG. Sets the value of `transform_matrix_str` in `Annoparams.m`. BRAVEHEART includes the Kors [3] and inverse Dower [4] transformation matrices. Additional transformation matrices can be added as described in **Chapter 8**.

3. Select and choose options for low-pass filtering. The `Wavelet Low Pass` checkbox enables/disables low-pass filtering by setting `lowpass = 1` (checked) or `lowpass = 0` (unchecked) in `Annoparams.m`. The dropdowns allow you to choose the wavelet used for low-pass filtering (`wavelet_name_lowpass`) and the level of filtering (`wavelet_level_lowpass`) in `Annoparams.m` (see **Chapter 6.2**).

After the ECG is loaded, the text to the right of GUI item **1.3** shows the low-pass cutoff

frequency which corresponds to the chosen wavelet level based on the equation $(f/2)/(2^n)$ where f is the ECG sampling frequency and n is the chosen level (`wavelet_level_lowpass`). In this example, the low-pass filter has a cutoff frequency of 62.5 Hz which corresponds to level 2 at a sampling frequency of 500 Hz. In general try to avoid choosing a level that results in low-pass filtering cutoff < 40 Hz as the QRST complex tends to include frequencies between 0.5-40 Hz [2]. Filtering can be visualized with a figure generated with the **Filtering** button (GUI item **1.15**) as shown in **Figure 46**.

4. Select and choose options for high-pass filtering. The **Wavelet High Pass** checkbox enables/disables high-pass filtering by setting `highpass = 1` (checked) or `highpass = 0` (unchecked) in `Annoparams.m`. The dropdowns allow you to choose the wavelet used for high-pass filtering (`wavelet_name_highpass`) and the level of filtering (`wavelet_level_highpass`) in `Annoparams.m` (see **Chapter 6.2**).

After the ECG is loaded, the text to the right of GUI item **1.4** shows the high-pass cutoff frequency which corresponds to the chosen wavelet level based on the equation $(f/2)/(2^n)$ where f is the ECG sampling frequency and n is the chosen level (`wavelet_level_highpass`). In this example, the high-pass filter has a cutoff frequency of 0.24 Hz which corresponds to level 10 at a sampling frequency of 500 Hz. In general try to avoid choosing a level that results in high-pass filtering cutoff > 0.5 Hz as the QRST complex tends to include frequencies between 0.5-40 Hz [2]. Filtering can be visualized with a figure generated with the **Filtering** button (GUI item **1.15**) as shown in **Figure 46**.

5. Checkbox to enable/disable physiological baseline correction. This part of ECG/VCG processing adjusts the baseline after filtering to remove any residual offsets so the TP segment (or the TQ segment in atrial fibrillation) of the ECG signal approximates 0 mV as this segment of the ECG is truly isoelectric. The **Baseline Correction** checkbox sets `baseline_correct_flag = 1` (checked) or `baseline_correct_flag = 0` (unchecked) in `Annoparams.m`. Setting the 0 mV reference correctly is *critical* for accurately calculating areas under median QRST complexes. Further details about baseline correction can be found in **Chapter 13.2**, **Figure 23**, **Figure 24**, and **Figure 25**.
 6. Textbox to set `maxBPM` in `Annoparams.m` for QRS peak detection. See **Chapter 13.1** and **Figure 22** for additional details of how this parameter controls QRS peak detection.
 7. Textbox to set `pkthresh` in `Annoparams.m` for QRS peak detection. See **Chapter 13.1** and **Figure 22** for additional details of how this parameter controls QRS peak detection.
-

8. Adjust parameters for automatic pacemaker spike/artifact removal. The **On** checkbox enables/disables pacemaker spike removal by setting `spike_removal = 1` (checked) or `spike_removal = 0` (unchecked) in `Annoparams.m`. The ‘Peak %’ textbox sets the value of `pacer_thresh` in `Annoparams.m` which sets the percentage of the pacing spike maximum amplitude used to estimate pacing spike width. The ‘Pk Width’ textbox sets the value of `pacer_spike_width` in ms in `Annoparams.m`. See **Chapter 6.2** and ECG Example 5 (**Chapter 5.4**) for further details.

9. The **Load** button opens a dialog box so the user can choose an ECG file to process. If the **Load Dir** checkbox (GUI item **1.11**) is checked, the load process also loads a list of all files in the same directory with the same extension as the loaded file so the user can quickly cycle through multiple files in a directory using GUI item **1.12** (see below).

10. Textbox which shows the full path of the ECG file which has been loaded. This can be manually edited; to load the file after manually editing the file path click the **Reload** button (See GUI item **1.13**) below.

11. The **Load Dir** checkbox loads an alphabetized list of all files of the same format within the directory the chosen file is loaded from to allow use of the **←** and **→** buttons (GUI item **1.12**) to easily cycle through files within a directory. If **Load Dir** if unchecked, only a single file is loaded and the **←** and **→** buttons have no effect. Checking **Load Dir** without subsequently loading an ECG using the **Load** button (GUI item **1.9**) has no effect as the list of files is loaded when the callback triggered by **Load** is activated. If there are a very large number of ECG files in the directory, disabling **Load Dir** may significantly speed up loading an individual ECG.

12. The **←** and **→** buttons cycle through all of the files with the same extension as the file chosen with the **Load** button if **Load Dir** is also checked as noted in GUI item **1.11** above. Files are sorted alphabetically.

13. After the ECG has been initially loaded using the **Load** button, the **Reload** button will reload the current ECG from scratch without having to select the file again. The **Reload** button is also used after manually editing the file path textbox (GUI item **1.10** above) to load the file in the path textbox. The **Reload** button does NOT reset the GUI parameters to the default values in `Annoparams.m`; this function is performed by the **Reset** button (GUI item **3.7**).

-
- 14.** The `Offsets` button displays a figure that shows the baseline offsets in all leads and how filtering and baseline correction have performed physiological re-zeroing of the ECG signal voltage. See **Figure 25** for additional information.
-
- 15.** The `Filtering` button displays a figure that shows the effect of the selected filtering on the ECG signal. See **Figure 46** for additional information.
-
- 16.** The `Threshold` button displays a figure that shows how the parameters `pkthresh` and `maxBPM` are working to identify R peaks in the VM lead as part of first pass VCG fiducial point processing. Further details are available in **Chapter 13.1** and **Figure 22**.
-
- 17.** Summary of ECG signal data that was loaded, including the sampling frequency, number of ms between samples, and signal duration in seconds and samples.
-
- 18.** Settings for running `BRAVEHEART_batch()`. The `Batch` button brings up a dialog box that allows the user to choose a folder of ECGs for batch processing. Checkboxes control output of batch processing. Further details of batch processing via the GUI can be found in **Chapter 12**.
-

10.3 GUI Section 2 – VCG Display

Section 2:

Display the X, Y, Z, and VM leads for the loaded 12-lead ECG after processing based on parameters set in GUI Section 1.

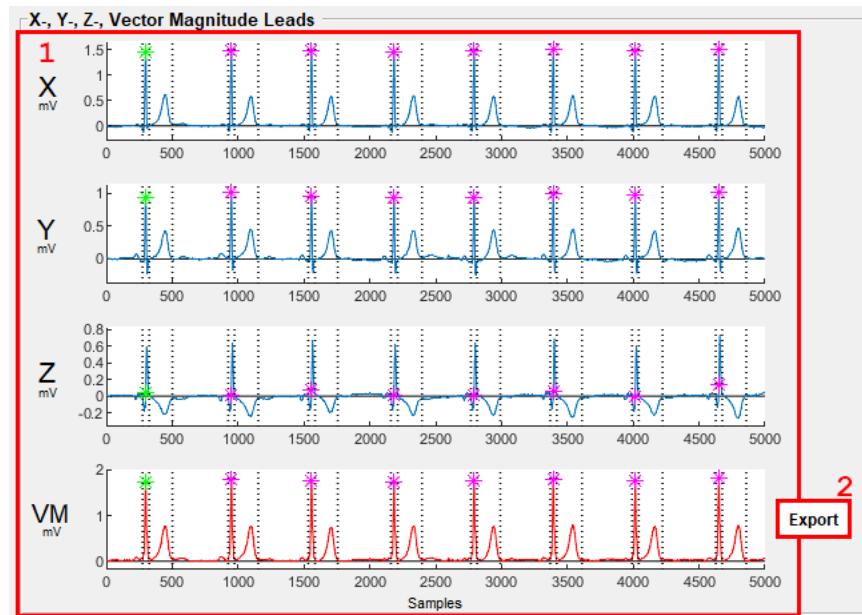


Figure 4: GUI Section 2

1. Display of the filtered and baseline corrected VCG (X, Y, and Z leads) and VM leads.
Detected QRS peaks are shown with a magenta * with the exact location based on the VM lead R wave peak. After first pass annotation is complete (user clicked **Calculate** – GUI item **3.6**), dashed black lines show the locations of Q_{on}, Q_{off}, and T_{off} (see **Figure 5** below). When a beat is selected in the '**Selected Beat Viewer**' (GUI item **8.2**), the magenta * is changed to a green * as shown in **Figure 5** below where the first beat has been selected:

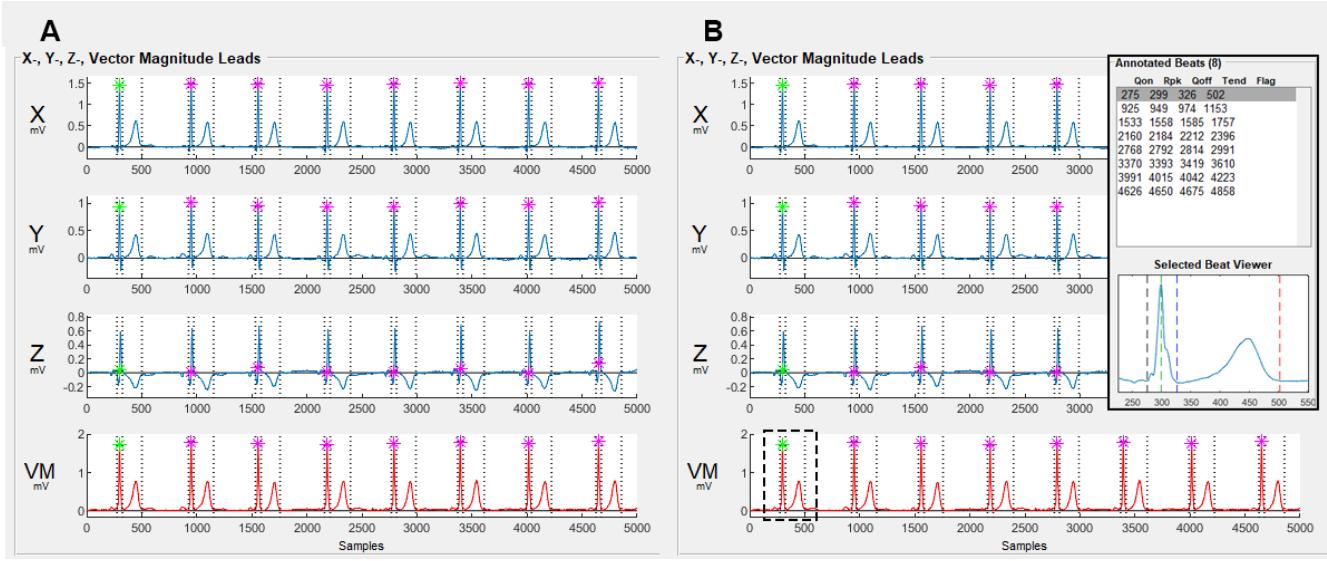


Figure 5: **A:** The * corresponds to each detected R peak in the VM lead. After first pass annotation, dashed vertical lines mark the Q_{on}, Q_{off}, and T_{off} for each beat. **B:** When a beat is selected in the ‘Annotated Beats’ section (GUI item 8.1), the selected beat (dashed rectangle) is highlighted with a green * and displayed in the ‘Selected Beat Viewer’ in GUI item 8.2 (inset panel).

Beats that are identified as ‘PVCs’ or other non-dominant QRST morphologies (see **Chapter 13.3**) will be marked with a triangle around the * (▲), and beats that are identified as ‘outliers’ will be marked with a circle around the * (●). These symbols correspond to the ‘#’ and ‘**’ symbols in the ‘Annotated Beats’ section of Section 8 (GUI item 8.1). Note that a beat can be labeled as both a “PVC” and an “outlier”, in which case it is labeled with both a triangle *and* circle in the ‘X-, Y-, Z-, Vector Magnitude Leads’ section, and with both a ‘#’ and ‘**’ in the ‘Annotate Beats’ list. See **Chapter 13.3** and **Chapter 13.4** for further information.

-
2. the **Export** button exports the VCG signal data (X, Y, Z, and VM leads) as **.mat** and **.csv** files. The exported files will appear in the same directory as the ECG file with the naming convention `<filename>_xyz_beats.mat` and `<filename>_xyz_beats.csv`. The **.mat** file contains a structure `xyz_beats` that contains a $n \times 4$ matrix with columns corresponding to the X, Y, Z, and VM leads in that order, and each row corresponding to a sample. The **.csv** file contains 4 columns corresponding to the X, Y, Z, and VM leads in that order. In both file formats, exported signals are in units of mV.
-

10.4 GUI Section 3 – Fiducial Point Annotation and Median Beat Creation/Annotation

Section 3:

Choose options for first pass fiducial point annotation and median beat creation and annotation.

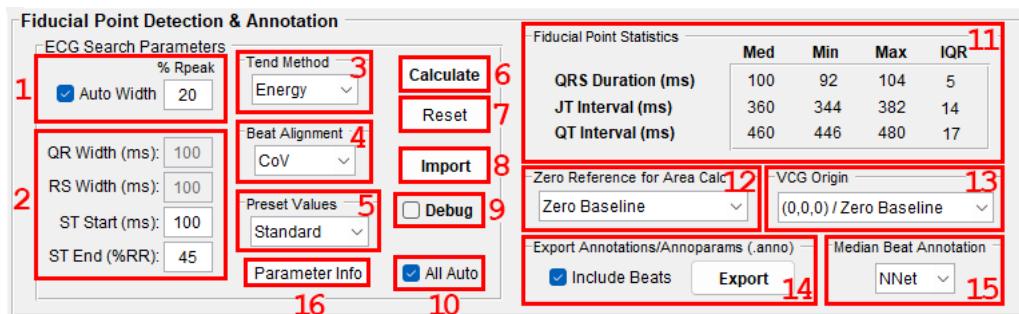


Figure 6: GUI Section 3

1. Select and set options for using automatic QRS width estimation during first pass heuristic annotation. **Auto Width** sets the value of `autoMF = 1` (checked) or `autoMF = 0` (unchecked) in `Annoparams.m`. The textbox ‘% Rpeak’ sets the value of `autoMF_thresh` in `Annoparams.m`. If `autoMF = 1` the first pass annotation algorithm dynamically estimates the QRS search window for each beat individually rather than using a fixed window as specified by `QRwidth` and `RSwidth` (see GUI item 3.2 below). Further details of annotation parameters can be found in **Chapter 6.2**, **Chapter 16**, and **Figure 30**.

2. Textboxes to set the value of `QRwidth`, `RSwidth`, `STstart`, and `STend` in `Annoparams.m`. Note that `QRwidth` and `RSwidth` can only be changed if **Auto Width** (GUI item 3.1) is unchecked, as otherwise the `QRwidth` and `RSwidth` are dynamically set for each beat individually based on QRS width estimation, which is usually the best option. For further details on these parameters and their relation to fiducial point annotation, see **Chapter 6.2**, **Chapter 16**, and **Figure 30**.

3. Dropdown to select the method of first pass T wave end (T_{off}) annotation by setting `Tendstr` in `Annoparams.m`. The nominal value of ‘Energy’ should be used in most cases as this method is more robust to abnormal T wave morphologies than are the other options of ‘Tangent’ (which uses the tangent method) and ‘Baseline’ (which finds the baseline crossing). Further details can be found in **Chapter 6.2**, **Chapter 16**, and **Figure 30**.

4. Dropdown to select the method of beat alignment for median beat construction by setting `align_flag` in `Annoparams.m`. ‘CoV’ uses the filtered center of voltage of the QRS complex

to align beats, while ‘Rpeak’ uses the location of the R wave peak voltage to align beats. See **Chapter 6.2** for additional details.

5. Dropdown to select preset values for `pkthresh`, `maxBPM`, `QRwidth`, `RSwidth`, `STstart`, and `STend`. This can be useful when you have certain types of ECGs (such as ECGs with very long QT intervals or frequent PVCs) and you want to quickly adjust the annotation settings and save them for future use. The dropdown pulls values from the external file `search_presets.csv`. Further details can be found in **Chapter 19**.
 6. The **Calculate** button begins processing of the ECG/VCG after it has been loaded and filtered. Press this once all filtering and annotation parameters are set appropriately.
 7. The **Reset** button resets all GUI parameters to their nominal values which are pulled from `Annoparams.m`.
 8. The **Import** button overrides the set GUI/annotation parameters and pulls annotation parameters and fiducial point annotations from an external `.anno` file. Further details can be found in quick start Example 5 (**Chapter 5.5**) and **Chapter 15**.
 9. Checkbox to enable/disable debug figures for both first pass and median beat annotation. The **Debug** checkbox sets `debug = 1` (checked) or `debug = 0` (unchecked) in `Annoparams.m`. Further details on using debugging can be found in **Chapter 25.6**, **Figure 30**, and **Figure 49**.
 10. Checkbox to easily enable/disable automatic outlier and automatic PVC removal using a single click. When **All Auto** is checked, the **Auto** checkboxes for both outlier removal (GUI item **9.4**), and PVC removal (GUI item **9.10**) are also checked, and `pvc_removal = 1` and `outlier_removal = 1` in `Annoparams.m`, thus enabling automatic outlier and PVC removal during ECG/VCG processing. When **All Auto** is unchecked, the **Auto** checkboxes for outlier removal and PVC removal both get unchecked, disabling both automatic outlier removal and automatic PVC removal (`pvc_removal = 0` and `outlier_removal = 0` in `Annoparams.m`).
 11. Summary of first pass annotation statistics. The median ('Med'), minimum ('Min'), maximum ('Max'), and interquartile range ('IQR') are displayed. This is one way of quickly assessing the quality and consistency of first pass annotation.
-

-
- 12.** Dropdown to set `baseline_flag` in `Annoparams.m`. In general, this should not be changed from the nominal value of ‘Zero Baseline’ if ECGs are filtered and baseline corrected appropriately. Further details can be found in **Chapter 6.2**.
-
- 13.** Dropdown to set `origin_flag` in `Annoparams.m`. In general, this should not be changed from the nominal value of ‘Zero Baseline’ if ECGs are filtered and baseline corrected appropriately. Further details can be found in **Chapter 6.2**.
-
- 14.** This section is used to export annotation (extension `.anno`) files. The **Export** button generates an `.anno` file that contains the annotation parameters used to process the file. If the **Include Beats** checkbox is checked, the `.anno` file also contains information on the beats used to construct the median beat. See quick start Example 5 (**Chapter 5.5**) and **Chapter 15** for additional information.
-
- 15.** Sets the method of annotating the median beat using either the standard heuristic annotator ‘Std’ or the custom BRAVEHEART neural network (NN) median beat annotater ‘NNet’. In almost all cases the nominal value of ‘NNet’ should be used as it is the most accurate way to annotate median beats. In rare cases where the NN fails to accurately annotate a median beat, switching to ‘Std’ may work, although usually ECGs that fail NN annotation are ECGs with significant noise and artifact that are difficult to annotate regardless of method. Details of neural network development and annotation performance are available in the methods manuscript [1] and **Chapter 17**.
-
- 16.** The **Parameter Info** button opens a file which contains information on annotation parameters and heuristic first pass annotation.
-

10.5 GUI Section 4 – Median Beat Display and Quality Assessment

Section 4:

Visualize median X, Y, Z, and VM beats, the individual beats that make up the median beat, and information about the quality of ECG processing, median beat construction, and median beat annotation.

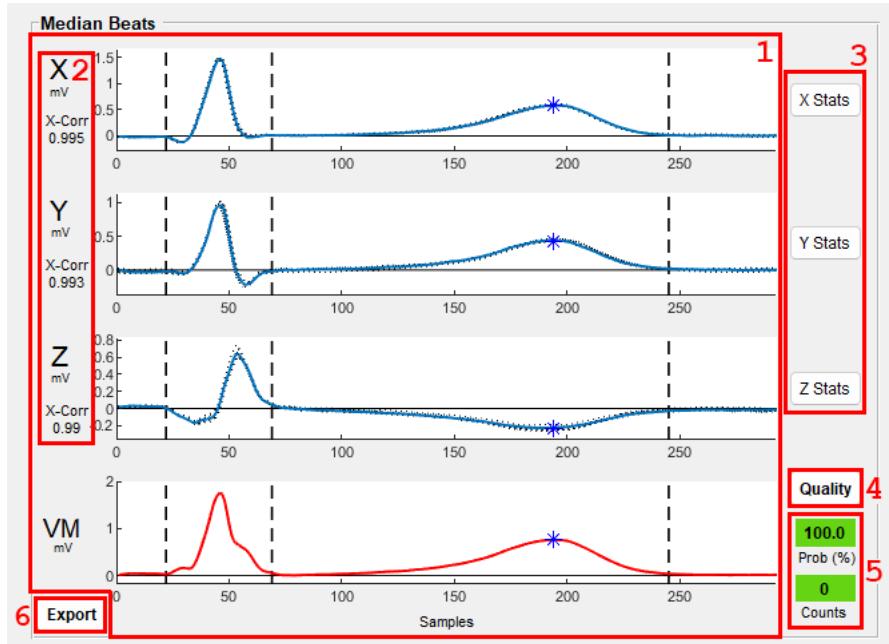


Figure 7: GUI Section 4

1. Display of the X, Y, Z, and VM median beats. The actual median beats are shown in blue for leads X, Y, and Z, and in red for lead VM. For leads X, Y, and Z, the individual beats that were aligned to construct the X, Y, and Z median beats are shown with black dotted lines. There are no individual beats shown for the VM median beat because the median VM beat (VM_{med}) is created only with the median X, Y, and Z beats as $VM_{med} = \sqrt{X_{med}^2 + Y_{med}^2 + Z_{med}^2}$. The location of the * corresponds the location of the maximum T wave amplitude in the VM lead. When a beat is selected in the ‘Annotated Beat Viewer’ (GUI item 8.1), the selected beat is highlighted in green:

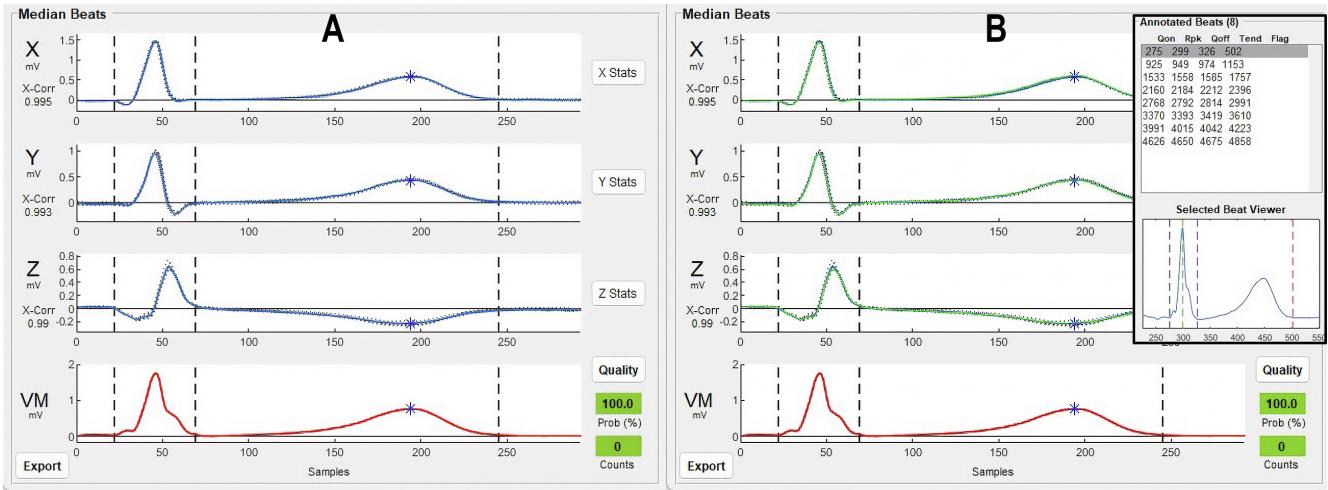


Figure 8: **A:** When a beat is not selected the individual beats that make up each of the X, Y, and Z median beats are shown in black dashed lines. **B:** When a beat is selected in the ‘Annotated Beats’ section (GUI item 8.1), the selected beat in the X, Y, and Z leads is highlighted in green.

2. Mean normalized cross correlation (NCC/‘X-Corr’) for the X, Y, and Z beats, respectively. Values close to 1.0 indicate that all beats in that lead which were used to construct the median beat were very similar in morphology and alignment, while low values suggest that there are multiple beat morphologies that differ significantly from each other and/or poor beat alignment which might impact the quality of median beat construction and subsequent calculations. This is used primarily as a quality control, and the lowest of the normalized cross correlation values for the X, Y, and Z leads is used as part of the quality assessment after ECG processing (see Chapter 14).

3. The **X Stats**, **Y Stats**, and **Z Stats** buttons display information on the individual beats used to create the median beat in the X, Y, and Z leads, respectively. This information can be useful to assess for outlier beats or beats that are causing issues with median beat construction. An example of the figure produced when clicking these buttons is shown in Figure 44.

4. The **Quality** button opens a figure that shows various quality metrics for the processed ECG. Further information can be found in Chapter 14 and Figure 29.

5. Measures of ECG processing/annotation quality (see Chapter 14). The ‘Prob (%)’ value is a predicted probability between 0 and 1 (expressed as a percentage) that is the output of a logistic regression which takes various morphologic features of the processed median beat as input and outputs the probability of the processed median beat being “good” quality.

Values above a set cutoff in `quality_presets.csv` are shown with a **green** background, while values below this cutoff are shown in **red** background. If the value is ‘NaN’ this signifies a significant issue with annotation that should be investigated (or an ECG has not been processed). See **Chapter 14** for further details.

The ‘Counts’ value reports the number of quality parameters that are outside of the bounds set in `quality_presets.csv`. Values of 0 are shown in **green**, while values > 0 are shown in **red**. The figure opened by clicking on the **Quality** button (see **Figure 29**), displays the individual quality parameters that are used for this metric. See **Chapter 14** for details.

6. The **Export** button exports the 16 median beats and median beat annotations as `.mat` and `.csv` files. The exported files will appear in the same directory as the ECG file with the naming convention `<filename>_xyz_medians.mat` and `<filename>_xyz_medians.csv`. The `.mat` file contains a structure `medians` that contains fields corresponding to all 16 leads (12 leads, X, Y, Z, and VM) (eg `medians.V1` loads the lead V1 median beat). The `.csv` file contains 16 columns corresponding to the 16 leads in the order I, II, III, avR, avF, avL, V1, V2, V3, V4, V5, V6, X, Y, Z, and VM. In both file formats, exported signals are in units of mV. In the `.mat` file, the median beat annotations are saved as `median.Q` (`Qon`), `median.S` (`Qoff`), and `median.Tend` (`Toff`) in samples. Median beat annotations are not saved to the `.csv` file.

10.6 GUI Section 5 – Select Displayed Information

Section 5:

Select what information is shown in the GUI information display (GUI Section 6).

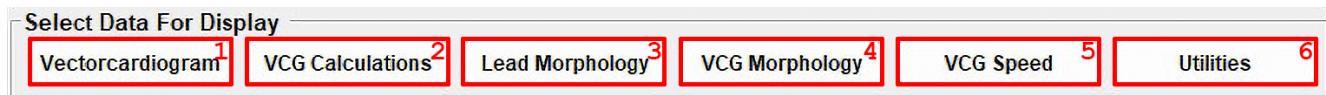


Figure 9: GUI section 5.

1. The **Vectorcardiogram** button displays the 3D VCG. See GUI Section 6.1 in **Chapter 10.7** for further details.
2. The **VCG Calculations** button displays a set of measurements obtained from the median ECG/VCG, and the majority of results contained in `VCG_Calc` results class. See GUI Section 6.2 in **Chapter 10.7** and **Chapter 22** for further details.

3. The **Lead Morphology** button displays a pop-out window with all 16 median beats, fiducial points, and the measurements of the R, S, and T waves. This displays the majority of results contained in the **Lead_Morphology** results class. See GUI Section 6.3 in **Chapter 10.7** and **Chapter 22** for further details.

4. The **VCG Morphology** button displays information on the morphology of the QRS and T loops, including coplanarity, total cosine R-to-T (TCRT), roundness, area, and perimeter, including the majority of results contained in the **VCG_Morphology** results class. See GUI Section 6.4 in **Chapter 10.7** and **Chapter 22** for further details.

5. The **VCG Speed** button displays measurements of median VCG speed and allows graphical display of median VCG speed and acceleration. See GUI section 6.5 in **Chapter 10.7** for further details.

6. The **Utilities** button brings up a set of ECG/VCG utilities and allows additional control over GUI function and output. See GUI Section 6.6 in **Chapter 10.7** further details.

10.7 GUI Section 6 – GUI Information Display

Section 6.1:

The **Vectorcardiogram** button displays the median beat VCG with various visualization options. The figure can be rotated in 3D.

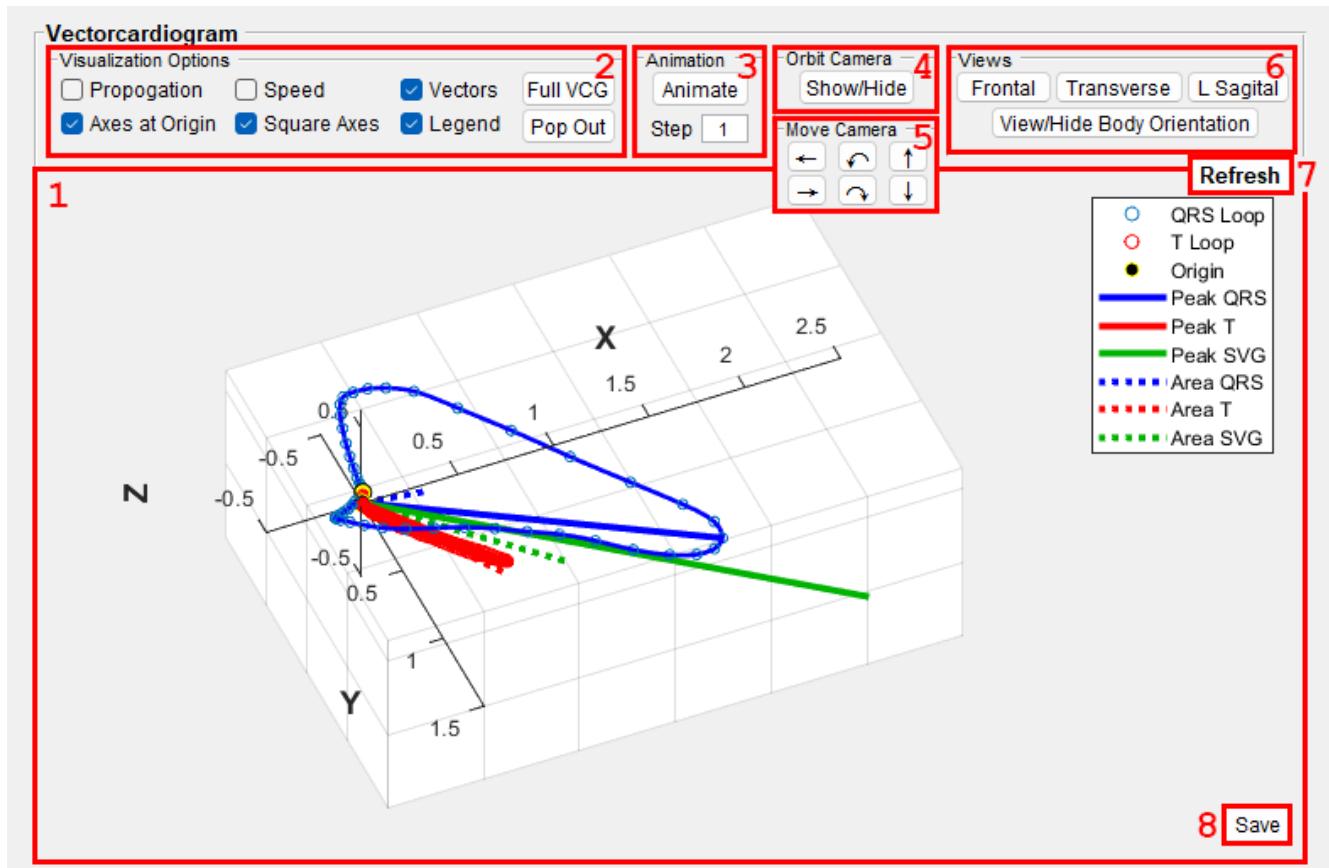


Figure 10: GUI Section 6.1

1. The median beat VCG is shown in the ‘**Vectorcardiogram**’ section of the GUI. The QRS loop is shown in blue and the T wave loop is shown in red. ‘**Visualization Options**’ (GUI item **6.1.2**) contains options for visualizing the VCG. When new options are checked/unchecked, clicking **Refresh** (GUI item **6.1.7**) will update the VCG graph without recalculating values. The VCG can be rotated with the mouse by using the rotation tool (GUI item **10.2**) or the ‘**Orbit Camera**’ in GUI item **6.1.4**.

2. VCG Visualization Options:

- **Propogation** : When checked this option shows a set of green circles at the start of the QRS loop and a set of yellow circles at the start of the T wave loop. This can be useful to visually determine the direction of rotation around each VCG loop.
 - **Speed** : When checked, this option shows the instantaneous speed (mV/ms) of the VCG loop. The loop coloring changes to reflect the relative speed according to the color key that is displayed. Faster sections of the loops are shown in red, and slower sections of the loops are shown in blue (see GUI section 6.5 in **Chapter 10.7**).
 - **Vectors** : When checked, this option shows the peak and area **QRS (blue)**, **T wave (red)**, and **QRST/SVG (green)** vectors. Peak vectors are shown as solid lines, while area vectors are shown as dashed lines.
 - **Axes at Origin** : When checked, this option moves axes labeling inside the 3D figure as opposed to being on the outside of the figure.
 - **Square Axes** : When checked, this option makes the X, Y, and Z axes all have the same scaling. If this is not checked the loop morphology may be distorted, but it may be easier to visualize some parts of the VCG loops.
 - **Legend** : Turns on or off the figure legend on the right hand side of the figure.
 - **Full VCG** : Clicking this button shows the plot of the full VCG throughout the entire VCG tracing, not just the median beat (see **Figure 45**).
 - **Pop Out** : Clicking this button allows visualization/manipulation of the VCG in a new, larger window.
-

3. The **Animate** button opens an animated figure of the VCG loop. The animation steps are in samples set by the ‘Step’ textbox.

4. The **Orbit Camera** opens a second toolbar that can be used to manipulate the camera for the 3D VCG. See https://www.mathworks.com/help/matlab/creating_plots/view-control-with-the-camera-toolbar.html for additional details.

5. This section is used to rotate the 3D VCG without using the rotation tool (GUI item **10.2**). All movements are relative to the user.

- Rotates the VCG towards the **left** of the user.
- Rotates the VCG towards the **right** of the user.
- Rotates the VCG **counter-clockwise** relative to the user.
- Rotates the VCG **clockwise** relative to the user.
- Rotates the VCG **cranial** relative to the user.
- Rotates the VCG **caudal** relative to the user.

6. This section is used to rotate the 3D VCG to common viewing angles.
- Frontal Displays the VCG in the XY plane.
 - Transverse Displays the VCG in the XZ plane.
 - L Sagital Displays the VCG in the YZ plane.
 - View/Hide Body Orientation Shows a head/face to orient the VCG loops in 3D space. The rotation of the VCG and this face are linked, so rotating one will also rotate the other by the same amount and to the same viewing angle.
-
7. The Refresh button reloads the VCG with the active VCG visualization options set in GUI item 6.1.1 above.
-
8. The Save button saves the current VCG as a .png image.
-

Section 6.2:

The VCG Calculations button displays results from the VCG_Calc results class and sets options for data export.

Calculations

Basic Parameters (ms)		QRST Angle (°)	
HR (bpm): 48	QT (ms): 446	Peak 3D QRST Ang: 19.97	Peak Front QRST Ang: 3.66
QRS (ms): 94	QTc (Baz): 400	Area 3D QRST Ang: 40.85	Area Front QRST Ang: 12.33
JT (ms): 352	QTc (Fr): 415		
Tpeak: 344	Tpeak/QT: 0.771		
QRS Vector (mV·ms) & (°)		SVG Angles (°)	
Peak QRS Mag: 1.76	Area QRS Mag: 37.79	Peak SVG-Peak QRS Ang: 5.98	
Peak QRS Az: 2.69	Area QRS Az: 18.25	Peak SVG-Peak T Ang: 13.99	
Peak QRS El: 56.94	Area QRS El: 65.57	Area SVG-Area QRS Ang: 29.31	
T Vector (mV·ms) & (°)		Area SVG-Area T Ang: 11.54	
Peak T Mag: 0.76	Area T Mag: 92.51	Area SVG-Area SVG Ang: 7.83	
Peak T Az: -21.35	Area T Az: -27.65	Area SVG-Area QRS Ang: 13.77	
Peak T El: 55.18	Area T El: 55.42	Vector Ratios	
SVG Vector (mV·ms) & (°)		Peak QRST Ratio: 2.32	Area QRS & T: 68.54
Peak SVG Mag: 2.49	Area SVG Mag: 123.6↑	Area QRST Ratio: 0.41	Peak QRS & T: 1.08
Peak SVG Az: -4.39	Area SVG Az: -13.78	Vector Distances (mV)	
Peak SVG El: 55.92	Area SVG El: 56.55	QRST Path Length: 6.33	T Path Length: 1.59
SVG Components (mV·ms)		QRS Path Length: 4.73	
SVG x: 100.15↑	SVG y: 68.14↑	Data Export	
SAI QRST (mV·ms)	SAI vm: 148.49↑	Dir.: C:\BRAVEHEART	Select 2
SAI x: 103.86	SAI QRST: 236.51↑	File: braveheart_output	.csv 3
SAI y: 76.75	SAI vm: 148.49↑	Note: 4	
SAI z: 55.89		Export Data (.csv) 5	Export Signals (.mat) 6

Figure 11: GUI Section 6.2

1. Displays values of various ECG/VCG calculations from the `VCG_Calc.m` results class based on the median beat. If **Show Normal Ranges** is checked in the **Utilities** section (GUI item **6.6.6**) then for select values, if they are out of range, to the right of the value there will be an arrow reflecting if the value is above (\uparrow) or below (\downarrow) the normal range (see **Figure 40** and **Chapter 20**). Definitions for azimuth and elevation can be found in **Figure 50**.

2. Textbox that shows the working directory for saving files. All saved files are stored in the directory displayed here. When an ECG is loaded, the working directory for saving data is set to the directory which contains the ECG file that was loaded. To change the working directory, click on the **Select** button and choose a new directory.

3. Textbox that specifies the name of the file used to export calculations/data from the current ECG/VCG. The dropdown allows the user to choose **.csv** or **.xlsx** format.

4. The **Export Data** button exports all of the current data from the active ECG/VCG (including all calculations from all 3 results classes, Annoparameters, and beat annotations), to a text file with the file name and extension as specified in GUI item **6.2.3**. The button text changes to reflect the value in the file extension dropdown box (**.csv** or **.xlsx**).

If a file with the same name/location as specified in the saving directory (GUI item **6.2.2**) and filename (GUI item **6.2.3**) does not exist, a new file is created. If a file with the same name/location as specified already exists, the current data is appended to the next empty row in the existing file. In this way the user can create a singular file with the results from multiple ECGs, or results from the same ECG with different processing parameters/included beats.

When the export is successful, **Success!** appears to the right of the buttons.

5. The **Export Signals (.mat)** button exports the signal data (ECG/VCG signals, median beat signals, individual beats, and results) in a **.mat** format file which contains a data structure with all of the exported data that can be analyzed outside of BRAVEHEART.

Section 6.3:

The **Lead Morphology** button opens a figure which contains the median beat R, S, and T wave measurements (all units in mV) for all 16 leads. The information displayed here is from the `Lead_Morphology.m` results class.

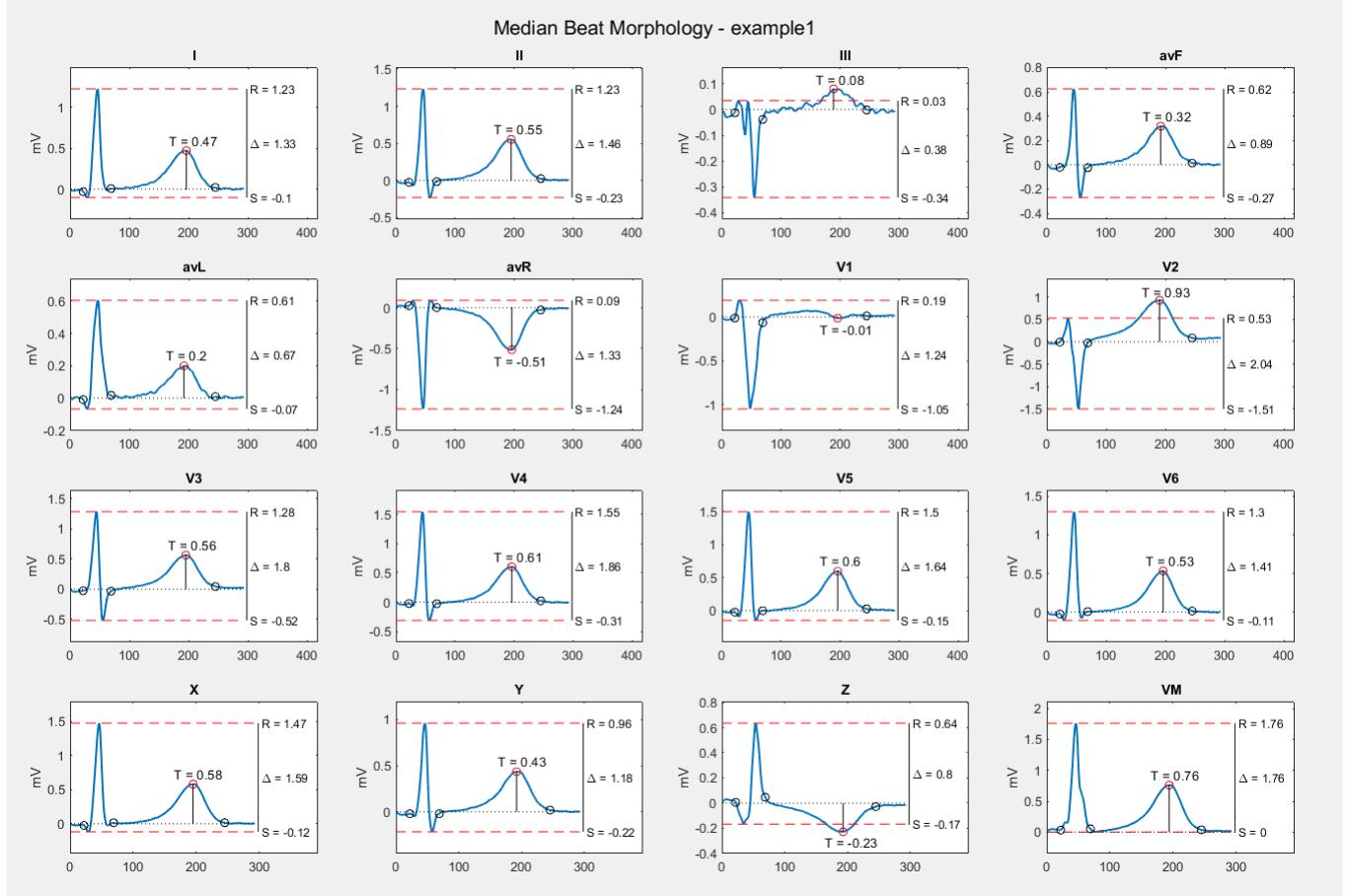


Figure 12: Figure displayed when the **Lead Morphology** button is pressed. The figure displays the R, S, and T wave measurements for all 16 leads. All values are in units of mV.

Section 6.4:

The **VCG Morphology** button displays information on VCG loop morphology and associated parameters. The information displayed here is contained in the **VCG_Morphology.m** results class.

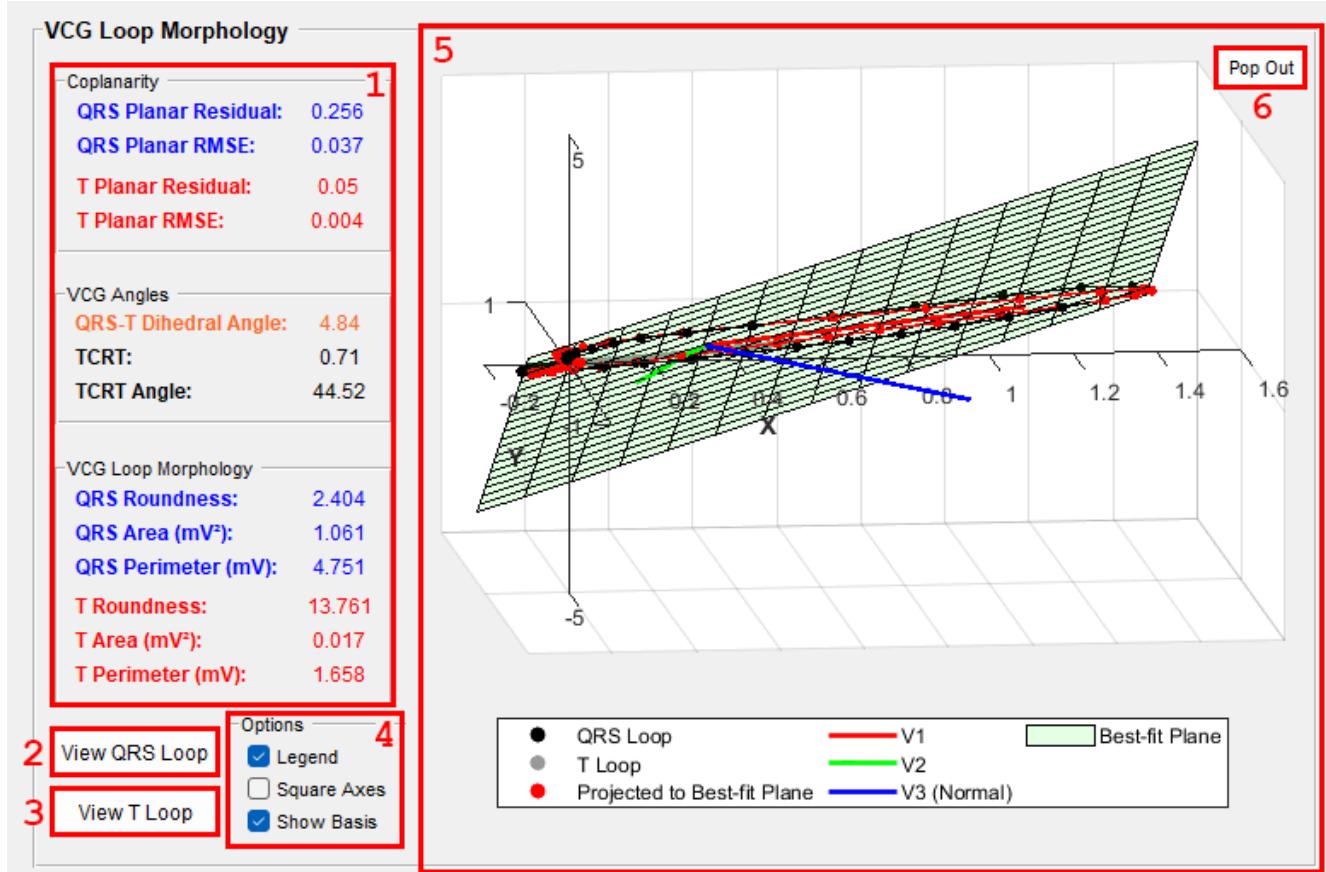


Figure 13: GUI Section 6.4

1. Displays values of various VCG morphology calculations such as coplanarity (how planar the QRS and T loops are), Total Cosine R-T, and QRS and T wave loop roundness and area which are part of the **VCG_Morphology** results class. All variables calculated in the **VCG_Morphology** results class are not displayed here. Further details can be found in the methods manuscript [1] and in **Chapter 22**.

2. The **View QRS Loop** button shows the best fit plane for the QRS loop and projections of the loop into the best fit plane. Vectors that span the best fit plane can be displayed as noted in GUI item **6.4.4**. The figure can be rotated.

3. The **View T Loop** button shows the best fit plane for the T loop and projections of the loop into the best fit plane. Vectors that span the best fit plane can be displayed as noted in GUI item **6.4.4**. The figure can be rotated.

4. These checkboxes control the appearance of the displayed QRS or T loop figure:

- Legend : shows the figure legend
- Square Axes : makes the X, Y, and Z axes have equal spacing.
- Show Basis : shows the orthogonal basis vectors for the best fit plane

Section 6.5:

The **VCG Speed** button displays information on VCG loop speed.

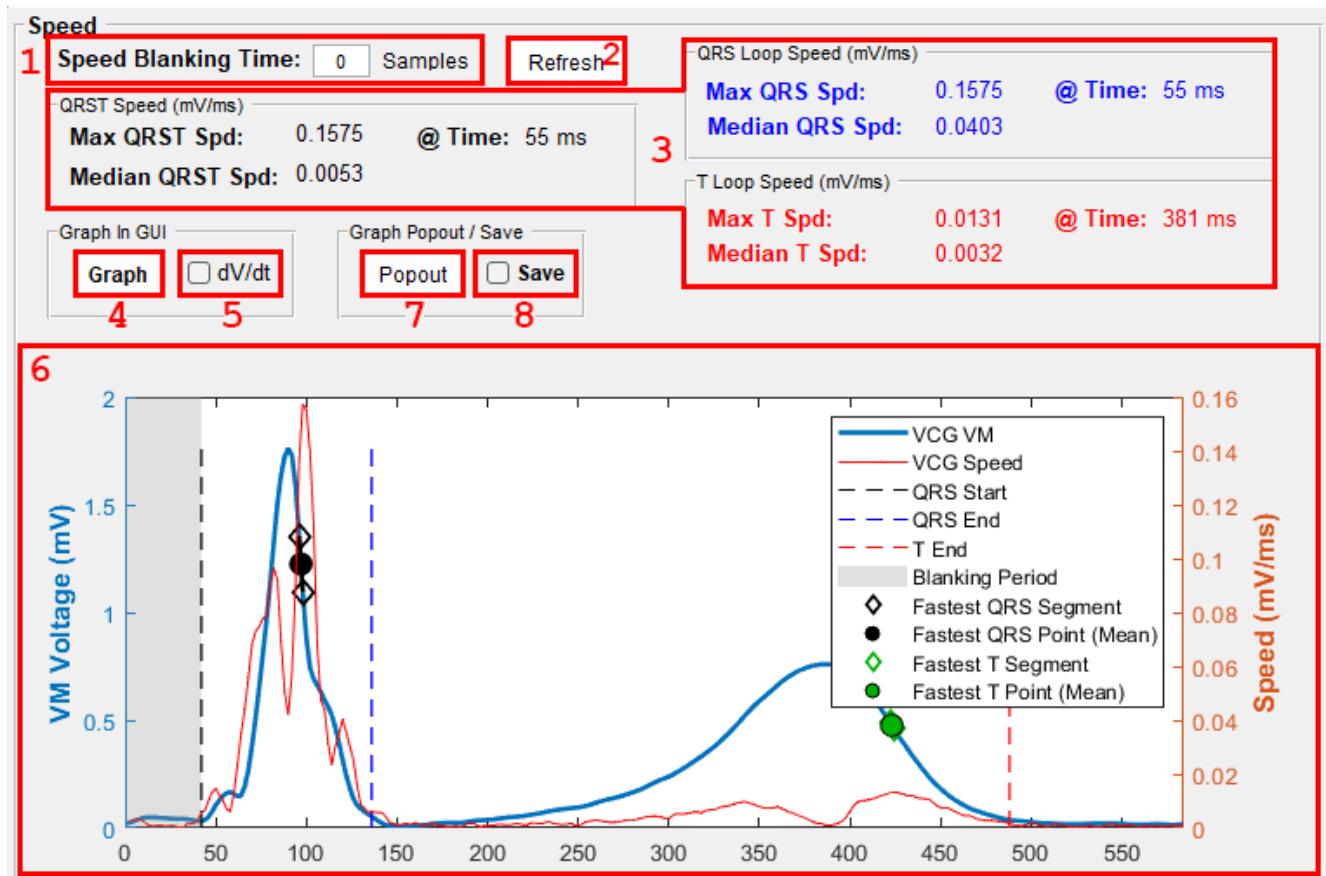


Figure 14: GUI Section 6.5

1. Textbox to set the value of `blanking_samples` in `Annoparams.m`. This corresponds to the length of the gray shading after QRS start (black vertical dashed line) in the figure above (GUI item 6.5.6). Any part of the QRST signal within the gray shading is ignored when calculating maximum speed. This can be useful to isolate specific parts of the QRST complex, or to deal with large/wide pacing artifact that contaminates the QRS complex. See **Chapter 6.2** for additional details.

2. The **Refresh** button updates the speed values in GUI item 6.5.3 (see below) based on the value set in the 'Speed Blanking Time' textbox (GUI item 6.5.1 which sets the value of

`blanking_samples` in `Annoparams.m`). Use the `Refresh` button to recalculate values of speed using new values of `blanking_samples` without having to reprocess the entire ECG.

3. Values for speed calculations of the entire QRST complex, QRS complex alone, and T wave alone.
 4. The `Graph` button displays the figure in GUI item **6.5.6** based on the value of `blanking_samples` set in GUI item **6.5.1** and the value of the `dV/dt` checkbox set in GUI item **6.5.5**.
 5. The `dV/dt` checkbox sets if acceleration is also shown in the speed figure (GUI item **6.5.6**).
 6. Figure showing speed (and acceleration if `dV/dt` is checked). The blanking period, which is assigned by GUI item **6.1.1** above is shown as gray shading after QRS onset (dashed vertical black line). The fiducial points for Q_{on} , Q_{off} , and T_{off} are shown with colored, dashed lines. The locations of the fastest segment of the QRS complex and T wave are noted with shaded circles as shown in the legend.
 7. The `Popout` button opens the speed figure displayed in GUI item **6.5.6** in a new window.
 8. The `Save` checkbox saves the speed figure shown in GUI item **6.5.6** as a `.png` file named `<filename>_speed.png` when the `Graph` button (GUI item **6.5.4**) is clicked.
-

Section 6.6:

The **Utilities** button brings up BRAVEHEART utilities and options which can be used to control ECG processing and utilize other useful functions and links.

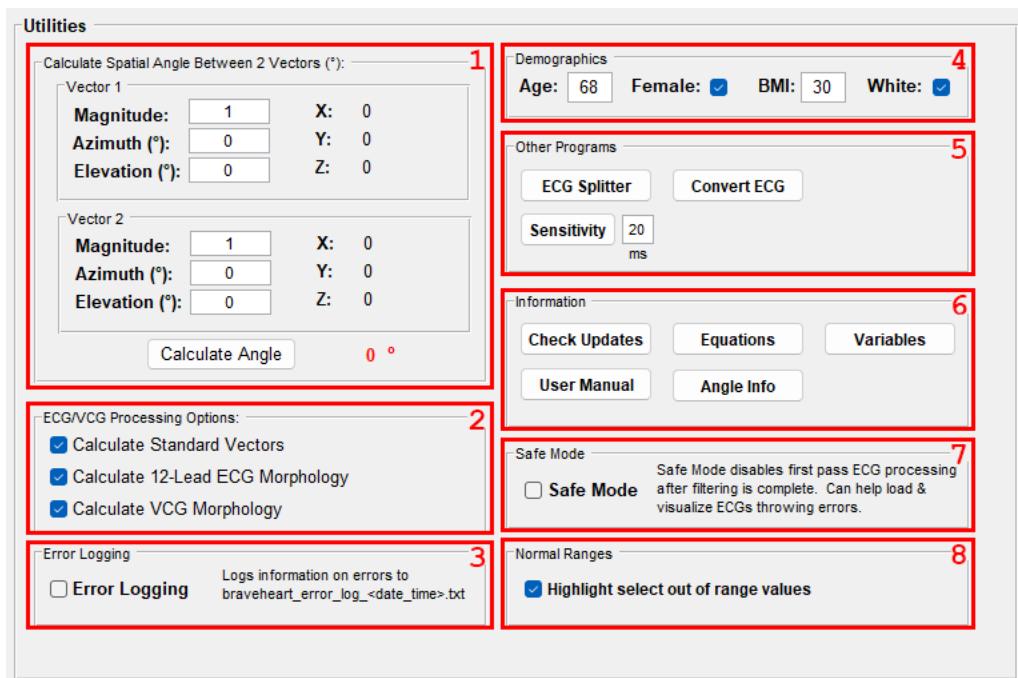


Figure 15: GUI Section 6.6

1. If needed, BRAVEHEART can convert vectors defined by magnitude, azimuth, and elevation (see **Figure 50**) into Cartesian coordinates. If 2 vectors are entered, the 3D angle between them can also be calculated by clicking the **Calculate Angle** button.
2. By default, BRAVEHEART calculates parameters in all 3 result classes (see **Chapter 22**). In certain cases the user may only care about some of the results classes. The 3 checkboxes here allow the user to enable/disable processing of specific results classes to speed up batch processing of large volumes of ECGs if the data contained in one or more specific results classes is not needed:
 - **✓ Calculate Standard Vectors** enables/disables the `VCG_Calc` results.
 - **✓ Calculate 12-Lead ECG Morphology** enables/disables the `Lead_Morphology` results.
 - **✓ Calculate VCG Morphology** enables/disables the `VCG_Morphology` results.These checkboxes set the values of `vcg_calc_flag`, `lead_morph_flag`, and `vcg_morph_flag` (see **Chapter 11**).
3. The **□ Error Logging** checkbox enables error logging to assist with troubleshooting ECGs that will not process correctly. Further details can be found in **Chapter 25**.

4. BRAVEHEART includes data on estimated normal limits for a selection of VCG parameters based on age, gender, body mass index (BMI), and race (see **Chapter 20**). This section of textboxes and checkboxes allows the user to specify the age, gender, BMI, and race (white or not white) to generate expected normal limits for these select parameters.

ECG files (usually `.xml`) that contain information on patient age and gender can have this information automatically pulled from the ECG file and extracted to this location of the GUI. If information on age and gender are not available, the default is to use a 50 year old man. To obtain the most accurate normal ranges for the ECG being processed, the BMI and race (white or not white) can be entered here as well. The software defaults to white race with $BMI = 30 \text{ m/kg}^2$ if values are not specified by the user. BRAVEHEART is currently able to extract age and gender from GE MUSE `.xml` and Philips `.xml` files (see **Chapter 21**).

If the **Highlight select of of range values** (GUI item **6.6.8** below) is checked, values outside of the normal ranges determined by the demographics entered in this section are noted on the GUI results displayed in the ‘**VCG Calculations**’ section of the GUI (GUI item **6.2.1**) with \uparrow or \downarrow reflecting if the value is above or below the normal range, respectively. Further details of displaying values outside of the normal range can be found in the documentation for GUI item **6.6.8** and **Chapter 20**.

-
5. This section is used to open various utility programs that may be useful to the user:

In certain situations the user may want to split an ECG file into 2 separate files to remove an area of significant noise/artifact, or to isolate a specific finding. Clicking on

ECG Splitter allows the user to split the current file into 2 separate files by specifying a sample at which to split the ECG. In a future release we plan to allow the user to maintain the current file format when splitting ECGs, but in the current version of BRAVEHEART all split ECGs are in the '**unformatted**' format which encodes the 12 leads as 12 columns in units of mV (see **Chapter 21**).

The current ECG can be converted into a different format using the **Convert ECG** button. This function is currently only able to convert into '**unformatted**' ECGs, although additional formats will be added in the future.

The **Sensitivity** button performs sensitivity analysis on the current ECG to determine how much changes in fiducial point annotations affect the reported measurements. The textbox next to the **Sensitivity** button is used to specify an interval in ms by which the Q_{on} , Q_{off} ,

and T_{off} fiducial points are adjusted, and all results recalculated. For example, if the textbox is set to the nominal value of ‘20’ ms, clicking the **Sensitivity** button will calculate results with all ranges of Q_{on} from $Q_{on} - 20$ ms to $Q_{on} + 20$ ms, and similarly for $Q_{off} \pm 20$ ms and $T_{off} \pm 20$ ms. Results are saved to the working directory with the filename `<filename>_sensitivity_analysis.csv`.

6. This section can be used to display and obtain various useful information:

- The **Check Updates** button opens the BRAVEHEART GitHub website, <http://www.github.com/BRAVEHEART>, so the user can check for any software updates.
 - The **Equations** button displays various equations used for calculations.
 - The **User Manual** button displays this document.
 - The **Angle Info** button displays a figure explaining the conventions used for angles in BRAVEHEART calculations (see **Figure 50**).
 - The **Variables** button displays the variable names and descriptions for output files.
-

7. Occasionally ECGs will throw errors when they are being loaded into BRAVEHEART.

When checked, the **Safe Mode** checkbox disables first pass ECG processing and annotation after initial filtering is complete. This can help trouble shoot ECGs that throw errors. The ECGs can be viewed by clicking on the **12L ECG** and other buttons in the ‘View/Save ECG’ section (GUI section 7). Further details of Safe Mode can be found in **Chapter 25**.

8. The **Highlight select out of range values** checkbox displays marks next to select measurements that are out of range in the ‘VCG Calculations’ section (GUI item **6.2.1**). Values that are above the normal range are displayed with an ↑, and values that are below the normal range and displayed with a ↓. If **Highlight select out of range values** is not checked, the arrows to visualize out of range values are not displayed. Further details of which parameters have normal ranges calculated are available in **Chapter 20**.

10.8 GUI Section 7 – Display Various Figures

Section 7:

View/Save ECGs, VCGs, and other figures.



Figure 16: GUI Section 7

This section of the GUI is used to display and save various ECG/VCG figures and visualizations.

1. Generate various figures of ECGs, VCGs, and other visualizations:

- The **12L ECG** button displays the 12-lead ECG as 12 continuous rhythm strips. The 12-lead ECG can be displayed after the ECG is loaded and before the **Calculate** button has been pressed. An example 12-lead ECG figure is shown in **Figure 37**.
- The **X, Y, Z VCG** button displays continuous rhythm strips of the X, Y, Z, and VM leads. The VCG ECG can be displayed after the ECG is loaded and before the **Calculate** button has been pressed. An example VCG figure is shown in **Figure 38**.
- The **Med. Beats** button displays all 16 median beats. This only works if the **Calculate** button has been pressed and the median ECG has been processed. An example median beats figure is shown in **Figure 39**.
- The **Summary** button displays measurements of the summary figure (See **Figure 35** and **Figure 36**). This only works if the **Calculate** button has been pressed and the median ECG has been processed.
- The **Polar SVG** button brings up a plot that shows orientation of the spatial ventricular gradient (SVG) and QRST angles. This only works if the **Calculate** button has been pressed and the median ECG has been processed.
- The **Normal Vals.** button brings up a figure that shows age, gender, race, and body mass index specific values for various VCG parameters. An example figure is shown in **Figure 40**. See **Chapter 20** for further details.
- The **VCG Loops** button brings up a figure that shows the median X, Y, and Z beats and the corresponding VCG loops. This only works if the **Calculate** button has been pressed/median ECG has been processed. An example figure is shown in **Figure 41**.

2. Dropdown to choose what gridlines are displayed when using **12L ECG**, **X, Y, Z VCG**, or **Med. Beats**. ‘All Grid’ enables major and minor grids (large and small boxes), ‘Maj Grid’ enables only the major grid (large boxes), ‘Min Grid’ enables only the minor grid lines (small boxes), and ‘No Grid’ disables the grid completely.

3. When checked, the **Save** checkbox saves the figures generated by any of the buttons in this section. Files are saved to the same directory that the ECG file is in and are saved in **.png** format.

10.9 GUI Section 8 – Beat Editing, Addition, and Removal

Section 8:

Edit the fiducial point annotations of individual beats, remove unwanted beats, or manually add new beats. After editing, adding, removing beats, a new median beat is created and calculations are performed on the new median beat.

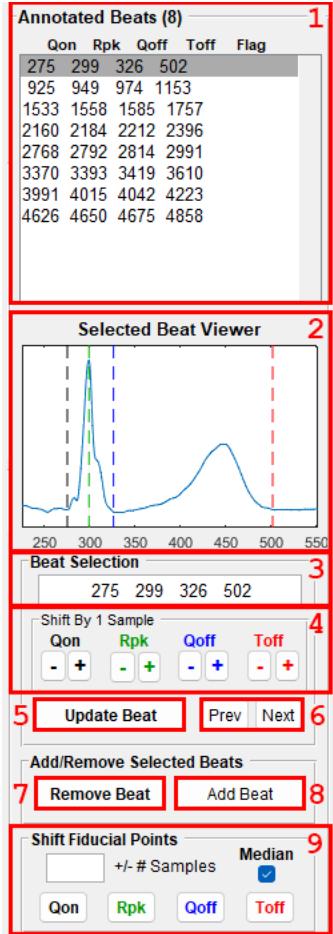


Figure 17: GUI Section 8.

1. The ‘Annotated Beats’ window lists the annotations for all individual beats that are included in the median beat. The order of annotations is shown at the top of the box as Q_{on}, R peak, Q_{off}, and T_{off} (in samples). Beats that are detected as PVCs/non-dominant beats will have a ‘#’ next to their annotations. Beats that are detected as outliers will have a ‘**’ next to their annotations. Some beats may be detected as both a PVC and an outlier, and will have both symbols. Clicking on a beat in the ‘Annotated Beats’ window displays the beat and fiducial points in the ‘Selected Beat Viewer’ (GUI item 7.2 below), highlights it in green in the Median Beat Viewer (GUI item 4.1) and

highlights the individual beat with a green * in the ‘X-, Y-, Z-, Vector Magnitude Leads’ section (GUI item 2.1).

2. The ‘Selected Beat Viewer’ shows a zoomed in view of the beat that is selected in the ‘Annotated Beats’ window along with its annotations visualized as a black dashed line (Q_{on}), green dashed line (R peak), blue dashed line (Q_{off}), and red dashed line (T_{off}). These lines can be dragged to adjust the respective fiducial point locations. The sample values that correspond to the location of the 4 colored dashed lines are reflected in the ‘Beat Selection’ textbox below the ‘Selected Beat Viewer’ (GUI item 7.3). As the lines are moved, the values in the ‘Beat Selection’ textbox will reflect the new location of the fiducial points (see Chapter 5.6).
-

3. The ‘Beat Selection’ textbox updates with the selected beat’s fiducial points in the order of Q_{on} , R Peak, Q_{off} , and T_{off} as they are adjusted. The fiducial points can be edited by dragging the colored dashed lines that correspond with Q_{on} , R peak, Q_{off} , and T_{off} as noted above, manually by updating their values in the textbox, or by shifting values by ± 1 sample using the $[+]$ and $[-]$ buttons corresponding to Q_{on} , Rpeak, Q_{off} , or T_{off} in GUI section 7.4. See Chapter 5.6 for additional information.

Once the adjusted fiducial points are in the ‘Beat Selection’ textbox, clicking the **Update Beat** button (GUI item 7.5) or **Remove Beat** button (GUI item 7.8) will update the fiducial points or remove the beat entirely, respectively.

4. The ‘Shift by 1 Sample’ section shifts one of the 4 fiducial points by ± 1 sample. For example, to shift Q_{on} by +1 sample, click on the $[+]$ button below **Qon**, and to shift T_{off} by -1 sample, click on the $[-]$ button below **Toff**.
5. The **Update Beat** button takes the 4 values in the ‘Beat Selection’ textbox corresponding to Q_{on} , R peak, Q_{off} , and T_{off} (in that order), saves these new values for the selected beat, and then recalculates the median beat and associated measurements using the updated beat fiducial points.
6. The **Prev** and **Next** buttons can be used to cycle through beats in the ‘Annotated Beats’ listbox without clicking on them.
7. The **Remove Beat** button removes the selected beat from the analysis and then recalculates the median beat and associated measurements. See the quick start guide (Chapter 5.7) for an example.

8. The **Add Beat** button takes the values in the ‘**Beat Selection**’ textbox, creates a new beat using these fiducial points, and then recalculates the median beat and associated measurements. In general, there are few uses for this function, as beats should be automatically detected, but in rare cases where a beat needs to be added manually, it can be done this way.

9. The ‘**Shift Fiducial Points**’ textbox allows manual shifting of a fiducial point for all individual beats simultaneously, or manual shifting of the median beat fiducial points. This section can be used for manual adjustment of median beat annotations when necessary:

If **Median** is checked, placing an integer n in the textbox and clicking on one of the buttons below (**Qon**, **Rpk**, **Qoff**, or **Toff**), will shift the relevant median beat fiducial point by n samples. This is useful if manual adjustments on median beat annotations are needed. After annotation adjustment calculations are updated using the new median beat fiducial points. See **Chapter 5.11** for an example of median beat annotation adjustment.

If **Median** is unchecked, placing an integer n in the textbox and clicking on one of the buttons below (**Qon**, **Rpk**, **Qoff**, or **Toff**), will shift the relevant fiducial point of ALL individual beats by n samples. In practice, this is useful if the median beat is being truncated before the end of the T wave which is preventing annotation of the median beat T_{off} ; shifting T_{off} (click **Toff**) by n samples in all individual beats has the effect of extending the window for median beat creation by n samples. The window before Q_{on} can be similarly extended by using a negative value and clicking **Qon**.

10.10 GUI Section 9 – PVC/Non-Dominant and Outlier Beat Removal

Section 9:

Analyze and remove PVCs/non-dominant beats and outlier beats. Detailed descriptions of PVC and outer identification/removal can be found in **Chapter 13.3** and **Chapter 13.4**.

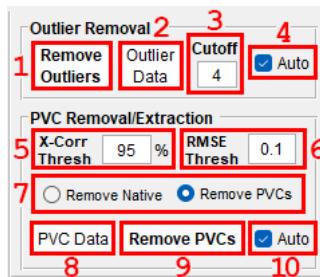


Figure 18: GUI Section 9

1. The **Remove Outliers** button removes all beats that have been flagged as outliers and then recalculates the median beat and associated measurements. Further details can be see in quick start Example 3 (**Chapter 5.3**), **Chapter 5.10**, and **Chapter 13.4**.

2. The **Outlier Data** button displays information on each beat and the values that are used for outlier determination. Further details can be found in **Chapter 13.4** and **Figure 27**.

3. The ‘Cutoff’ textbox sets the value of `modz_cutoff` in `Annoparams.m` which determines the modified Z-score cutoff that is used to determine if a beat is an outlier. See **Chapter 13.4** for further details.

4. **Auto** sets if outliers are automatically removed when **Calculate** has been pressed. If **Auto** is unchecked, outliers are marked but not removed.

5. The ‘X-Corr Thresh’ textbox sets the value of `pvcthresh` in `Annoparams.m`. See **Chapter 13.3** for further details.

6. The ‘RMSE Thresh’ textbox sets the value of `rmse_pvcthresh` in `Annoparams.m`. See **Chapter 13.3** for further details.

7. Radio buttons that sets the value of `keep_pvc` in `Annoparams.m`. If ‘Remove Native’ is checked `keep_pvc = 1`, and if ‘Remove PVCs’ is checked `keep_pvc = 0`. See **Chapter 13.3** for further details.

8. The **PVC Data** button displays a figure that summarizes the data that is used for PVC detection. Further details can be found in **Chapter 13.3** and **Figure 26**.
-

9. the **Remove PVCs** button removes all beats that have been flagged as PVCs and then recalculates the median beat and associated measurements. Further details can be see in quick start Example 2 (**Chapter 5.2**), **Chapter 5.9**, and **Chapter 13.3**.
-

10. **Auto** sets if PVCs are automatically removed when **Calculate** has been pressed. If **Auto** is unchecked, PVCs are marked but not removed.
-

10.11 GUI Section 10 – GUI Toolbar for Interacting with Figures

Section 10:

GUI Toolbar for interacting with figures. The GUI toolbar can be used to navigate within various figures that are displayed in the GUI. Click on an icon in the toolbar and then use in the selected GUI figure.

-  : Pan figure
-  : Rotate figure
-  : Select point in figure
-  : Zoom in on figure
-  : Zoom out of figure
-  : Print figure

11 Batch Processing ECGs with `braveheart_batch.m`

BRAVEHEART allows rapid batch processing of a directory of ECGs via `braveheart_batch.m`. This can be called directly without using the GUI. In batch processing mode there is less graphical output compared to the BRAVEHEART GUI, but when batch processing a large number of ECGs, the batch processing mode of BRAVEHEART is more efficient than manually processing multiple ECGs sequentially in the GUI.

Batch processing of ECGs can be launched from within the GUI (see [Chapter 12](#)) or via the `braveheart_batch()` function directly from the MATLAB command line. The command line mode is useful for large and complex datasets that may require running multiple batches with different parameters. `braveheart_batch.m` output includes a single `.csv` or `.xlsx` file with ECG/VCG measurements for all batched ECGs, and optional summary figures (See [Figure 35](#) and [Figure 36](#)), `.anno` annotation files (see [Chapter 15](#)), and/or ECG/VCG signals and data in MATLAB `.mat` format (See [Chapter 11.4](#)).

11.1 Batch Processing Parameters

The parameters that govern how `BRAVEHEART_batch.m` functions can be adjusted at the beginning of the file:

```
% Parameters controlling batch behavior -> Edit as needed

folder = ''; % ECG Folder; set as '' to use system dialog box
format = 'muse_xml'; % ECG format string
output_ext = '.csv'; % Output file extension; '.csv' or '.xlsx'
output_note = 'batch'; % Note added to output

parallel_proc = 0; % Use parallel processing; 1 = yes, 0 = no
progressbar = 1; % Display progress bar; 1 = yes, 0 = no

save_figures = 0; % Save figure of processing/annotation; 1 = yes, 0 = no
save_data = 0; % Save .mat file of signals/annotations; 1 = yes, 0 = no
save_annotations = 0; % Save beat annotation file (.anno); 1 = yes, 0 = no

vcg_calc_flag = 1; % Process VCG_Calc module; 1 = yes, 0 = no
lead_morph_flag = 1; % Process Lead_Morphology module; 1 = yes, 0 = no
vcg_morph_flag = 1; % Process VCG_Morphology module; 1 = yes, 0 = no
```

The parameters that can be set to control batch ECG processing include:

parameter | *possible values*

parameter description

folder | **string**

Sets the path of the folder of ECGs to batch process. If this value is set empty as `' '`, the program will bring up a dialog box to allow the user to choose the folder. This parameter is only used when running the command line version of BRAVEHEART from the source code, and is primarily designed for cases when passing in these parameters into the function as shown in **Chapter 11.2**. All other ways of running batch processing (via compiled command line version or via GUI) require the folder input to be via dialog box.

format | **string**

String which describes the ECG format to be used. See **Chapter 21** for details of included formats. Formats that are included by default include:

- `'muse_xml'` - GE MUSE .xml
 - `'bidmc_format'` - Space delimited ASCII .txt (legacy BIDMC format)
 - `'prucka_format'` - GE Prucka recording system ASCII .txt
 - `'ISHNE'` - International Society for Holter & Noninvasive Electrocardiology .ecg
 - `'DICOM'` - DICOM .dcm
 - `'hl7_xml'` - HL7 .xml
 - `'philips_xml'` - Philips .xml
 - `'mrq_ascii'` - GE Marquee ASCII .mrq
 - `'unformatted'` - Unformatted column data in units of mV .txt
-

output_ext | `'.csv'` or `'.xlsx'`

Sets the format of the output file that contains all measurements after batch processing is complete. If set to `'.csv'` the program will generate a comma separated values file, and if set to `'.xlsx'` it will generate a Microsoft Excel spreadsheet file. The information contained in the output file is the same with either output format.

output_note | **string**

Sets a string that is included in the measurement output file. This can be used to indicate something about the dataset that is being processed.

`parallel_proc` | 0 or 1

Sets if MATLAB's parallel computing toolbox is used to process ECGs in parallel. If `parallel_proc = 1` and the user does not have MATLAB's parallel computing toolbox installed, the ECGs will process sequentially without throwing an error. When parallel computing is used, the program uses the maximum number of workers that are available.

`progressbar` | 0 or 1

Sets if a progress bar pop-up is generated to show the progress of ECG processing.

`save_figures` | 0 or 1

Sets if output includes a summary figure for each processed ECG. If the number of ECGs to process is large and if figures are not needed, setting `save_figures = 0` can significantly reduce the time required for ECG processing. Examples of summary figures can be seen in **Figure 35** and **Figure 36**.

`save_data` | 0 or 1

Sets if output includes the raw and filtered signals (individual beats and median beats), annotations, and calculated parameters saved as a `.mat` file. If this data is not needed, setting `save_data = 0` can speed up ECG processing.

`save_annotations` | 0 or 1

Sets if output includes annotation files for each processed ECG. Annotation files (extension `.anno`) contain the annotation parameters used to process the ECG (from `Annoparams.m` - see **Chapter 6**) and individual beat fiducial point annotations for each ECG. If an `.anno` file is placed in the same directory as an ECG with the same name (eg `ecg_name.xml` and `ecg_name.anno`), the BRAVEHEART command line program overrides the nominal annotation parameters and beat annotations, loading these from the `.anno` file instead. `.anno` files therefore allow fine control over individual ECG processing via `braveheart_batch.m` without needing to use the GUI. For further details on `.anno` files see **Chapter 15**. `.anno` files behave slightly differently when used with the GUI and more information on use of `.anno` files and the GUI can be found in **Chapter 15**.

`vcg_calc_flag` | 0 or 1

Sets if data from the VCG Calculation results class `VCG_Calc.m`, which primarily includes vectorcardiographic measurements, is included in the measurement output file. Further details of the data included in the VCG Calculation results class can be found in **Chapter 22**.

```
lead_morph_flag | 0 or 1
```

Sets if data from the Lead Morphology results class `Lead_Morphology.m`, which primarily includes data on R, S, and T wave measurements, is included in the measurement output file. Further details of the data included in the Lead Morphology results class can be found in [Chapter 22](#).

```
vcg_morph_flag | 0 or 1
```

Sets if data from the VCG Morphology results class `VCG_Morphology.m`, which primarily includes vectorcardiographic morphology measurements, is included in the measurement output file. Further details of the data included in the VCG Morphology results class can be found in [Chapter 22](#).

11.2 Batch Processing via MATLAB Command Line

Once the parameters noted above in [Chapter 11.1](#) have been set at the beginning of `braveheart_batch.m`, the program is ready to run. In MATLAB, type `braveheart_batch()` in the MATLAB command window and press Enter. If `folder = []`, a dialog box will appear to choose the directory which contains the ECGs to be processed, otherwise the specified folder is used. The script will then loop through all of the ECGs with format `format` and the appropriate file extension in the specified directory until complete. Once processing is complete a message will display in the command window noting the number of ECGs processed and if there were any errors during ECG processing. The output will include the folders and files as noted in [Chapter 11.4](#).

Alternatively, the parameters can be passed directly into `BRAVEHEART_batch.m` as:

```
BRAVEHEART_batch(folder, source_str, output_ext, output_note, parallel_proc, ...
progressbar, save_figures, save_data, save_annotations, ...
vcg_calc_flag, lead_morph_flag, vcg_morph_flag, aps)
```

 where the first 12 inputs are as noted above, and `aps` passes in a set of annotation parameters. If `aps` is not passed in (only 12 inputs are specified), the program uses the default values contained within `Annoparams.m`. Passing in specific annotation parameters allows the user to run multiple batches with different annotation parameters without needing to manually reset each time.

To construct an `Annoparams` class simply call the `Annoparams` constructor without any inputs. Next, to change a specific annotation parameter, assign it a new value as follows:

```
aps1 = Annoparams();
aps1.lowpass = 0;
aps1.pkthresh = 90;
aps1.STend = 55;
...
```

11.3 Batch Processing Using the Command Line Stand-Alone Executable

The parameters that need to be set when running the executable version of `braveheart_batch.m` are the same as when running it via source code (see [Chapter 11.1](#) for detailed descriptions of the variables that must be set). The only difference is that because `braveheart_batch.m` is not directly editable when the program is run via executable, the parameters are edited in an external file, `batch_settings.csv`, where the first column is the parameter name, and the second column is the parameter value (with columns separated by commas).

Open `batch_settings.csv`:

format,	muse_xml
output_ext,	.csv
output_note,	batch
parallel_proc,	1
progressbar,	1
save_figures,	1
save_data,	1
save_annotations,	1
vcg_calc_flag,	1
lead_morph_flag,	1
vcg_morph_flag,	1

and simply edit the values in column 2 as noted in [Chapter 11.1](#). Unlike when setting string variables in MATLAB, the string values for `format`, `output_ext`, and `output_note` should **not** be enclosed in quotes. The exact order of variables in `batch_settings.csv` is not important, but all 11 variables must be included with appropriate values to avoid any errors. As noted in [Chapter 11.1](#), the parameter `folder` is only used when running BRAVEHEART via source code in MATLAB, and it is therefore not set in `batch_settings.csv`. When running the command line version of BRAVEHEART via executable, the ECG folder can only be chosen via dialogue box after starting the program, and the annotation parameters can only be set via editing `Annoparams.csv` or using the GUI.

Once the parameters noted above in **Chapter 11.1** have been set in `batch_settings.csv` and annotation parameters have been set in `Annoparams.csv` (see **Chapter 6**) make sure these files are saved. The program is now ready to run. Run the executable file. Choose the directory which contains the ECGs to be processed. The script will then loop through all of the ECGs with format `format` in the chosen directory until complete. Once processing is complete text will display how many ECGs were processed, the number of ECGs that were flagged for quality (see **Chapter 14**), and the number that caused errors. The output will include the folders and files as noted in **Chapter 11.4**.

11.4 `braveheart_batch.m` Output

Once batch processing is complete, the output will include:

`processed_ecgs_<timestamp>.csv` (or `.xlsx`)

Contains electrocardiographic/vectorcardiographic measurements for every ECG that was processed from the directory (1 row per ECG). If specific results classes are disabled (e.g. `vcg_calc_flag = 0`), those values are replaced with `NaN`.

Folder `figures_<timestamp>/`

Location where summary figures (see **Figure 35**) are saved if `save_figures = 1`.

 Summary figure files are named `<ecg_name>.png`.

Folder `data_<timestamp>/`

Location where signal and annotation data are stored if `save_data = 1`.

 Data files are named `<ecg_name>.mat`.

Folder `annotations_<timestamp>/`

Location where annotation files are stored if `save_annotations = 1`.

 Annotation files are named `<ecg_name>.anno`.

`check_ecg_list_<timestamp>.csv`

Lists ECGs that tripped the quality detector and the specific reason for being flagged (see **Chapter 14**).

Folder `figures_<timestamp>_check_ecg_list/`

Folder where summary figures are copied for ECGs whose annotations tripped the quality detector (see **Chapter 14**).

 **errors_<timestamp>.csv**

Lists ECGs that threw an exception during processing and information on the specific exception.

12 Batch Processing ECGs via GUI (`braveheart_gui.m`)

BRAVEHEART can process a batch of ECGs within the same directory from the command line or GUI versions of BRAVEHEART. For information on running BRAVEHEART on a batch of ECGs from the command line version of BRAVEHEART see [Chapter 11](#). The outputs and functions of batch processing are identical when batch processing ECGs from the command line or GUI; the GUI is just a wrapper for passing parameters into the command line batch processing program `braveheart_batch.m`.

When using the GUI for batch processing, the settings within the GUI (filtering, annotation parameters, etc.) are used as the annotation parameters (see [Chapter 10](#) and [Chapter 6.2](#)) instead of pulling data from `Annoparams.m` (or `Annoparams.csv` if running via executable).

When using the GUI, batch ECG processing can be controlled from GUI Sections 1, 6.2, and 6.6. Parameters in other sections are used to set annotation parameters as noted in prior sections, which is similar to setting values within `Annoparams.m` when using the command line version of BRAVEHEART for batch processing.

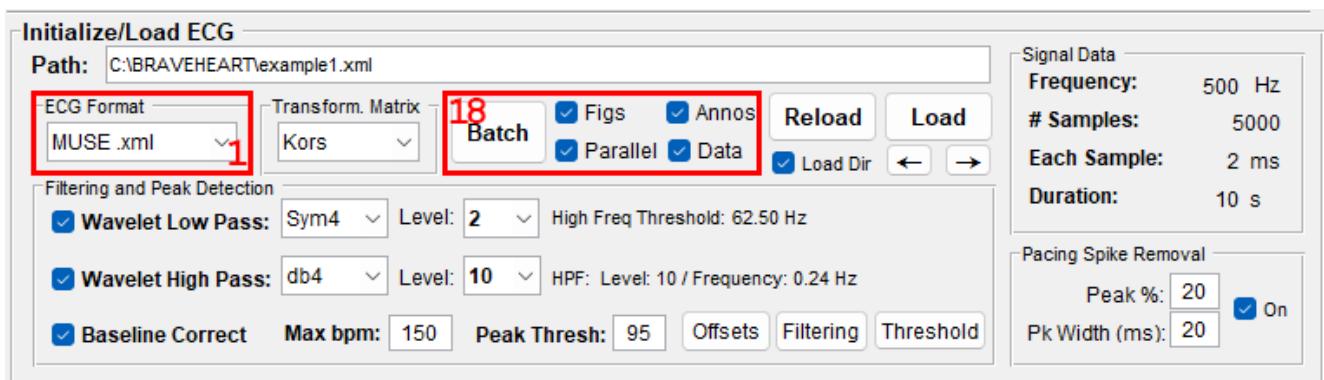


Figure 19: GUI items used to control batch processing in GUI section 1.

`format` is set using the ‘ECG Format’ dropdown box in GUI item [1.1](#).

Instead of setting parameters to control batch processing in `braveheart_batch.m`, in the GUI these are set using checkboxes in GUI item [1.18](#):

- `Figs` – sets value of `save_figures` as `1` (checked) or `0` (unchecked).
- `Parallel` – sets value of `parallel_proc` as `1` (checked) or `0` (unchecked).
- `Annos` – sets value of `save_annotations` as `1` (checked) or `0` (unchecked).
- `Data` – sets value of `save_data` as `1` (checked) or `0` (unchecked).

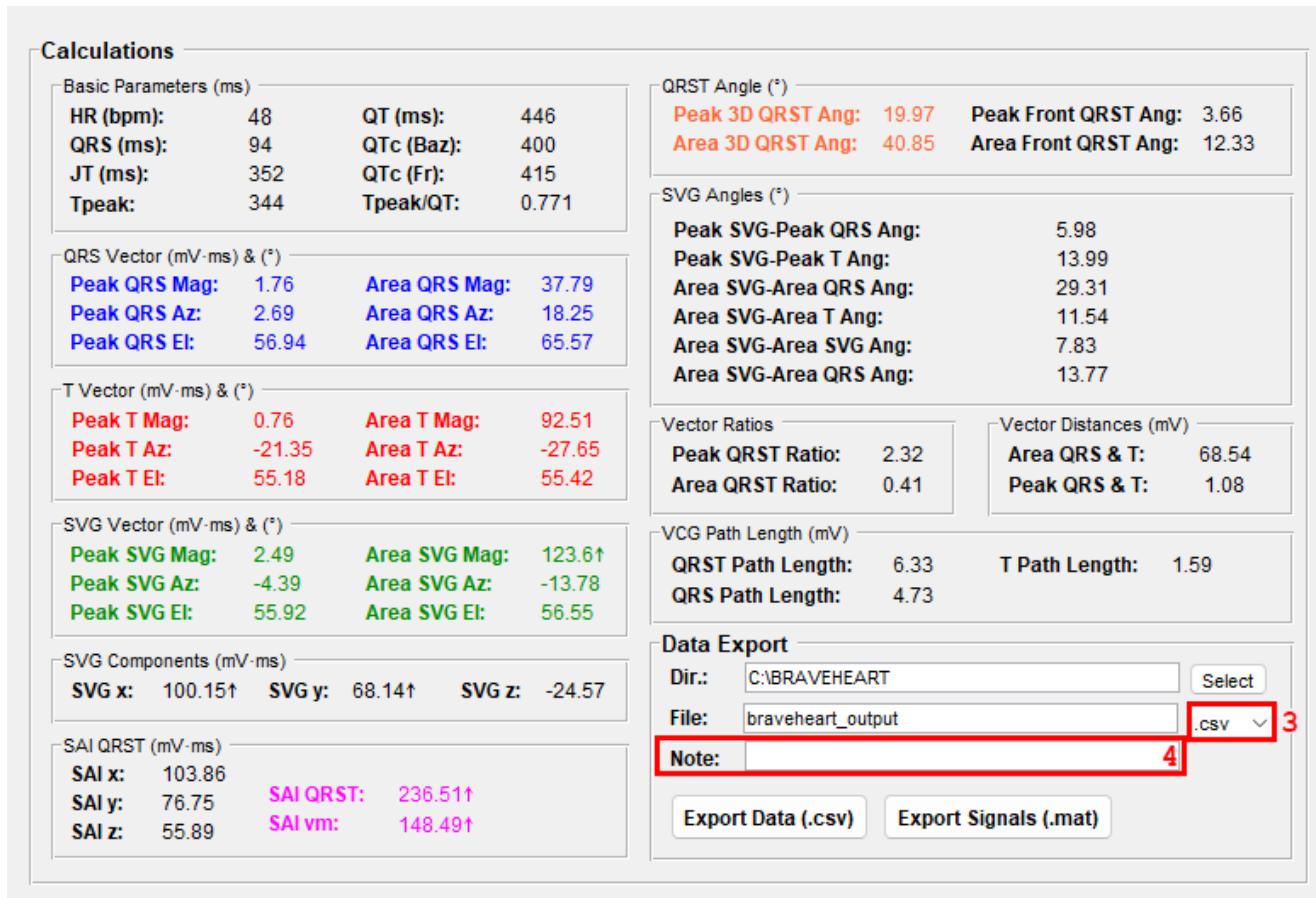


Figure 20: GUI items used to control batch processing in GUI Section 6.2.

- `output_ext` is set using the `VCG Calculations` section in dropdown GUI item **6.2.3**.
- `output_note` is set using the `VCG Calculations` section in the ‘Note:’ textbox GUI item **6.2.4**.

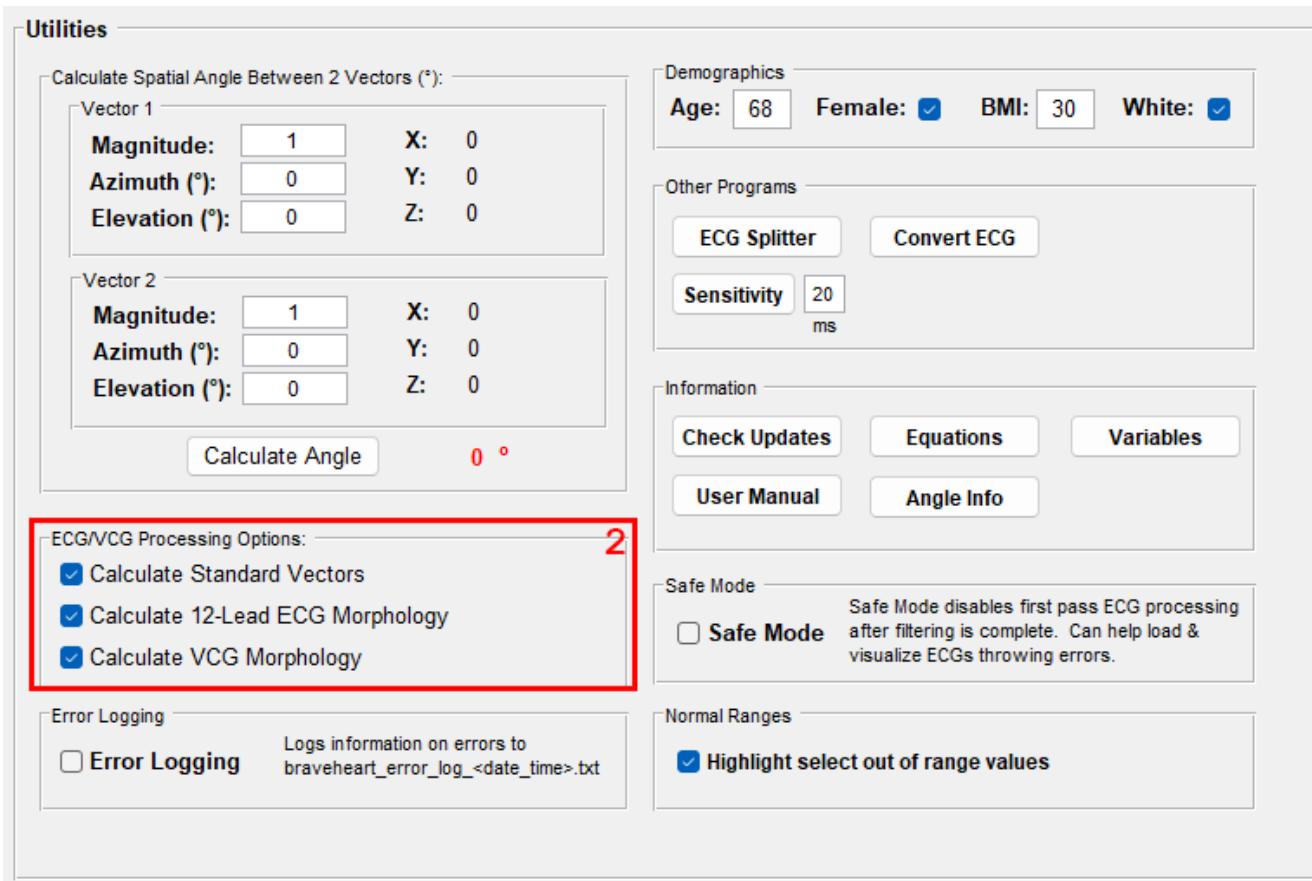


Figure 21: GUI items used to control batch processing in GUI Section 6.6.

Control over what data is processed is set by checkboxes in the **Utilities** section and GUI item **6.6.2**:

- **Calculate Standard Vectors** – sets value of `vcg_calc_flag` as **1** (checked) or **0** (unchecked).
- **Calculate 12-Lead ECG Morphology** – sets value of `lead_morph_flag` as **1** (checked) or **0** (unchecked).
- **Calculate VCG Morphology** – sets value of `vcg_morph_flag` as **1** (checked) or **0** (unchecked).

There is no way to disable the progress bar via the GUI.

Once all batch parameters and annotation parameters have been set in the GUI, click on the **Batch** button (GUI item **1.18**). A dialog box will appear; select the directory that contains the ECGs and click ‘Open’. Batch will begin. A progress bar displays the progress of batch ECG processing. Once finished, a pop-up will display how many ECGs were processed, the number of ECGs that were flagged for quality (see **Chapter 14**), and the number that caused errors. Output directory structure and file naming conventions are the same as noted in **Chapter 11.4**.

13 BRAVEHEART ECG/VCG Processing

13.1 R Peak Detection

QRS Complexes (R peaks) are detected in the vector magnitude (VM) lead by finding peaks in the top $n\%$ of values (where $n = \text{pkthresh}$ in `Annoparams.m`) subject to a minimum R-R interval constraint (`maxBPM` in `Annoparams.m`) which helps prevent incorrect detections of fractionated R peaks within the same QRS or large amplitude T waves. The VM lead is used for R peak detection because it is always positive, and the QRS complex peak amplitude is usually significantly larger than the T wave peak amplitude. In general, the nominal value for `peakthresh = 95` works well for most applications, but may have to be slightly adjusted in ECGs that have significant artifact (see [Chapter 25](#)), ECGs with ectopic/paced beats with a large range of QRS amplitude in different beats, or ECGs with very large amplitude T waves.

Figure 22 below illustrates how the parameters `peakthresh` and `maxBPM` can be adjusted for R peak detection. Issues with R peak detection (usually due to large artifact) are a common cause of ECGs failing to load properly (see [Chapter 25](#)).

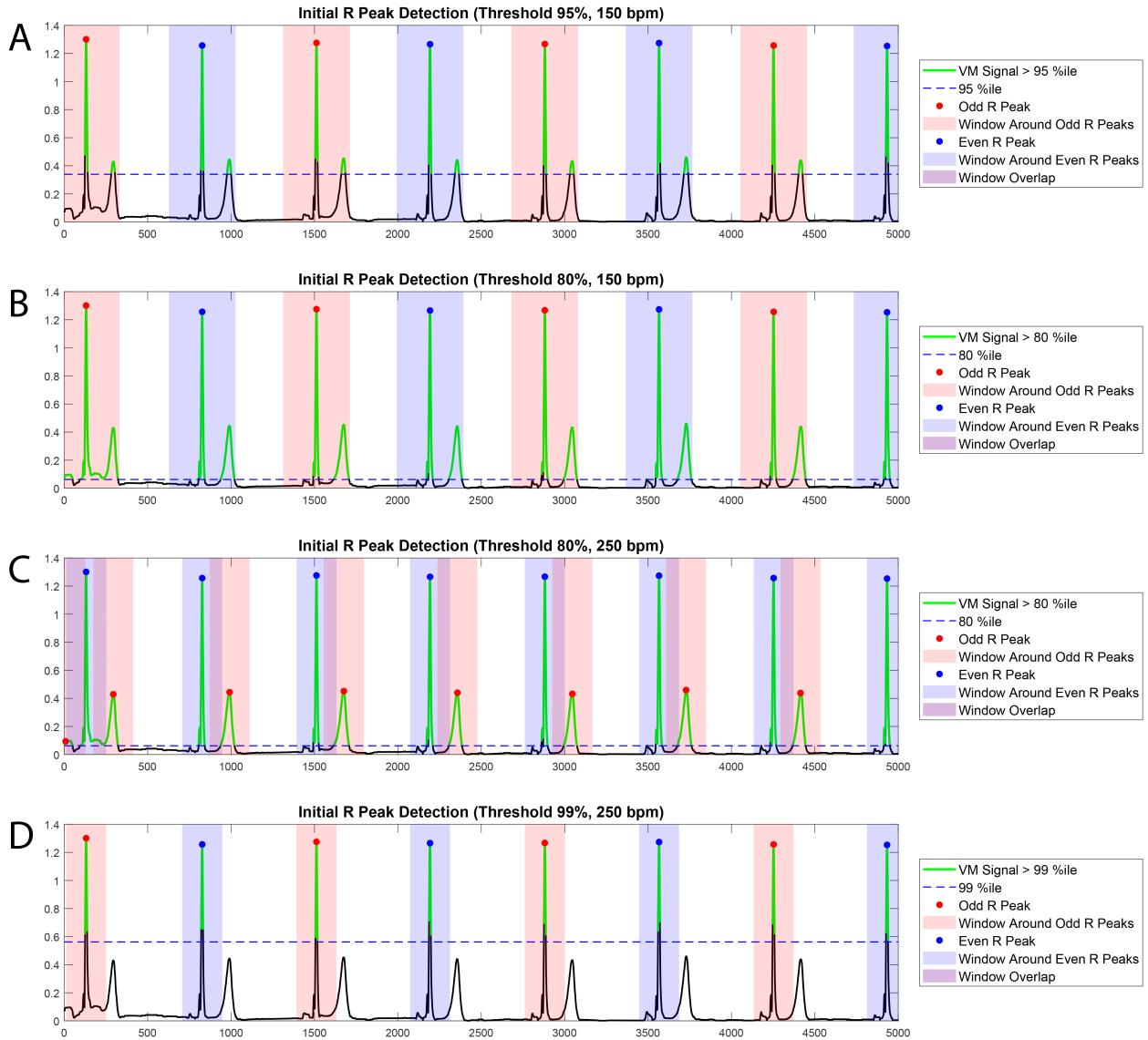


Figure 22: Examples of how peak thresholding (`pkthresh`) works in the context of heart rate constraints (`maxBPM`). The same results can be obtained with different combinations of `pkthresh` and `maxBPM`. **A:** Nominal settings with `pkthresh = 95` and `maxBPM = 150`. The R peaks are appropriately identified (red and blue circles), but even though the T wave peak also is above the 95th percentile (green signal above the blue dashed line), this is not identified as a R peak because it falls within the blanking period (red and blue shaded areas) defined by `maxBPM`. In this case, `maxBPM = 150` corresponds to an interval of 400 ms or 200 samples at 500 Hz on each side of the detected R wave. **B:** The same ECG with `pkthresh = 80`. The R peak detection does not change because the majority of the QRST complex that is above the 80th percentile (green signal above dashed blue line) still falls with the appropriate blanking period. **C:** In this example `pkthresh = 80` but `maxBPM = 250`. In this case, because the blanking windows are significantly shorter (120 samples on each side of each detected peak), the peak of the T wave which is above the 80th percentile (green signal above dashed blue line) is now detected as a R peak (red dots). **D:** Using `maxBPM = 250`, R peaks are now appropriately identified without detecting T wave peaks by increasing the threshold to `pkthresh = 99`. Although the blanking window is short, the T wave peak is now below the 99th percentile (green signal above blue dashed line), so even though the T wave peak falls outside the blanking window, it is no longer detected as an R wave peak because its amplitude is below the 99th percentile (dashed line).

13.2 Baseline Correction

ECG machines do not usually set the zero voltage reference at the isoelectric interval of each lead. Setting the zero voltage reference correctly on an ECG lead is critically important to accurate measurements of the area under an ECG/VCG lead. The true isoelectric (zero voltage) part of an ECG/VCG signal is the segment between the end of ventricular repolarization (T_{off}), and the start of the P wave (TP segment). The importance of setting the zero voltage reference appropriately can be seen in this figure, where incorrectly setting the zero voltage can result in very large differences in measured areas:

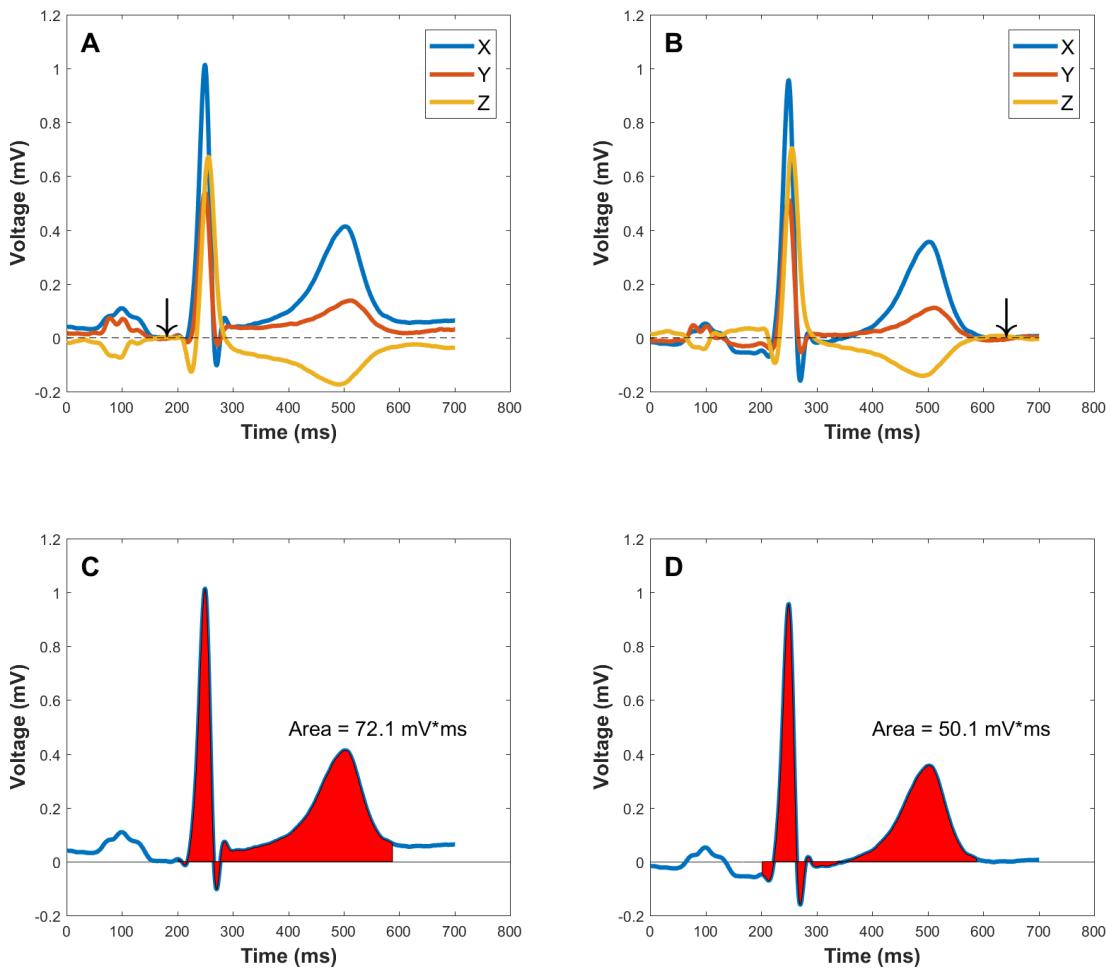


Figure 23: Significant differences in QRST area calculations due to different definitions of the vectorcardiographic origin point. **A:** Median VCG beats (X, Y, Z) without any baseline processing where the onset of the QRS complex (arrow) is defined as zero voltage. **B:** After baseline correction using the method described in the text, the TP segment, a physiologically isoelectric interval is now set as the zero voltage (arrow). **C** and **D:** Physiological baseline correction results in a 30% decrease in area under the X median beat. Reproduced with permission from [7].

High-pass filtering does remove DC offsets, but after filtering, the TP segment is not necessarily going to be set to approximate zero voltage. BRAVEHEART baseline correction adds a constant to the ECG lead such that the TP segment approximates zero voltage. This can be seen in **Figure 24** below, where high-pass filtering removes a significant amount of DC offset, but additional baseline correction is needed to set the TP segment as the zero voltage reference:

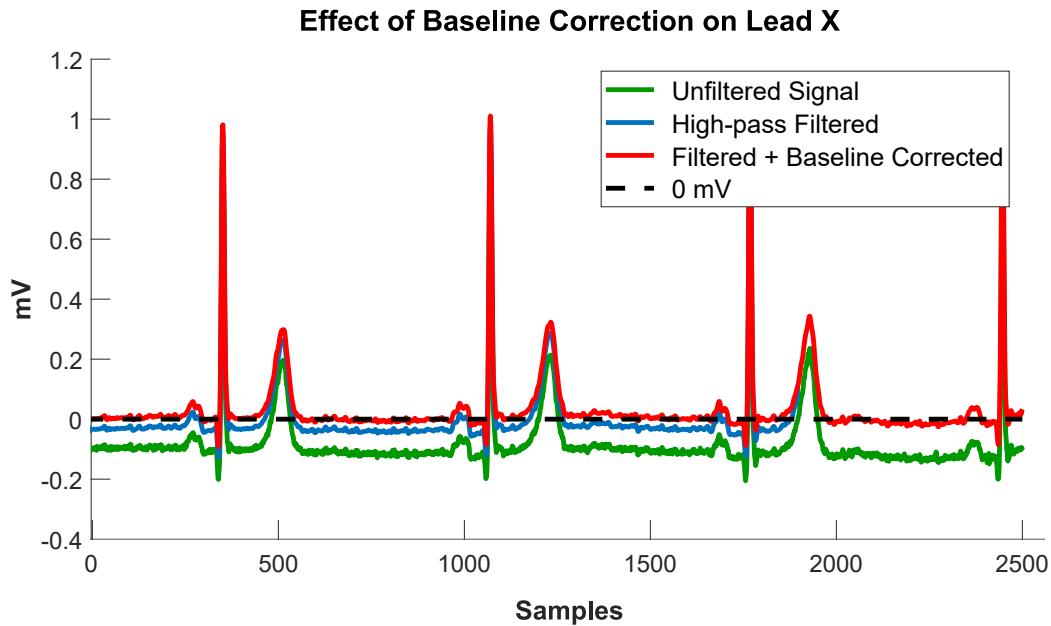


Figure 24: Effect of baseline correction after high-pass filtering. The green signal is unfiltered and has a large offset from the physiologic zero voltage. After high-pass filtering (blue), a large amount of this offset and low-frequency baseline wander is removed, but the TP segment, which is the true isoelectric interval of the ECG lead, is still not approximately zero voltage as the filters have no way to know to set the TP segment at 0 mV. After additional baseline correction (red), the TP segment approximates 0 mV (dashed black line).

Details of the procedure for baseline correction are available in the methods manuscript [1] .

The effect of baseline offset correction can be seen by clicking on the **Offsets** button (GUI item **1.14**). The original signals are shown in black, and the baseline corrected signals are shown in red. Two figures are generated – one shows all 16 leads and their baseline corrections, and the other is a zoomed in view of the VM lead. An example of the offsets figure is shown here:

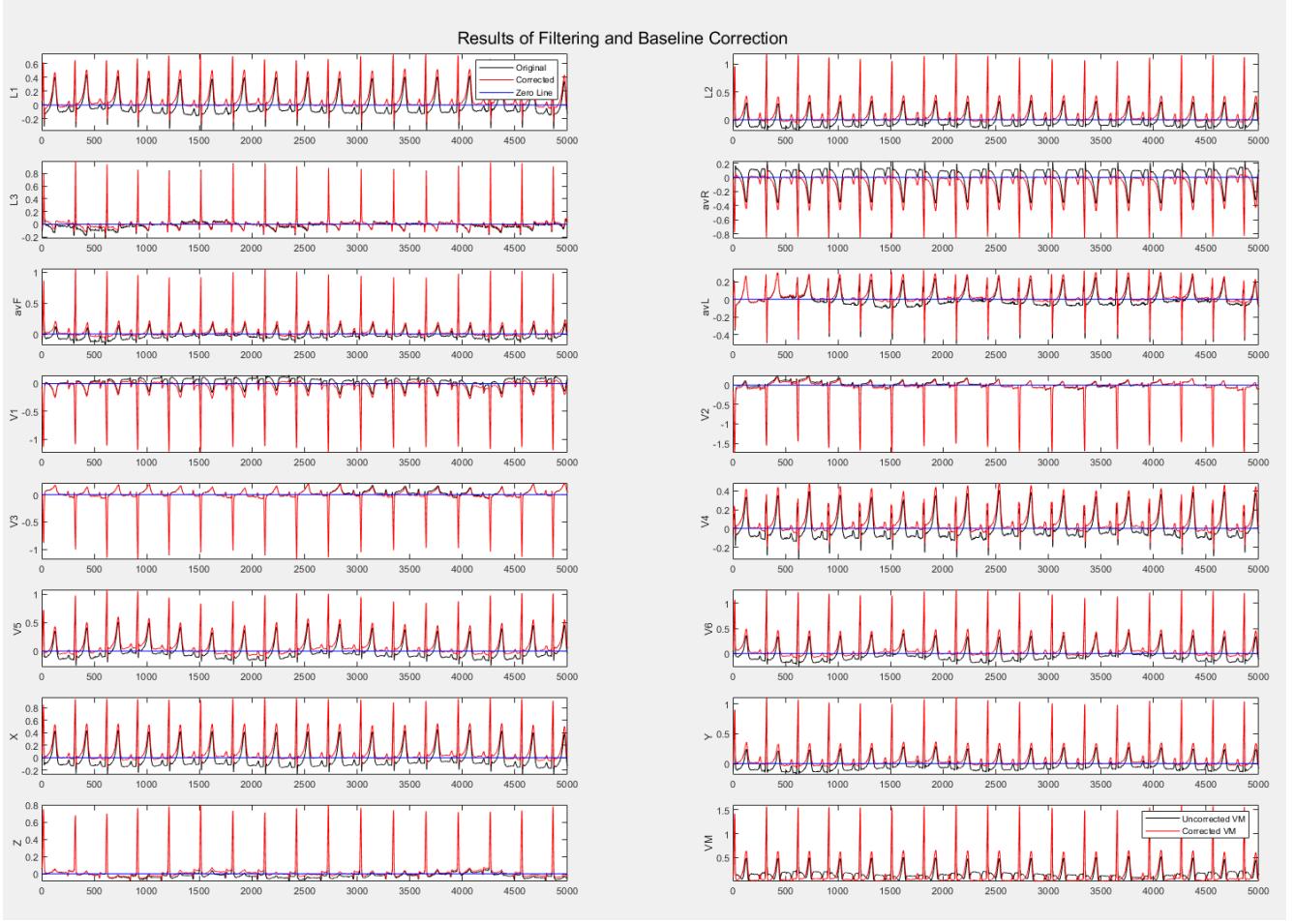


Figure 25: Effect of filtering and baseline correction on an ECG with significant baseline DC offset. The original signals are shown in black, and the filtered and baseline corrected signals are shown in red. The zero voltage line is shown in blue. Note that especially in leads I (L1), II (L2), V1, and X, there is significant deviation from zero baseline originally, and after filtering and baseline correction the TP segments now approximate zero voltage. The vector magnitude (VM) lead is significantly distorted (black signal in the bottom right) without appropriate baseline correction as inappropriate DC offsets in the X, Y, and Z leads are amplified when calculating the $VM = \sqrt{X^2 + Y^2 + Z^2}$.

13.3 PVC and Non-Dominant Beat Morphology Detection

Accurate median beat construction and measurements depend on having a single QRST morphology among the beats that make up the median beat. Although median beat construction can deal with a few beats with disparate QRST morphology as long as these beats make up a low percentage of the total beats, results are more accurate if non-dominant beats such as PVCs or aberrant beats are excluded from analysis prior to median beat creation. In more extreme cases such as ventricular bigeminy with equal numbers of PVCs and normal QRST beats, if PVCs are not removed from analysis, the median beat will be a superposition of the normal QRST complex and the PVC, and calculated results will be highly inaccurate. For this same reason, it is not possible to rely on comparing each individual beat morphology to the median

beat morphology in order to determine what beats are PVCs or other non-dominant beats that should be excluded. BRAVEHEART has a module to automatically detect (and remove) PVCs and other non-dominant beats (from this point on the term “PVC” will refer to PVCs or other non-dominant QRST morphologies which could be due to aberration or ventricular pacing).

A detailed technical discussion of the methods used for PVC detection is available in the methods manuscript [1]. In brief, PVC detection utilizes normalized cross correlation (NCC) and normalized root mean squared error (RMSE) to compare the QRST morphologies between pairs of QRST complexes. All pairs of beats are compared with NCC and RMSE, and the beat that has the best correlation with the most of the other beats is chosen as the “dominant” QRST morphology template. Compared to this template, beats that are outside of limits set by the user in the parameter `pvcthresh` for NCC (nominally 95%) and the parameter `rmse_pvcthresh` for RMSE (nominally 0.1) in `Annoparams.m`, are flagged as PVCs. BRAVEHEART compares morphologies like this in the X, Y, and Z leads, and given that a PVC can look similar to a native beat in a single lead, if a PVC is detected in 2 out of the 3 orthogonal X, Y, and Z leads, the beat is flagged as a “PVC”. The user can then set if PVCs should be removed, or if the non-PVC beats should be removed (see `keep_pvc` in **Chapter 6.2**). In this way it is possible to analyze PVCs rather than dominant beats, automatically. In an analysis of the BRAVEHEART PVC identification algorithm, using NCC = 95% and RMSE = 0.1, sensitivity was 98.2%, specificity was 99.5%, and F1 was 97.7% for PVC detection (see methods manuscript [1] for additional details).

PVC detection and removal are controlled by the following parameters in `Annoparams.m` which are described in detail in **Chapter 6.2**.

- `pvc_removal` which enables or disables automatic PVC removal.
- `pvcthresh` which sets the value for NCC (range 0–1).
- `rmse_pvcthresh` which sets the value for RMSE.
- `keep_pvc` which determines if PVCs are removed and retained for analysis.

When the GUI is used to control PVC detection/removal, as shown in **Chapter 10.10**, values for the above annotation parameters can be set in GUI section 9. The GUI additionally has a function which is called by the `PVC Data` button (GUI item **9.8**). This brings up a figure which summarizes PVC detection in the X, Y, and Z leads, and can be useful for troubleshooting if needed:



Figure 26: Summary of PVC detection algorithm generated by clicking the **PVC Data** button (GUI item 9.8). NCC and RMSE are displayed relative to a reference beat which is the beat that has the best correlation with most of the other beats in the lead (in this case beat 1 in all 3 leads). This reference can vary by ECG lead. Beat 10 is identified as a PVC based on NCC below threshold (`pvcthresh = 0.95`) and RMSE above threshold (`rmse_pvcthresh = 0.1`) in all leads (red box), and is flagged as a PVC (red box in the lowest row, ‘Final PVC Markers’).

13.4 Outlier Beat Detection

After PVCs, aberrant beats, paced beats, or other abnormal QRST morphology beats are removed, there may still be some beats that are contaminated with noise that are detrimental to median beat creation and subsequent calculations. This can occur because the PVC detector algorithm cannot look at the entire QRST complex since beats are of different length, and the algorithm therefore looks primarily around the QRS peak (see the methods manuscript [1] for additional details). Some beats that pass PVC detection can still have significant artifact in

other parts of the QRST complex that prevent accurate annotation and alignment to create the median beat. BRAVEHEART attempts to deal with this issue through removal of these “outlier” beats.

A detailed technical description of the outlier identification algorithm is presented in the methods manuscript [1]. In brief, to identify outliers, BRAVEHEART looks at the QR and RT intervals of all remaining beats after first pass annotation and PVC removal. A modified Z-score is calculated for each beats’ QR and RT intervals. Beats that have a modified Z-score for the QR or RT interval above a threshold set by `modz_cutoff` in `Annoparams.m` are identified as outliers and can then be automatically removed based on the value of `outlier_removal` in `Annoparams.m` (see [Chapter 6.2](#)).

When using the GUI, Section 9 (see [Chapter 10.10](#)) is used to control outlier detection/removal. The GUI additionally has a function which is called by the [Outlier Data](#) button. This brings up a figure which summarizes outlier detection and can be useful for troubleshooting if needed:

Beat & Intervals (in Samples) for VM Lead with Mod Z-Score Cutpoint = 4.0									
QR Interval Outliers (**)									
26	27	27	27	26	50	29	27	27	
1	2	3	4	5	6	7	8	9	
RT Interval Outliers (**)									
189	174	192	185	177	169	204	204	176	
1	2	3	4	5	6	7	8	9	
RS Interval Outliers									
19	22	19	20	19	20	20	20	20	
1	2	3	4	5	6	7	8	9	
JT Interval Outliers									
170	152	173	165	158	149	184	184	156	
1	2	3	4	5	6	7	8	9	
QT Interval Outliers									
215	201	219	212	203	219	233	231	203	
1	2	3	4	5	6	7	8	9	
Area Outliers									
55	50	51	54	53	52	57	56	52	
1	2	3	4	5	6	7	8	9	
Beat #									

Figure 27: Summary of outlier detection algorithm generated by clicking the **Outlier Data** button in GUI item **9.2** for `example3.xml`. The first 2 rows display the QR and RT intervals for each beat, with each column representing a beat. QR or RT intervals that have a modified Z-score above the cutoff set in `Annoparams.m` are noted in red. In this example, beat 6 is classified as an outlier because the QR interval is out of range. Rows 3–6 can help diagnose issues with annotation, but are not used for classify a beat as an outlier, and beats with a modified Z-score above the set cutoff for rows 3–6 are displayed in black rather than red.

14 ECG Quality Assessment

BRAVEHEART was designed to allow efficient batch processing of large numbers of ECGs. The sample of the full batch of ECGs which are of overall poor quality, however, may not be known ahead of time, and with large ECG datasets it may not be feasible to manually review every processed ECG to ensure there is no significant artifact or other problems that may result in incorrect measurements reported by BRAVEHEART. To address this issue, BRAVEHEART has a module that assesses the quality of each processed ECG so that ECGs with the highest probability of being poor quality can be manually reviewed, while ECGs that are likely good quality without processing errors will not require manual review. All ECGs that trip the quality detector will not be of such poor quality that they need to be excluded from an analysis, but they likely should be reviewed to ensure they are of adequate quality. The quality assessment is designed to allow the user to easily customize the sensitivity and specificity of detection based on the quality of the ECG data being processed (e.g. data from a trial vs clinically acquired data), and quality detection can be completely disabled if wanted.

14.1 Quality Probability

BRAVEHEART quality assessment takes place in 2 ways. First we developed a logistic regression model where the output was ECG quality (“good quality” or “needs review”) and the inputs were various features of the processed median ECG/VCG signals. Further details can be found in the methods manuscript [1] . After each ECG is processed, a probability (range 0–1) is reported in the BRAVEHART output files as variable `quality_prob`, and as a percentage (range 0–100) in GUI item **4.5** (‘Prob (%)’) where values above a set threshold (see below) are shown in green indicating “good quality”, while values shown in red indicate “needs review”. The cutoff used to distinguish “good quality” and “needs review” ECGs can be adjusted to increase/decrease sensitivity or specificity as needed for a specific project. In general, a cutoff of ~80% tends to have a good mix of sensitivity and specificity, with both values >90%. Values >90% have higher specificity at the expense of lower sensitivity, and values <70% have higher sensitivity at the expense of lower specificity (see methods manuscript [1] for additional details). An example of ECG quality estimation using this regression method is shown here:

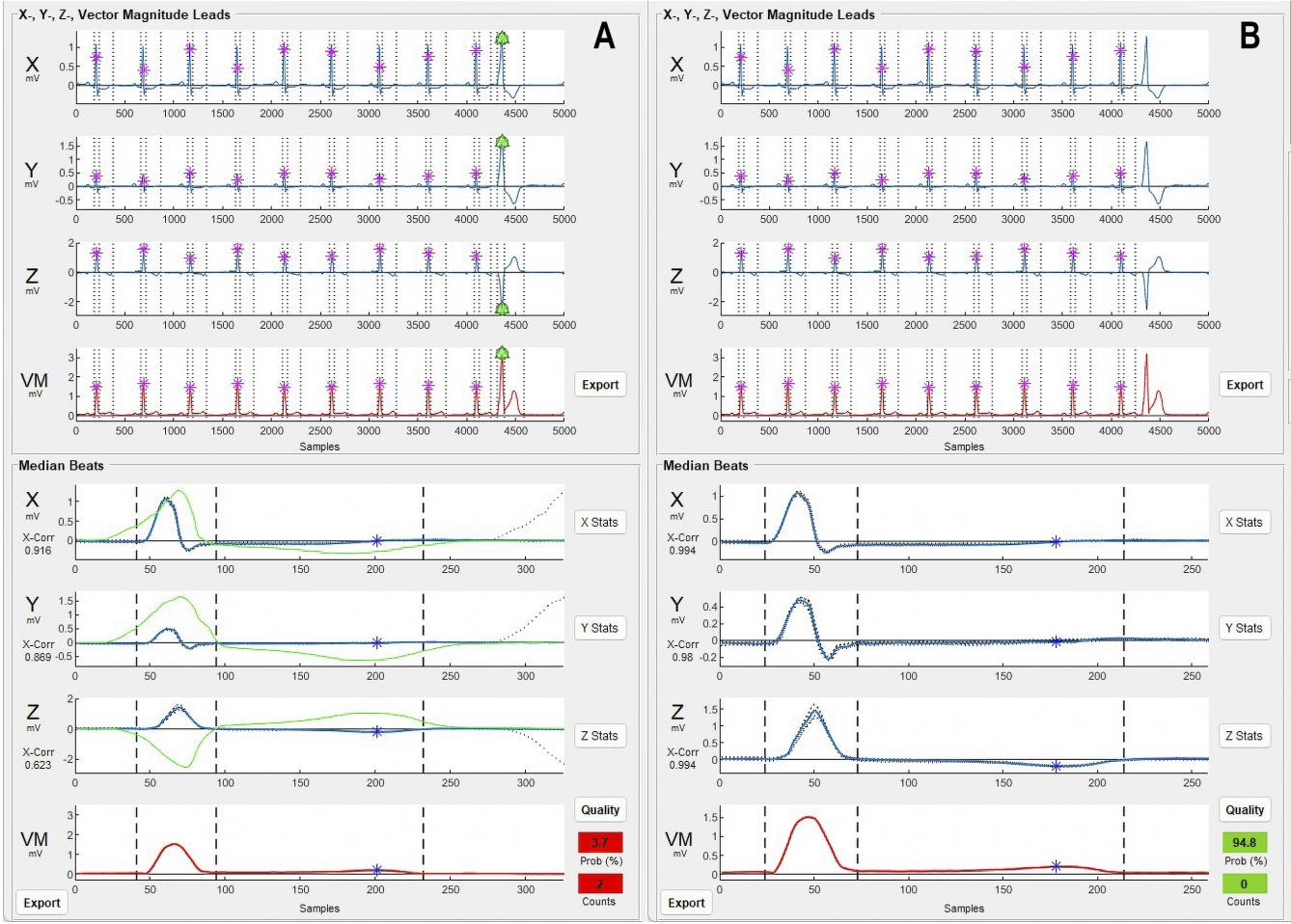


Figure 28: Example of changes in predicted quality in the setting of a PVC. **A:** Prior to PVC removal. The PVC (last beat) is highlighted in green. Because the PVC is not removed, the predicted probability of the median beat being “good quality” is low at 3.7%. **B:** Once the PVC is removed via automated PVC removal (see **Chapter 13.3**), the predicted probability of the median beat being “good quality” is now excellent at 94.8%. Additionally, in panel **A**, when the PVC is present, 2 quality flags (low predicted probability and low NCC) are triggered, while in **B**, after PVC removal, 0 quality flags are triggered (see **Chapter 14.2** below and **Figure 29**).

14.2 Quality Filters

The second way BRAVEHEART assesses quality is by using a set of filters that look at the results from ECG/VCG processing. Annotated median beats are checked for possible processing errors or missannotation by checking metrics including the heart rate, QT interval, QRS duration, number of beats included in the median beat construction, number of beats removed during PVC and outlier exclusion, T peak to QT ratio, T wave magnitude, average NCC between beats that make up the median beat, and low neural network annotation confidence. If any of these values are outside of a range which can be set by the user, the ECG is flagged for review.

14.3 Editing Quality Filtering Parameters - `quality_presets.csv`

Quality filtering is controlled by an external file named `quality_presets.csv`. In this comma delimited file, the first column is the variable name, the second column is the minimum acceptable value for the variable, and the third column is the maximum acceptable value for the variable. Additional descriptive information is available in column 5. BRAVEHEART will flag an ECG if the variable value falls outside of the range set in this file. If there is no lower/upper bound the value can be left blank. The `quality_presets.csv` file with nominal values is reproduced here for illustrative purposes (The descriptive text in column 5 has been edited slightly to fit on the page):

Table 1: `quality_presets.csv`

qrs,	60,	200,	Min/max range of QRS duration
qt,	200,	700,	Min/max range of QT interval
tpqt,	0.5,	,	Min/max range of T peak/QT ratio
t_mag,	0.05,	,	Min/max range for T wave magnitude
hr,	30,	150,	Min/max range for HR
num_beats,	4,	,	# beats left after PVC and outlier removal
pct_beats_removed,	,	60,	% of total number of beats removed
corr,	0.8,	,	Min/max range for average NCC
baseline,	,	0.1,	Min/max range for baseline at the end of the T wave
missing_lead,	,	,	Missing lead - leave this one blank
hf_noise,	10,	,	SNR for HF noise cutoff
lf_noise,	,	0.02,	mV for cutoff in variance in LF noise
prob,	0.8,	,	Logistic regression probability (range 0-1)

Note that `missing_lead`, which looks to see if it seems as if a lead has been disconnected/missing in the ECG, is a special case where both the minimum and maximum values should be left blank.

To edit any of these parameters, simply edit the values in columns 2 and/or 3, save the file, and reload BRAVEHEART. For example, if you wanted to change the logistic regression probability cutoff to 0.8 (80%), you would change the `0.85` to `0.8` in column 2 of the `prob` row. This will flag the result as abnormal if the “good quality” probability is <80%. If you wanted to remove the minimum QT interval so that any QT interval < the maximum (700) would be acceptable, you would remove the value of `200` in column 2 of the `qt` row. A filter can be completely disabled by setting columns 2 and 3 blank which sets the range of acceptable values from $-\infty$ to $+\infty$

Adding new variables to the quality flagging can be done without too much difficulty, although doing so is beyond the scope of this guide.

14.4 Quality Output Files During Batch Processing

To facilitate review of ECGs that are potentially of poor quality during batch ECG processing, if any ECG is flagged for quality, a file named `check_ecg_list_<timestep>.csv` is created which lists the ECGs which were flagged and the reason for flagging. The file contains columns which correspond to specific quality flags in `quality_presets.csv`:

- `qt_error` – `qt` (QT interval) is out of range
- `qrs_error` – `qrs` (QRS duration) is out of range
- `tpeakqt_error` – `tpqt` (ratio of T peak time to QT interval) is out of range
- `tmag_error` – `t_mag` (T wave magnitude) is out of range
- `HR_error` – `hr` (heart rate) is out of range
- `num_beats_error` – `num_beats` (number of beats in the median beat) is out of range
- `num_removed_beats_error` – `pct_beats_removed` (% of beats removed with PVC/outlier removal) is out of range
- `median_sig_corr_error` – `corr` (NCC) is out of range
- `baseline` – `baseline` (median VM voltage after T_{off}) is out of range
- `missing_lead` – A lead appears to be missing (Note: not editable in `quality_presets.csv`)
- `hf_noise` – `hf_noise` (estimate of high-frequency noise) is out of range - see **Chapter 18.12**
- `lf_noise` – `lf_noise` (estimate of low-frequency baseline wander) is out of range
- `probability` – `probability` (predicted probability for “good quality”) is out of range - see **Chapter 18.12**
- `NNNet_prob_flag` – `NNNet_prob_flag` was activated due to low NN median beat annotation confidence (see **Chapter 17**)
- `NNNet_NaN` – `NNNet_NaN` was activated because the NN was unable to find all median beat fiducial points (see **Chapter 17**).

Values of **1** indicate that the specific quality metric was flagged, while values of **0** are normal.

When the **Quality** button (GUI item **4.4**) is pressed, it brings up a figure that shows which quality flags are normal in green (value = **0**), and which quality flags are abnormal in red (value = **1**) for the processed ECG:

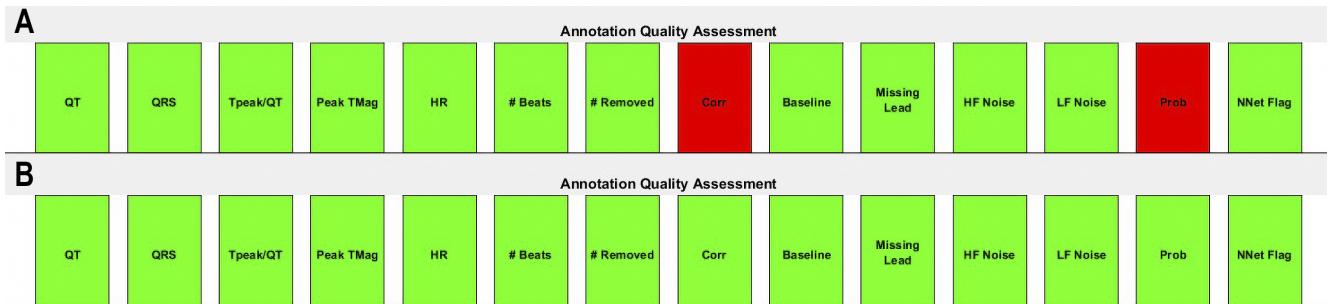


Figure 29: Example of changes in quality flags in the setting of a PVC as shown in **Figure 28**. **A:** Prior to PVC removal, 2 quality flags (low predicted probability and low NCC) are triggered, while in **B**, after PVC removal, 0 quality flags are triggered.

If batch processing is set to save summary figures, BRAVEHEART also creates a separate directory of summary figures (folder named `figures_<timestamp>_check_ecg_list/`) only for the ECGs which are flagged for quality. In this way, it is easier to look through only the flagged ECGs rather than having to manually find flagged ECGs from within the full dataset.

14.5 Other Uses for Quality Filtering

Although the quality filters are designed primarily for catching poor quality ECGs, they can also be used for other purposes including selecting ECGs from a large unlabeled dataset that meet certain morphologic criteria such as those with a certain heart rate range, prolonged QRS duration, or large T wave amplitude, among others.

15 Using .anno Files

.anno files have 2 main uses within BRAVEHEART. They are used to store the specific annotation parameters and beats that were used to process a specific ECG (these parameters are stored within the BRAVEHEART output data files as well), and to allow specific ECGs that don't conform to the standard parameter values within `Annoparams.m` or ECGs that require manual beat adjustment or removal, to be easily reprocessed within a batch of ECGs without having to manually adjust them over and over.

.anno files are .csv files that have the .anno extension to avoid issues with potential ECG file formats or results files that could also have the .csv extension. An example (and truncated) .anno file is shown below, and use of .anno files in the batch processing mode of BRAVHEART is shown in quick start Example 5 ([Chapter 5.5](#)).

Table 2: Example .anno file

275,	299,	326,	502
925,	949,	974,	1153
1533,	1558,	1585,	1757
2160,	2184,	2212,	2396
2768,	2792,	2814,	2991
3370,	3393,	3419,	3610
3991,	4015,	4042,	4223
4626,	4650,	4675,	4858
maxBPM,	150,	,	
pkthresh,	95,	,	
lowpass,	1,	,	
highpass,	1,	,	
wavelet_level_lowpass,	2,	,	
wavelet_level_highpass,	10,	,	
wavelet_name_lowpass,	Sym4,	,	
wavelet_name_highpass,	db4,	,	
...			
keep_pvc,	0,	,	
blanking_samples,	0,	,	
debug,	0,	,	

The first n rows are the individual fiducial points for the n beats which were used to create the median beat. If **Include Beats** is not checked in the GUI, the beats are omitted. When .anno files are generated during batch processing of ECGs, the fiducial points are always included. The remaining rows starting with `maxBPM` correspond to all of the parameters in `Annoparams.m` and the parameter values that were used to process the ECG (see [Chapter 6](#)).

15.1 Generating .anno Files

There are 2 ways to generate an `.anno` file. In the GUI, item **3.14** includes an **Export** button to generate an `.anno` file for the ECG that is loaded. If the **Include Beats** checkbox is checked, the individual beats/fiducial points which make up the median beat are also saved in the `.anno` file. This can be useful if you had to manually remove a beat for some reason such as noise, if the automated outlier and PVC detection/removal was not effective, or other projects that involve looking at specific beats.

When performing batch ECG processing, checking the **Annos** box in the GUI, or setting `save_annotations = 1` in either `BRAVEHEART_batch.m` or `batch_settings.csv` when running via command line, will generate an `.anno` file, which includes beat fiducial points and annotation parameters, for each processed ECG. These files are stored in a folder called `annotations_<timestamp>/`. The annotation files within will have the same name as the processed ECG with the `.anno` extension.

15.2 Using .anno Files

An example of using `.anno` files with the GUI is shown in quick start Example 5 (**Chapter 5.5**). To use an `.anno` file within the GUI, first load the ECG as normal. Then click **Import** (GUI item **3.8**). A dialogue box will appear; choose the `.anno` file you want to load and click ‘Open’. The current GUI settings are overwritten by the parameters in the `.anno` file, and if beat fiducial point annotations are included in the `.anno` file, only the included beats will be used to construct the median beat. ECG measurements are then calculated without needing to press the **Calculate** button. If you are processing other ECGs in the GUI after processing an ECG that included loading an `.anno` file, remember to reset the default annotation parameters with the **Reset** (GUI item **3.7**) before processing other ECGs.

When in batch processing mode via command line or GUI, BRAVEHEART checks the ECG file directory for any files with the same name as the ECG being processed with the file extension `.anno`. If an `.anno` file with the same name as the ECG being processed is present in the same directory as the ECG file, the ECG is processed using the annotation parameter values within the `.anno` file rather than `Annoparams.m`, and only using the beats specified in the file. In this way, if there is an ECG that requires a specific non-nominal values of a parameter such as `STend` to process properly, you can process the ECG and generate an `.anno` file. Edit the `.anno` file with the correct value of `STend` or whatever other parameters need to be adjusted. Likewise, if outlier and PVC detection and removal are having an issue with a specific ECG and you want to

manually exclude a specific beat, simply delete that beat from the `.anno` file. Then the next time you run a batch using BRAVEHEART with the same ECG (perhaps you want to run the batch of ECGs with a different transformation matrix or filtering parameters, or if you added a new parameter and want to calculate it on the same batch of ECGs), the different value of `STend` will load **for that ECG ONLY**, and the specific beat in question will be deleted. This can save time when running batch analyses multiple times.

16 First Pass Annotation

16.1 First Pass Annotation Algorithm

First pass annotation uses a heuristic algorithm to find Q_{on} , Q_{off} , and T_{off} for each QRST complex in the VM lead. The VM lead is used for first pass annotation because it is always positive and the QRS magnitude tends to be larger than the T wave magnitude which helps simplify calculations. First pass annotation is controlled with the following parameters in `Annoparams.m` (see [Chapter 6.2](#)):

- `autoMF`
- `autoMF_thresh`
- `MF_width`
- `QRwidth`
- `RSwidth`
- `STstart`
- `STend`
- `Tendstr`

First pass annotation is controlled by the `autoMFannotate.m` subroutine which uses these parameters, the locations of the dominant R peaks in the VM lead (see [Chapter 13.1](#)), and any pacing spikes (see [Chapter 5.4](#)), in order to set the search windows for the beginning and ending of the QRS complex and T wave. If `autoMF = 1` the QRS search algorithm dynamically estimates the QRS search window by estimating the width of the QRS peak in the VM lead after median filtering with a filter width of `MF_width`. Using `autoMF = 1` is usually better than manually setting a static QRS search window using `QRwidth` and `RSwidth` because all beats are not necessarily the same width, and a fixed search window may not work for all beats. The search window is set for each individual peak to twice the width of the region of points greater than the percentage `autoMF_thresh` of the height of the median-filtered dominant R-wave peak. If `autoMF = 0`, the provided, and static, values of `QRwidth` and `RSwidth` are used to set the QRS search window for all peaks.

Once the QRS search window is established, for each QRS complex, the start (Q_{on}) and end (Q_{off}) are determined as follows. First, the algorithm determines if there is an additional peak in the VM lead before the dominant R wave peak within a short distance (i.e. a Q wave). Two methods are then used to determine the start of the peak. Method A finds the maximum slope and walks out until it finds a point where the absolute value of the derivative is 2% of the maximum slope (or the smallest value found if not 2%). Method B looks for the first local minimum and labels this as the fiducial point. The point closest to dominant R-wave from methods A and B is chosen as the fiducial point.

After Q_{on} and Q_{off} are located, a blanking window equal to **STstart** ms is set after the location of Q_{off} during which the T wave cannot be detected to avoid issues if Q_{off} is not detected correctly. At the end of this **STstart** window, the T wave search window starts and is extended by **STend** % of the mean RR interval. **STend** is set as a % of the mean RR interval rather than an absolute value in ms to minimize the need to change parameter values as QT interval is related to RR interval. The location of T_{off} is then detected by the method specified in **Tendstr**.

If **Tendstr** is '**baseline**' or '**tangent**', the second half of the T-wave is fit to $A \exp\{(t/\sigma)^B\}$. The intersection of the function, or the tangent to the maximum negative slope with the baseline, is then calculated. If **Tendstr** is '**energy**', the T-wave offset is chosen by a method based on the derivative of the signal (see reference [5]).

16.2 First Pass Annotation Figure

First pass annotation is summarized in the following figure:

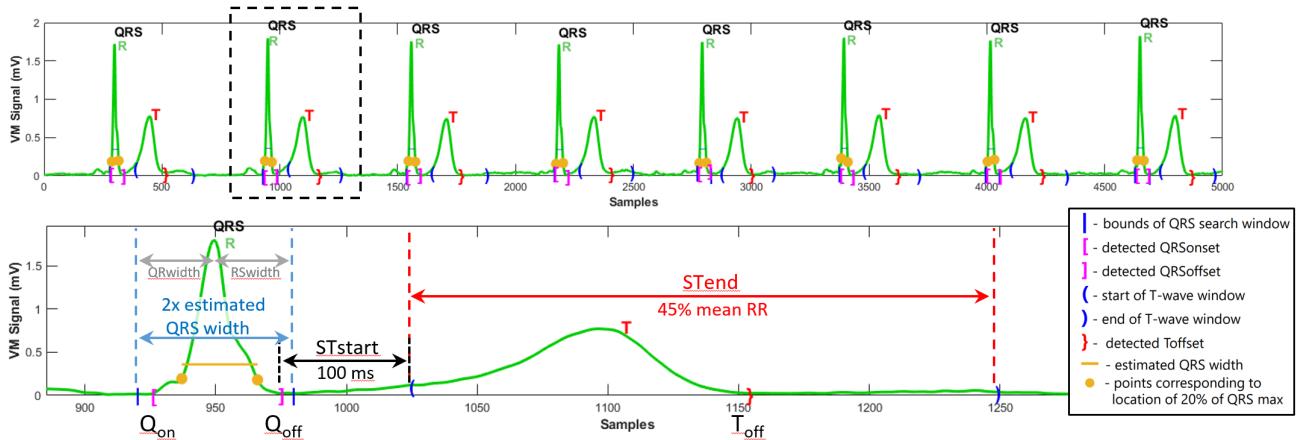


Figure 30: First pass annotation and search windows. The upper panel shows annotation search windows/detected points for the entire VM lead. The bottom panel shows a zoomed in view of the second beat (dashed box). If **auto_mf = 1**, the values of **QRwidth** and **RSwidth** (grey) are disabled and the QRS search window is dynamically estimated for each beat as twice the width of the median filtered QRS complex at **autoMF_thresh** % of the R peak voltage (nominally 20% - yellow dots/line) for that beat centered on the R peak. If **auto_mf = 0** the values of **QRwidth** and **RSwidth** are used to set the width of the QRS search window before and after the R peak, respectively. The blue | symbols denote the beginning and end of the QRS search window and can help determine if the QRS detection window is too wide/narrow. Within the bounds of the QRS search window, Q_{on} and Q_{off} are detected as noted in the text with locations noted as [and], respectively. Once Q_{off} is detected, a blanking period set by **STstart** (nominally 100 ms) extends forward from the location of Q_{off} , marking the start of the T wave search window (()). The T wave search window extends forward by **STend** % of the mean RR interval (nominally 45%) and ends at the) symbol. Within the T wave search window bounds, the location of T_{off} is marked with a }.

16.3 Common Annotation Parameter Problems

The nominal value of `autoMF_thresh = 20`. Consider what can happen if `autoMF_thresh` is set too low:

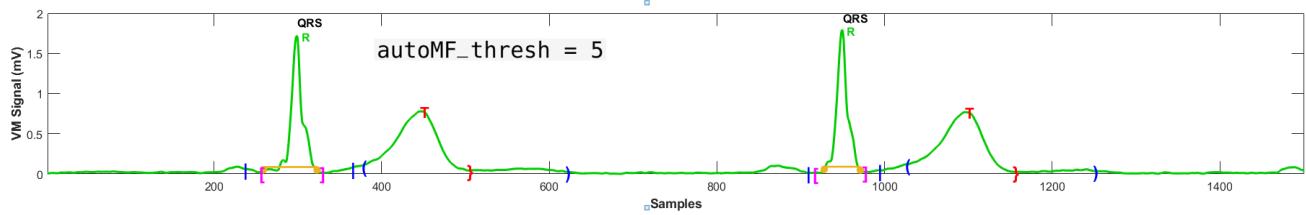


Figure 31: `autoMF_thresh = 5` is set too low. See text for details.

As shown in **Figure 31**, if `autoMF_thresh = 5` is set too low, more than the true QRS complex may be detected as part of the QRS complex (see orange circles and line), resulting in the estimated QRS width and the QRS search window (|) being too wide. This prevents accurate annotation of Q_{on} (|) and Q_{off} (|), but also can interfere with the T wave search window ((to)) and locating T_{off} (}) because the onset of the T wave search window starts `STstart` ms after the location of Q_{off} .

As shown in **Figure 32**, if `autoMF_thresh` is set too high, the QRS search window is likely to be too narrow:

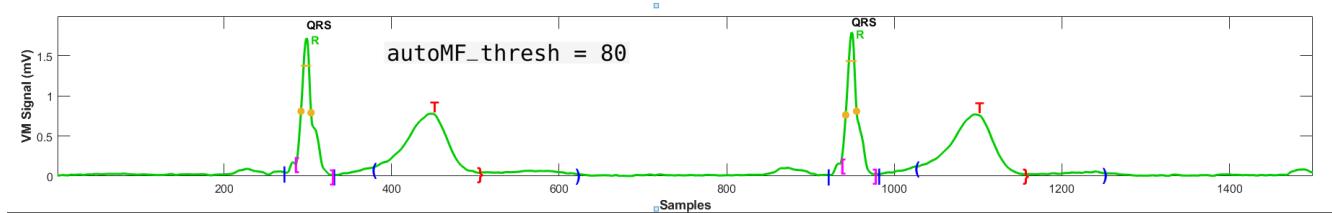


Figure 32: `autoMF_thresh = 80` is set too high. See text for details.

Note that in this example, Q_{on} ((|)) is annotated later than the true QRS onset because the search window is not wide enough.

In cases where atypical QRST morphology is causing issues with first pass annotation, setting `autoMF = 0` in `Annoparams.m` or by unchecking the `Auto Width` checkbox, can allow manually setting the QRS search window by setting the values of `QRwidth` and `RSwidth`.

As shown in **Figure 33**, if `STend` is too short, the end of the T wave may not be found:

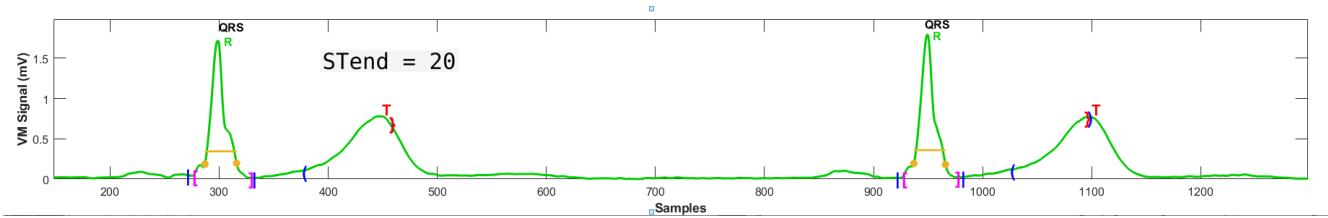


Figure 33: `STend = 20` is set too short. See text for details.

In this example, the end of the T wave search window (()) is too short to include the entire T wave, and the location of T_{off} (}) is therefore not accurate. If `STend` is longer than necessary this usually does not cause as many issues as if `STend` is too short, as long as the end of the T wave search window does not encroach on the start of the next PQRST complex.

17 Neural Network Median Beat Annotation

Accurate annotation of the median beat is important for obtaining accurate measurements. We found that the heuristic methods which are used for first pass annotation were not accurate enough for median beat annotation, especially when QRST complexes had abnormal or very low amplitude T waves. This accuracy is less important for first pass annotation because first pass annotation needs to be just good enough to properly align each beat for median beat creation. We therefore trained and validated a custom bidirectional Long-Short Term Memory (LSTM) neural network (NN) designed specifically to annotate median VM beats. The technical details of NN training and validation are available in the methods manuscript [1] .

The NN included with BRAVEHEART is highly accurate when compared to board certified cardiac electrophysiologists and its accuracy was tested in 2 separate datasets.

Testing set 1 was performed at the time of NN training using data that was not used for training or validation of the NN, and showed excellent agreement with ground truth, well within acceptable limits for computer based automatic fiducial point annotation [8, 9, 10, 11]. Testing set 2 was performed using a completely different dataset collected for different purposes. The NN also had an excellent accuracy with this second, independent dataset. Results are summarized here:

Table 3: Neural Network Annotation Accuracy

Result	Q_{on}	Q_{off}	T_{off}	QRS duration	QT interval
Set 1 Error Mean \pm SD (ms)	-0.3 \pm 3.9	-1.2 \pm 5.1	-0.1 \pm 7.0	-0.9 \pm 6.2	0.2 \pm 7.9
Set 2 Error Mean \pm SD (ms)	-0.1 \pm 3.3	-1.7 \pm 4.0	1.2 \pm 5.8	-1.6 \pm 5.4	1.3 \pm 6.7

As can be seen, the mean difference between NN predicted and ground truth fiducial point locations were $< \pm 2$ ms (1 sample at 500 Hz) for all points in both testing datasets. The methods manuscript [1] contains extensive information about NN architecture, training, and testing results.

The output of the NN can be visualized by viewing the ‘Debug’ figures enabled with the **Debug** checkbox (GUI Section 3 **Chapter 10**) and generated after pressing **Calculate** which shows the probability scores for each sample being either a “QRS complex”, “T wave”, or “other”:

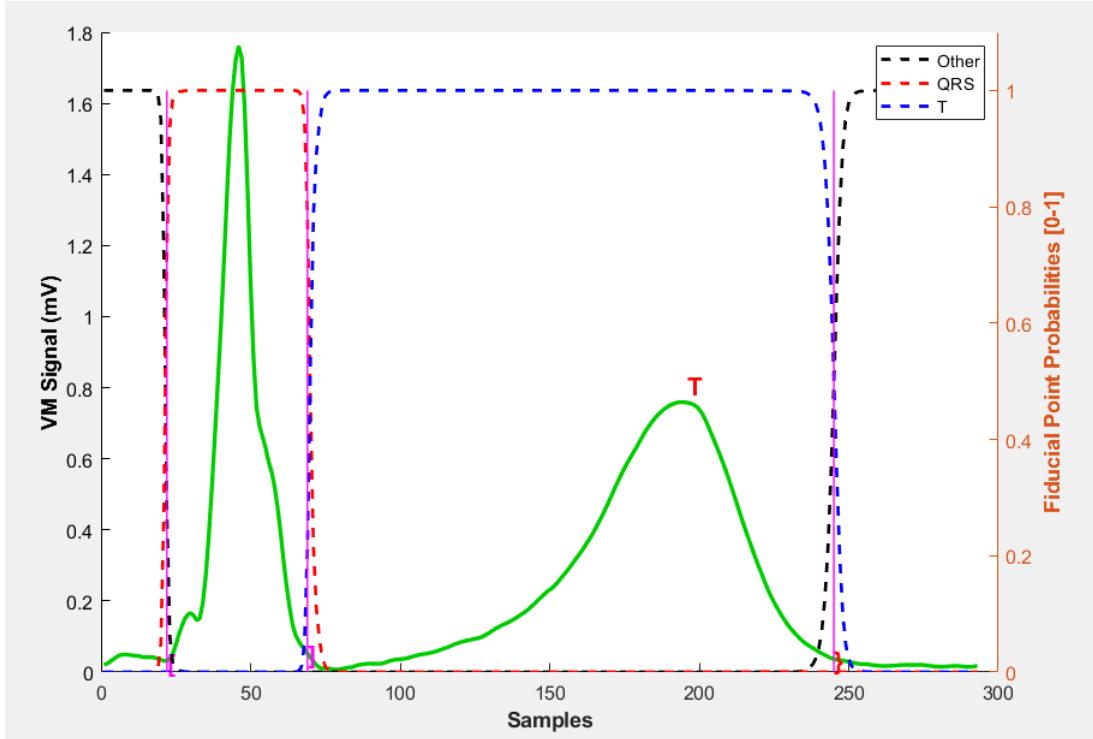


Figure 34: Debug figure for median beat annotation. The dashed lines are the NN predicted probabilities of a sample being a “QRS complex” (red), “T wave” (blue), or “other” (black). Each sample in the median beat signal is assigned the label that is the highest of the 3 probabilities. Q_{on} is set as the sample where “other” transitions to “QRS complex”, Q_{off} is set as the sample where “QRS complex” transitions to “T wave”, and T_{off} is set as the sample where “T wave” transitions to “other”. Q_{on} is marked with a [, Q_{off} is marked with a], and T_{off} is marked with a } similarly to first pass debug figures. In rare cases where multiple potential fiducial points are detected, logic is used to select the best point – see methods manuscript [1] for additional details.

18 Figures

BRAVEHEART allows visualization of ECG and VCG data in numerous ways. The following section describes the figures/visualizations that can be generated primarily by the BRAVEHEART GUI. When batch processing, normally only summary figures (**Figure 35** and **Figure 36**) are generated, although with code modification it is possible to generate any of the figures in this section during batch ECG processing.

18.1 Summary Figure

The summary figure is generated by batch processing for each ECG that is processed if `save_figures = 1` or when **Figs** is checked (GUI item **1.18**).

When using the GUI to analyze individual ECGs, the summary figure can be generated using the **Summary** button in GUI item **7.1**. To save the summary figure as a `.png` file click the **Save** checkbox (GUI item **7.3**) prior to clicking **Summary**. Two examples and descriptions of the Summary Figure are shown here:

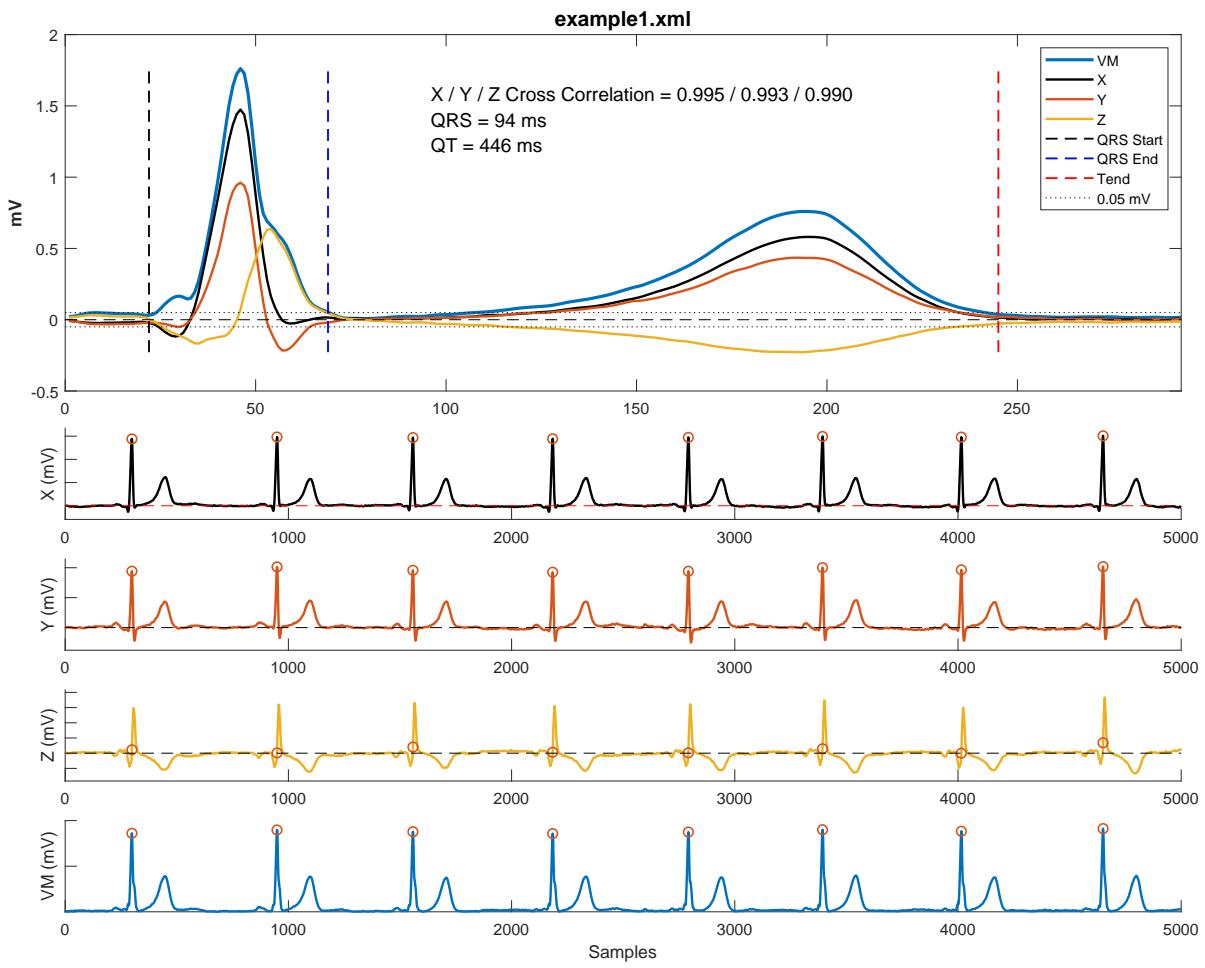


Figure 35: Summary figure for `example1.xml` generated when `save_figures = 1` when set in `braveheart_batch.m`, when **Figs** is checked prior to running batch ECG processing from the BRAVEHEART GUI, or when clicking **Summary** in the ‘View/Save ECGs’ section of the GUI after ECG/VCG processing. The summary figure shows the median X, Y, Z, and VM beats in the upper half, and the individual beats used to create the median beats in the lower half. Beats that are included in the median beat are marked with an orange circle on the VM R peak. Beats that are not included do not have an orange circle on the VM R peak. Beats that are removed due to PVC or outlier detection are marked with ‘PVC’ or ‘Out’, respectively. Beats that do not have an orange circle and were not annotated as either a PVC or outlier were removed either due to being too close to the start/end of the ECG signal, due to manual beat removal, or due to being missed by initial QRS detection (below threshold or within the blanking period). The summary figure is useful to give you a quick view of which beats are included, which beats were excluded and why, the quality of median beat creation (via cross correlation values) at the top, and median beat intervals and annotations.

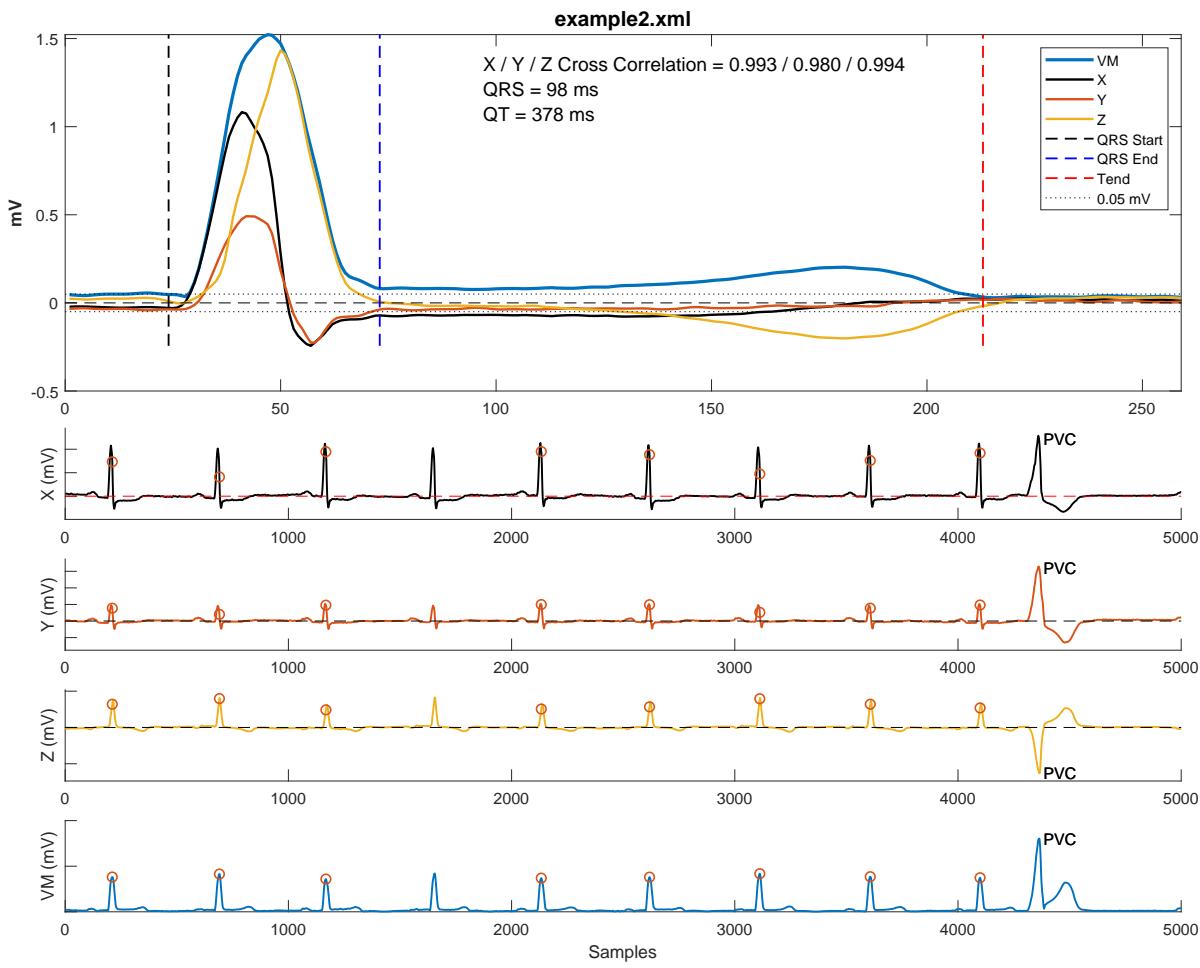


Figure 36: Summary figure for `example2.xml`. The figure layout is the same as noted in **Figure 35**. In this example the PVC has been removed by automatic PVC detection and removal. Note that the PVC does not have an orange circle on the VM R peak, indicating the the beat is not included in the median beat. The PVC is labeled as “PVC” indicating that the beat was removed with PVC detection/removal. For illustrative purposes beat 4 has also been manually removed and therefore does not have an orange circle on the VM R peak. Beats that were detected and removed as outliers are labeled as “Out” (not present in this example).

18.2 12-Lead ECG/VCG

Once an ECG is loaded, the 12-Lead ECG and/or VCG can be displayed with the `(12L ECG)` and VCG `(X,Y,Z VCG)` buttons in GUI item **7.1**. The inclusion of major/minor grid lines can be enabled/disabled by choosing an option in dropdown in GUI item **7.2**. To save the ECG/VCG as a `.png` file click the `Save` checkbox (GUI item **7.3**) prior to clicking the `(12L ECG)` or `(X,Y,Z VCG)` buttons. The 12-lead ECG and VCG for `example1.xml` are shown here:

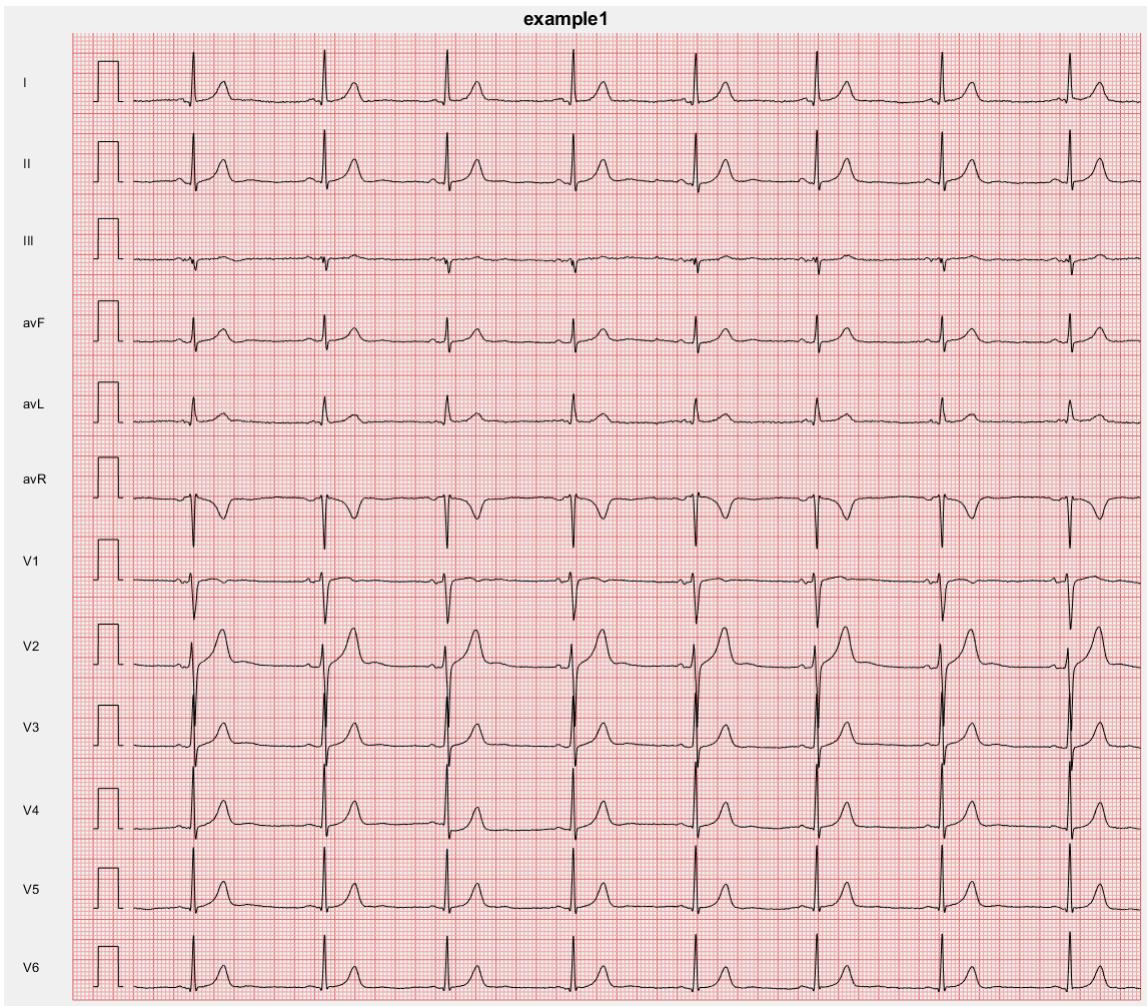


Figure 37: 12-lead rhythm strips for `example1.xml`.

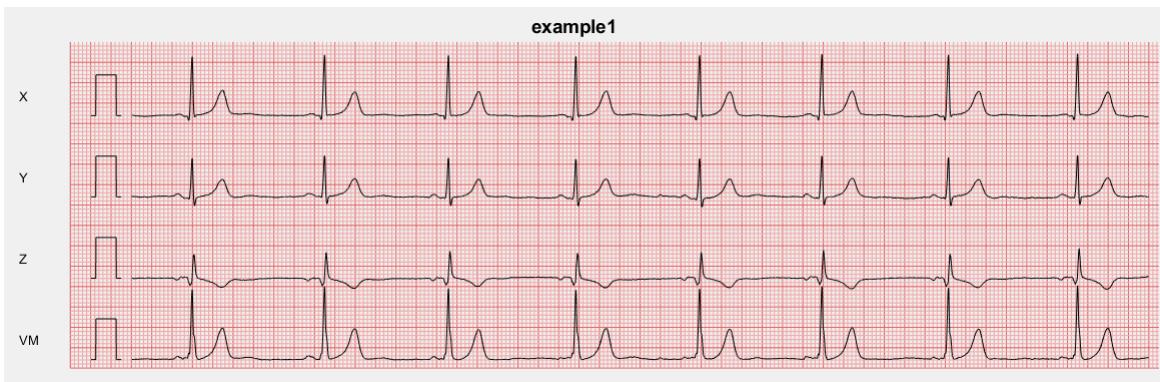


Figure 38: VCG and VM rhythm strips for `example1.xml`.

18.3 Median Beats

The 16 median beats can be displayed by clicking the **Med. Beats** button in GUI item **7.1**. The inclusion of major/minor grid lines can be enabled/disabled by choosing an option in the

dropdown in GUI item **7.2**. To save the median beat figure as a **.png** file click the **Save** checkbox (GUI item **7.3**) prior to clicking the **Med. Beat** button. The median beat figure for **example1.xml** is shown here:

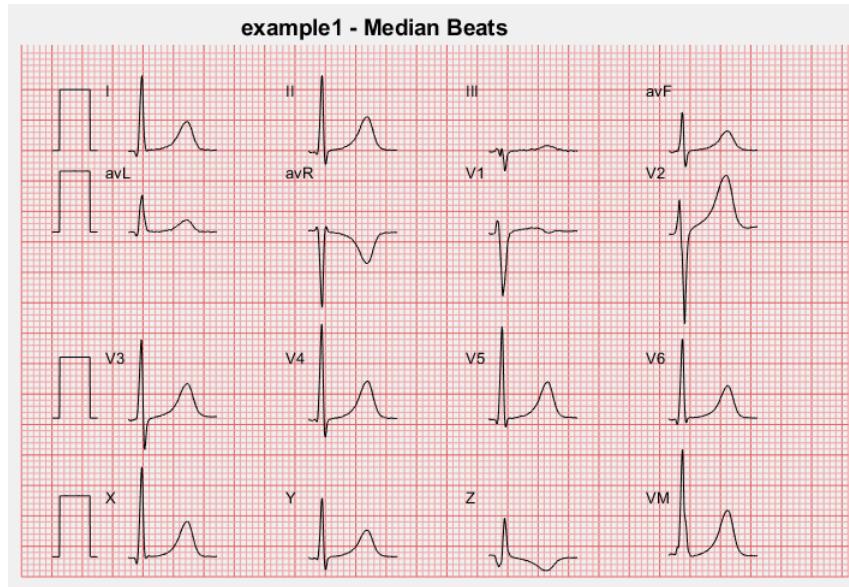


Figure 39: 16 median beats for **example1.xml**.

Detailed measurements of the median beats can be shown by clicking the **Lead Morphology** button (GUI item **5.3**). See **Figure 43** for additional information.

18.4 Normal Values

BRAVEHEART can display age, sex, BMI, and race specific normal ranges for certain parameters, and show if calculated values are within normal range by clicking on the **Normal Vals.** button. Values in black are within normal range, and values in red are outside the normal range. The parameters shown in this figure are the same parameters that will have \uparrow or \downarrow next to them in the ‘VCG Calculations’ section (GUI item **6.2.1**) to indicate if the value is above or below the normal range, respectively. To save the normal values figure as a **.png** file click the **Save** checkbox (GUI item **7.3**) prior to clicking the **Normal Vals.** button. Further details on normal values/ranges can be found in **Chapter 20**. The normal values figure for **example1.xml** is shown here:

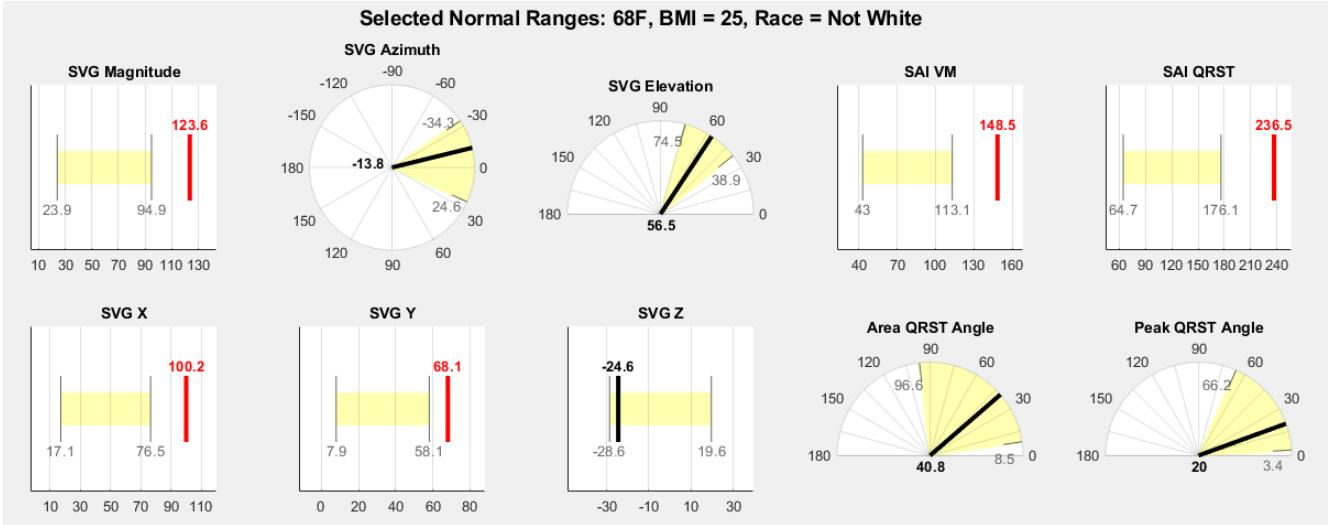


Figure 40: VCG calculations and their relationship with age, sex, BMI, and race specific normal values for `example1.xml`. The normal ranges are shown in yellow, with the upper and lower bounds shown with grey text. In this example, SVG X, SVG Y, SVG magnitude, SAI VM, and SAI QRST are out of range (red lines and text), while the other parameters which are within the normal range with black lines and black text.

18.5 VCG Loops

The VCG loops figure displays the X, Y, and Z median beats and the associated VCG loops displayed in orthogonal views, and can be generated by clicking the **VCG Loops** button. To save the VCG loops figure as a `.png` file click the **Save** checkbox (GUI item **7.3**) prior to clicking the **VCG Loops** button. The VCG Loop figure for `example1.xml` is shown here:

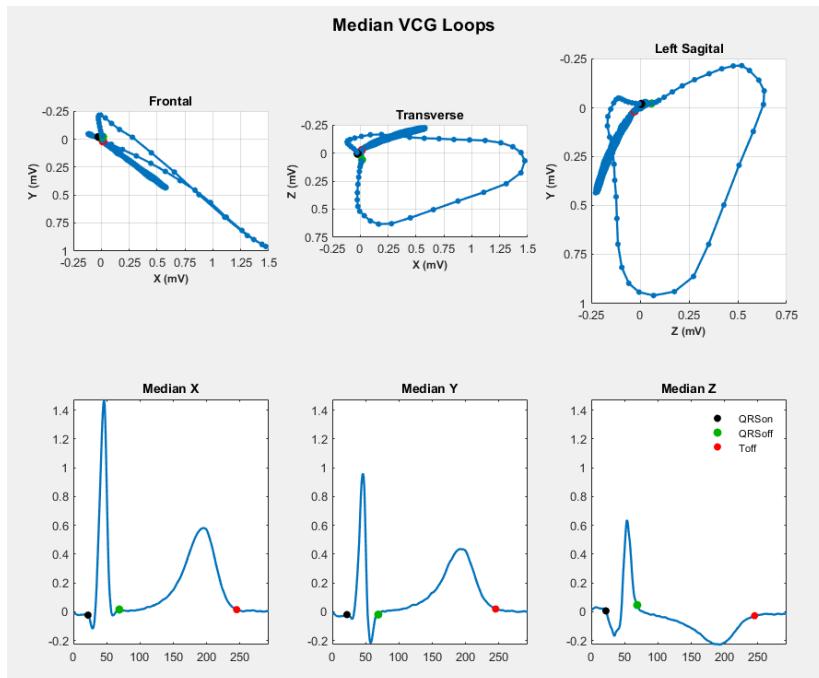


Figure 41: VCG loop figure for `example1.xml`.

18.6 3D VCG

The 3D VCG is displayed in GUI section **6.1** by clicking on the **Vectorcardiogram** button (GUI item **5.1**). This figure can be rotated by using the rotation tool (GUI item **10.1**), and options in GUI item **6.1.1** can be used to change what information is displayed in the figure (see **Chapter 10.7**). To save the 3D VCG figure in the current orientation, click on the **Save** button in the lower right of the figure (GUI item **6.2.8**).

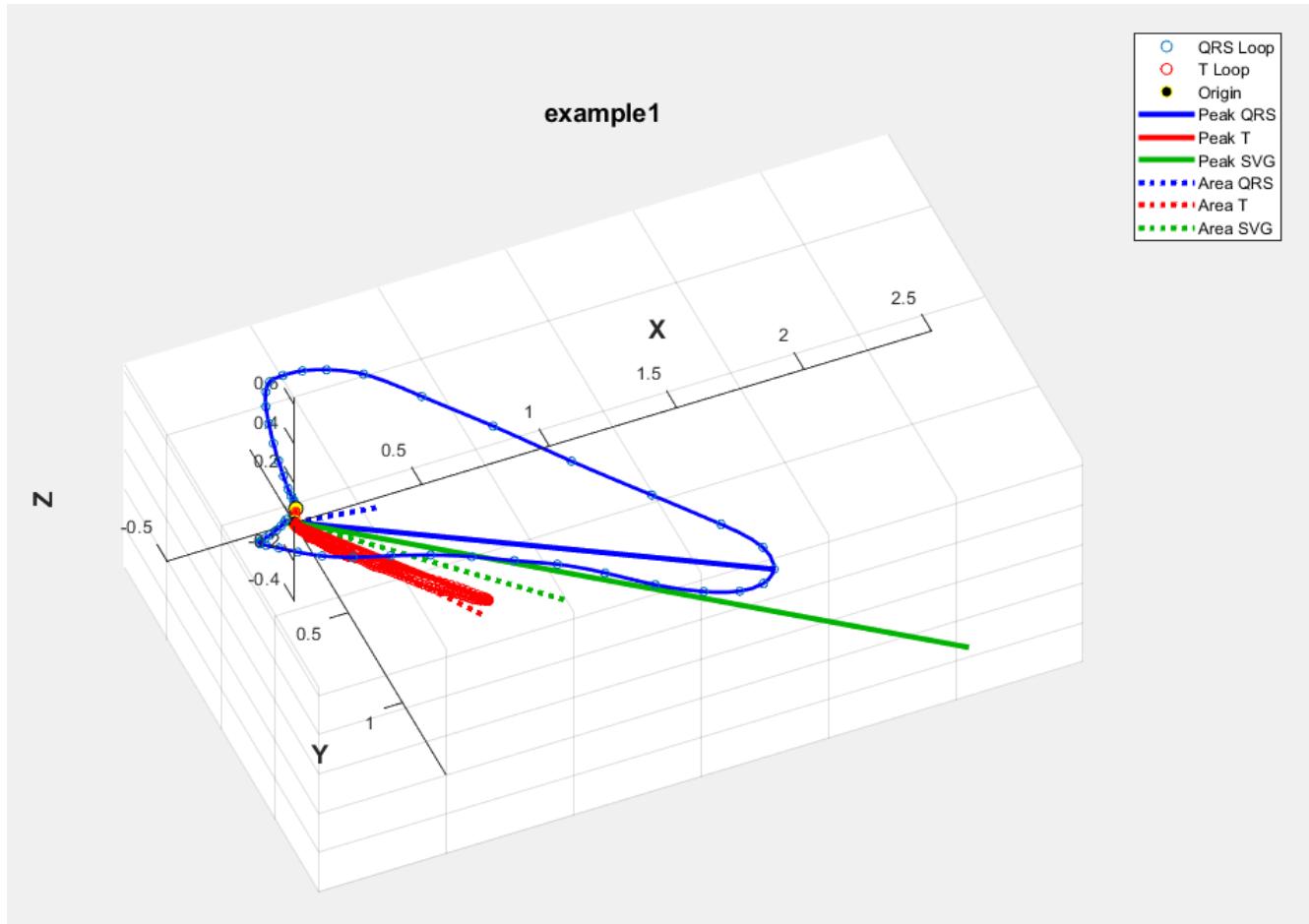


Figure 42: 3D VCG as displayed in GUI item **6.1**. The QRS loop is shown in blue and the T wave loop is shown in red. In this specific situation various vectors are shown as described in the legend. Options for VCG display are shown in GUI item **6.1.1**.

18.7 Lead Morphology

The **Lead Morphology** button (GUI item **5.3**) displays a pop-out window with all 16 median beats, fiducial points, and the measurements of the R, S, and T waves. This displays the majority of results contained in the **Lead_Morphology** results class. The lead morphology figure for `example1.xml` is shown here:

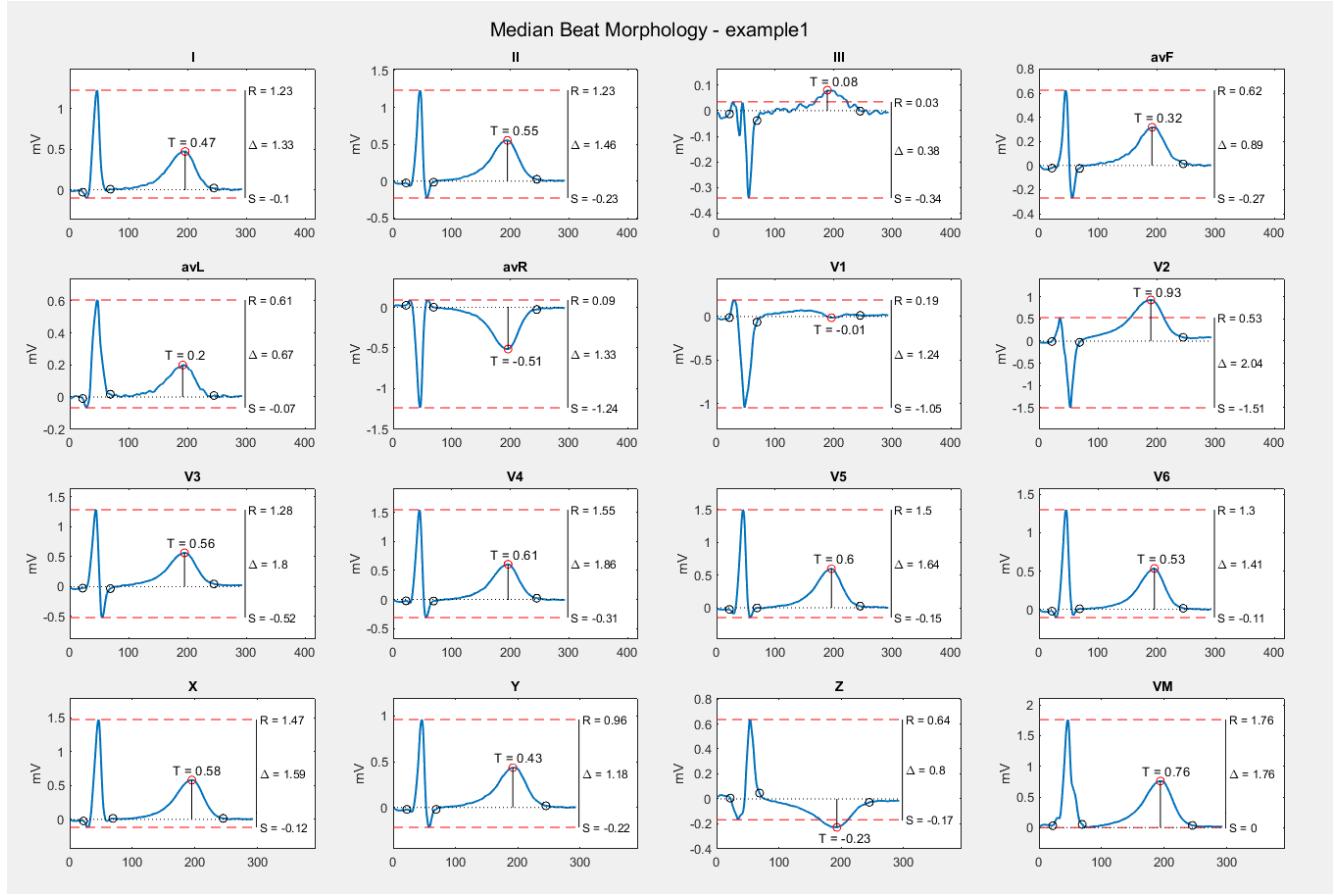


Figure 43: Measurements on 16 median beats. Values are in mV.

18.8 Animated VCG

An animated VCG can be generated by clicking the **Animate** button (GUI item **6.1.3**). The ‘Step’ textbox sets the number of samples that are advanced per frame.

18.9 X-, Y-, Z- Stats Figures

The X-, Y-, and Z- stats figures display information on the beats that make up the median X, median Y, and median Z beats, respectively. These figures are generated by clicking on the **X Stats**, **Y Stats**, or **Z Stats** buttons (GUI item **6.4.3**). Beat-by-beat QRS duration, QT interval, QRST area (SVG), absolute QRST area (SAI), and the individual beats (black tracings) that make up the median beat (green tracing) are shown with normalized cross correlation (NCC). The X-stats figure for `example1.xml` is shown here:

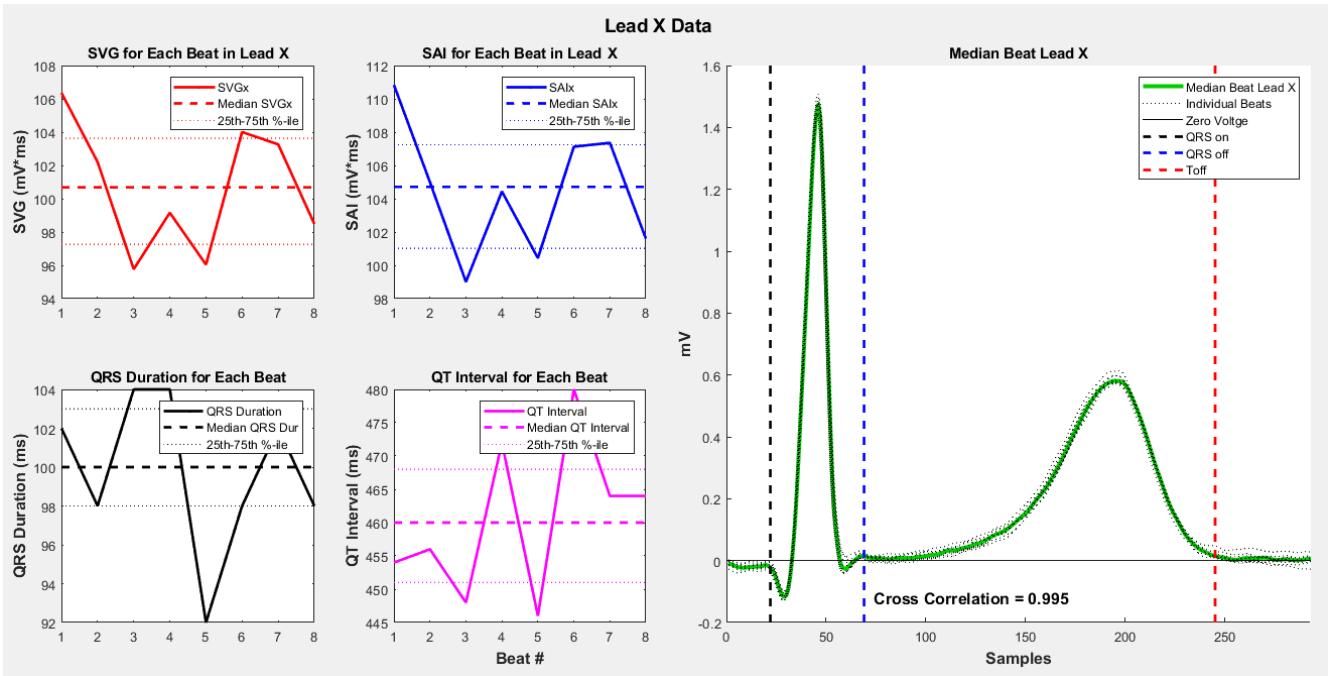


Figure 44: Individual beat stats for lead X in `example1.xml`. The QRS duration, QT interval, area under the QRST complex (SVG), and absolute area under the QRST complex (SAI) are shown. The right panel shows the median beat in green and the individual beats that make up the median beat in black. The NCC (0.995) is displayed.

18.10 Full VCG

This displays the “rhythm strip” VCG rather than the median beat VCG.

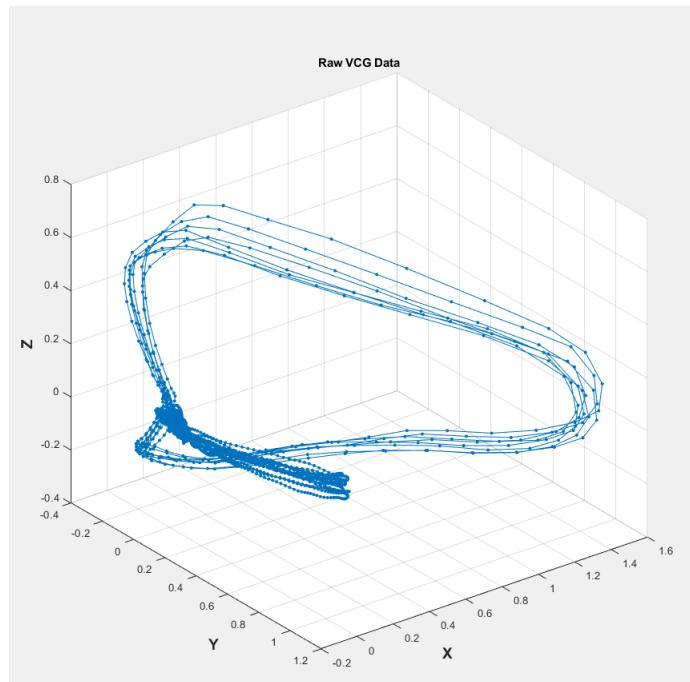


Figure 45: Raw VCG plotted in 3D for `example1.xml`.

18.11 Offsets

The **Offsets** button shows the effect of baseline correction, which is a process that attempts to set the TP segment, which is a true isoelectric interval of the ECG, to 0 voltage. An example of the offsets figure is shown in **Figure 25**. Further details can be found in **Chapter 13.2**.

18.12 Filtering

The **Filtering** button displays how the selected filtering parameters affects the loaded ECG. The original, unfiltered ECG signals are shown in black, and the signal post filtering (and baseline correction) is shown in red. The approximation of baseline wander is shown as a dashed blue line. An example filtering figure is shown here:

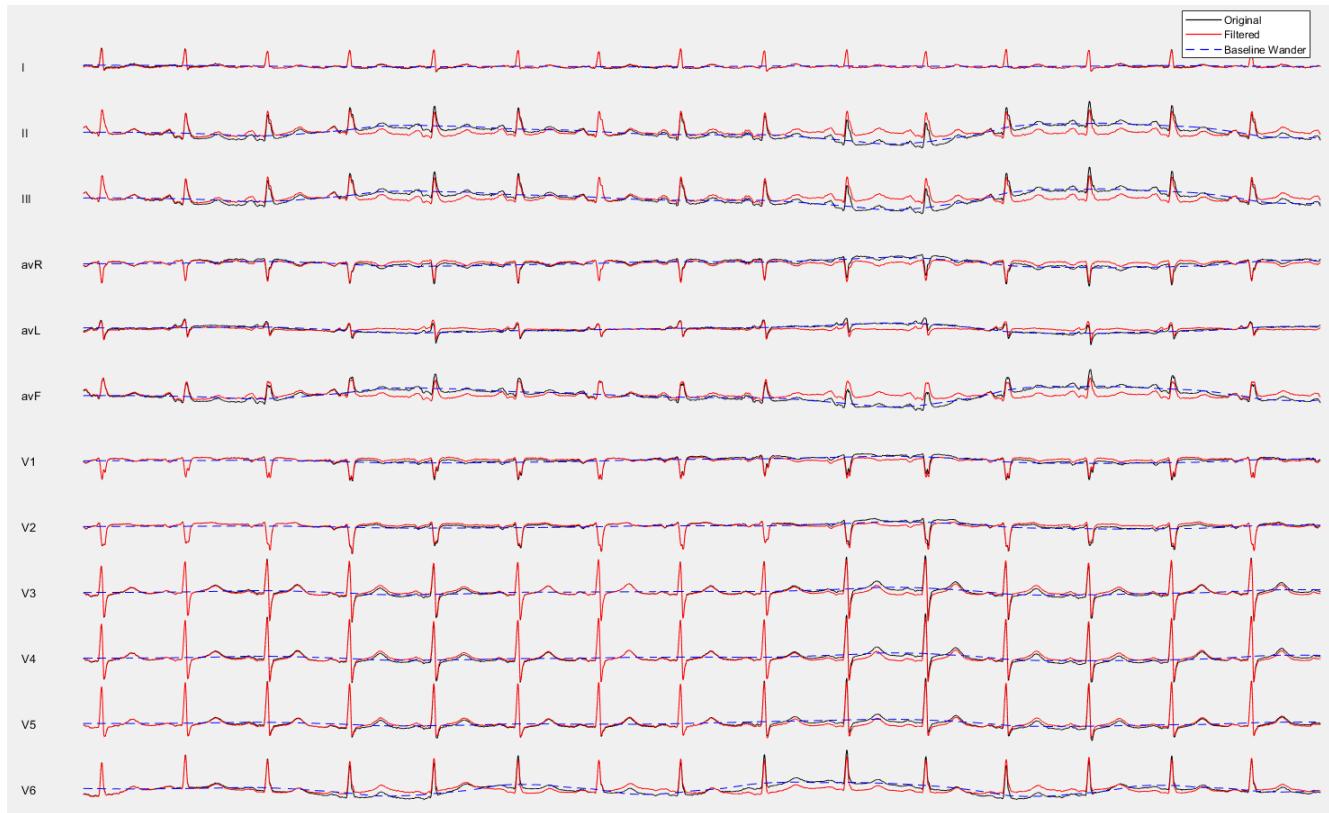


Figure 46: Filtering figure. The original, non-filtered, raw signal is shown in black, and the filtered signal is shown in red. The dashed blue line is the estimated baseline wander. In this example, note how leads II, III, avF, and V6 have significant baseline wander that is successfully removed with high-pass filtering. See filtering sub-figure (**Figure 47**) for additional detail.

In addition to the filtering figure shown above, clicking on the **Filtering** button brings up a sub-figure that displays the estimated signal to noise ratio (SNR) to estimate high frequency noise, and an estimation of low frequency noise/wander. *High* values of SNR are indicative of minimal high frequency noise, and *low* values of baseline wander estimates indicate minimal

baseline wander. The cutoffs that are used to indicate good quality (green boxes) vs poor quality (red boxes) are set with quality parameters (`hf_noise` and `lf_noise`) in the external file `quality_presets.csv`. See [Chapter 14](#) for additional information.

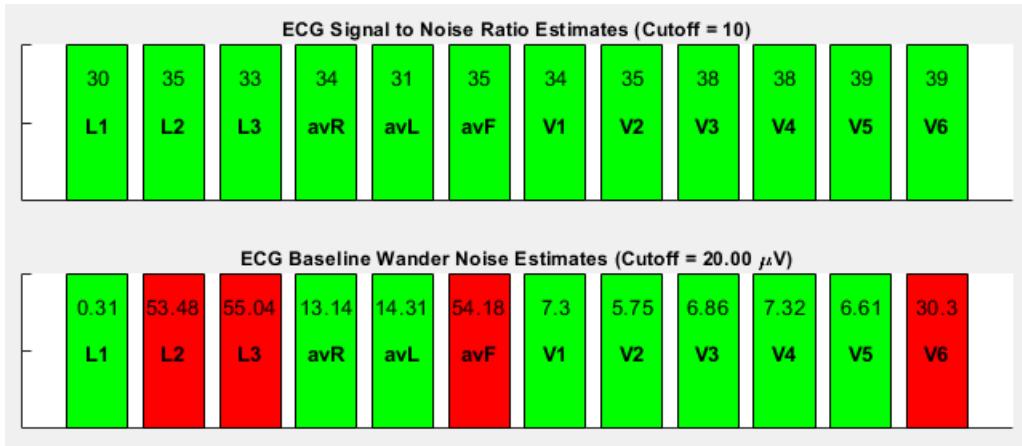


Figure 47: Filtering sub-figure for [Figure 46](#). Note how in [Figure 46](#) leads II, III, avF, and V6 have significant baseline wander, and the sub-figure shows these leads have low-frequency noise above the set cutoff of $20 \mu\text{V}$ (red bars).

18.13 Threshold

The `Threshold` button displays the R peak threshold figure which is described in detail in [Chapter 13.1](#) and [Figure 22](#).

18.14 Debug Figures

The `Debug` checkbox enables debug figures that show information on first pass and median beat annotation that can help troubleshoot ECGs that are not processing to see if specific annotation parameters need to be adjusted. When `Debug` is checked, clicking `Calculate` brings up a figure showing the annotation markings/search windows for the full VM lead:

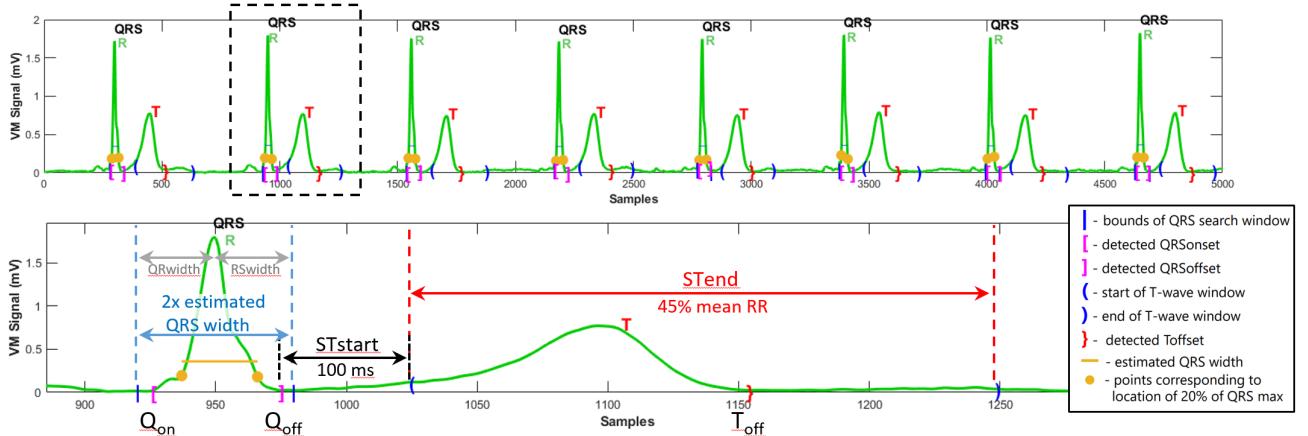


Figure 48: First pass annotation parameters and search windows. See **Chapter 16** for details.

As the median beat is annotated by a NN, the debug figure for median beat annotation shows the scores for each segment of the QRST complex being a “QRS complex”, “T wave”, or “other”:

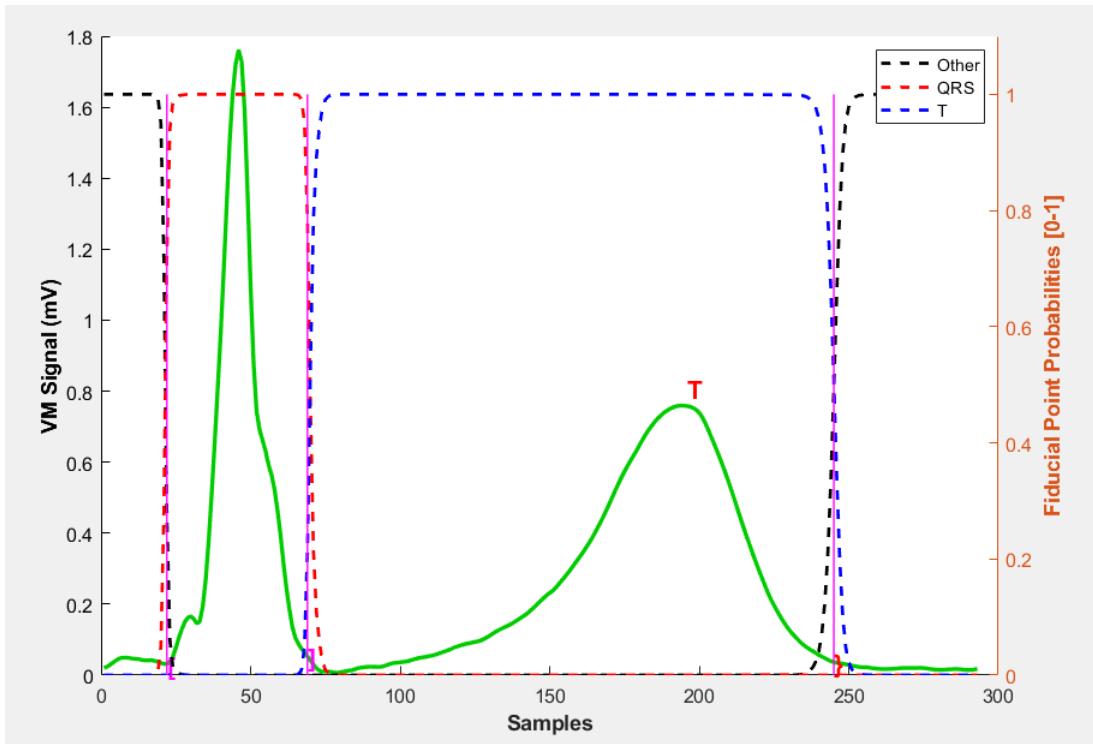


Figure 49: Debug figure for median beat annotation. The dashed lines are the NN predicted probabilities of a sample being a “QRS complex” (red), “T wave” (blue), or “other” (black). Each sample in the median beat signal is assigned the label that is the highest of the 3 probabilities. Q_{on} is set as the sample where “other” transitions to “QRS complex”, Q_{off} is set as the sample where “QRS complex” transitions to “T wave”, and T_{off} is set as the sample where “T wave” transitions to “other”. Q_{on} is marked with a [, Q_{off} is marked with a], and T_{off} is marked with a } similarly to first pass debug figures. In rare cases where multiple potential fiducial points are detected, logic is used to select the best point – see methods manuscript [1] for additional details.

18.15 Angle Conventions

The 3D angle conventions are shown visually in **Figure 50** below:

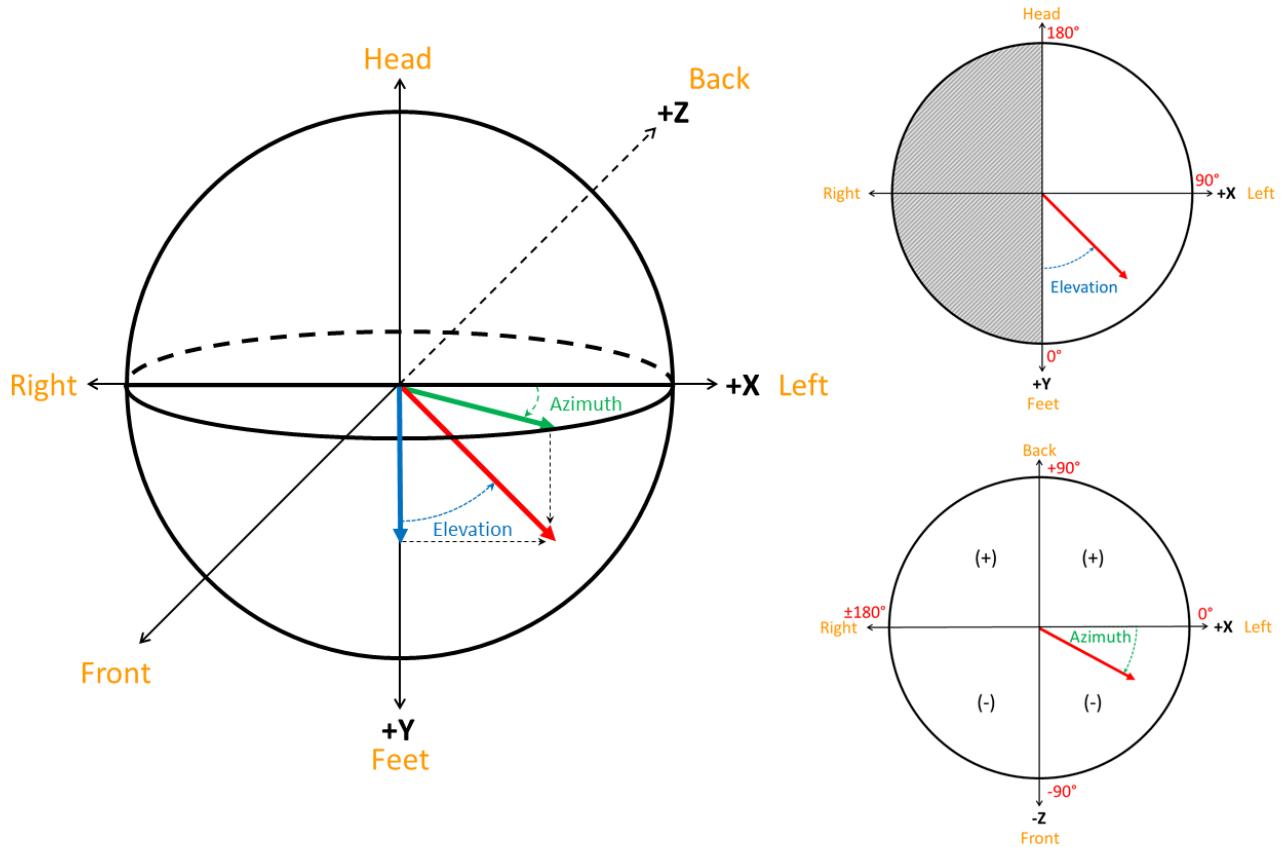


Figure 50: The following conventions for 3D angles are used by BRAVEHEART: Elevation is the angle in the frontal plane that can be between 0 and 180° . 0° points towards the feet and 180° points towards the head. Azimuth is the angle in the transverse plane that can be between 0 and $\pm 180^\circ$. Positive azimuth angles are posterior, and negative azimuth angles are anterior.

19 Annotation Parameter Presets

Presets for first pass fiducial point detection can be saved to allow rapid switching between multiple parameters if needed. For example, if you are looking at ECGs with long QT syndrome, the nominal value of `STend` which is ‘45%’ may result in missing the true ends of T waves, or if you want to look looking at tightly coupled PVCs, you may need to increase `maxBPM` from its nominal value of ‘150 bpm’ and decrease `pkthresh` from its nominal value of ‘95’. You could manually adjust the value of `STend`, `maxBPM`, and/or `pkthresh` in `Annoparams.m` or using the GUI, but using presets allows you to save certain groups of parameters for later use.

Presets can only be used with the GUI version of BRAVEHEART. An alternative to use of manual adjustment of annotation parameters or use of presets is to specify non-nominal annotation parameters in an `.anno` file which allows much finer control over ECG/VCG processing and annotation than can be set with a preset (see [Chapter 15](#)).

Presets are set via the external file `search_presets.csv`. The file contains 7 columns separated by commas. Column 1 is the preset name that shows up in the BRAVEHEART GUI, and the next 6 columns correspond to the values of `pkthresh`, `maxBPM`, `QRwidth`, `RSwidth`, `STstart`, and `STend`, in that order as shown here:

name,	pkthresh,	maxBPM,	QRwidth,	RSwidth,	STstart,	STend
Standard,	95,	150,	100,	100,	100,	45
PVCs,	85,	200,	150,	150,	150,	35
BBB/Paced,	95,	150,	150,	150,	150,	45
Bigeminy,	85,	170,	150,	150,	150,	70

To add a new preset, simply add a new line with a preset name and the appropriate values of `pkthresh`, `maxBPM`, `QRwidth`, `RSwidth`, `STstart`, and `STend` in the appropriate columns, save the file, and restart BRAVEHEART (presets are only loaded when the BRAVEHEART GUI initializes).

To use a preset, select the preset name from dropdown GUI item [3.5](#):

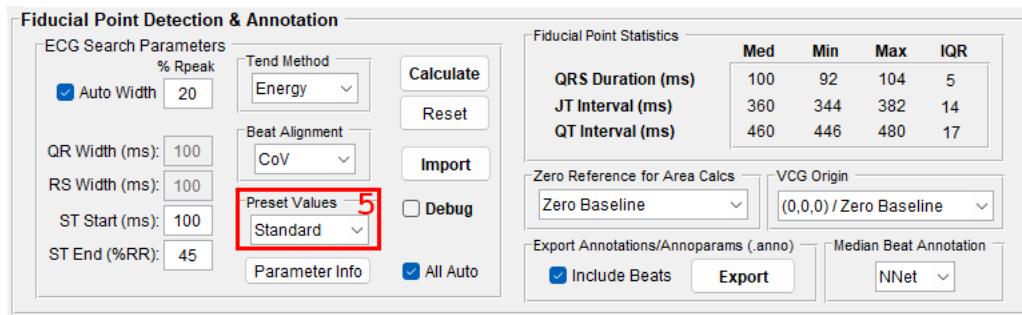


Figure 51: Preset dropdown in GUI

20 Normal Ranges

BRAVEHART can calculate normal ranges for a select number of VCG parameters based on age, gender, race, and BMI. Normal ranges were obtained by measuring VCG parameters on 3,301 patients with normal ECGs and no history of cardiovascular, pulmonary, or renal disease, and no abnormal cardiovascular imaging. A manuscript with further details is currently under review.

The following parameters have normal ranges which can be displayed in the GUI:

- SVG area magnitude – `svg_area_mag`
- SVG area azimuth – `svg_area_az` (see **Figure 50**)
- SVG area elevation – `svg_area_el` (see **Figure 50**)
- SVG area X – `svg_x`
- SVG area Y – `svg_y`
- SVG area Z – `svg_z`
- SAI QRST – `sai_qrst`
- SAI VM – `sai_vm`
- Area QRST angle – `qrst_angle_area`
- Peak QRST angle – `qrst_angle_peak`

Further details of each parameter can be found in **Chapter 22**.

21 ECG Format Information

BRAVEHEART can read a variety of ECG file formats. This section includes brief descriptions of the file formats that can be read by BRAVEHEART without modification. Additional file formats can be added as described in [Chapter 7](#).

Unformatted .txt

Unformatted text files (extension .txt) use `format = 'unformatted'` and load via the file `load_ecg.m`. These files contain 12 columns with data in the order of lead I, II, III, avR, avL, avF, V1, V2, V3, V4, V5, and V6. The sampling frequency is encoded in the file as the first value in each column, and the ECG signal data starts in row 2 for each column. The file's units are mV, so no conversion is needed. This is a simple file format, but the downside is that file sizes tend to be larger than if the same signals were stored using encoded .xml or other formats.

BIDMC .txt

BIDMC formatted text files (extension .txt) use `format = 'bidmc_txt'` and load via the file `load_ecg.m`. This file format is used to export ECGs using the legacy ECG system at BIDMC. Files contain 13 columns with the first column being the sample number starting at 1, and the next 12 columns being the data in the order of lead I, II, III, avR, avL, avF, V1, V2, V3, V4, V5, and V6. Sampling frequency is 500 Hz and is not encoded in the file. The values at each sample are in units where 1 unit = 5 μ V.

Prucka .txt

General Electric (GE) Prucka recording system formatted text files (extension .txt) use `format = 'prucka_txt'` and load via the file `load_ecg.m`. This file format is generated when exporting ECGs from the GE MacLab/Prucka electrophysiology recording system. These files contain 12 columns with data in the order of lead I, II, III, avR, avL, avF, V1, V2, V3, V4, V5, and V6. Sampling frequency is 997 Hz and is not encoded in the file. The file units are mV, so no conversion is needed.

MUSE .xml

GE MUSE XML files (extension .xml) use `format = 'muse_xml'` and load via the file `load_musexml.m`. Sampling frequency is 500 Hz and is encoded in the XML. Lead data are stored in the relevant XML sections in base64 encoding in units where 1 unit = 4.88 μ V which is also encoded in the XML. Files that have not been deidentified or had identifiers removed include age and gender encoded in the XML.

Philips .xml

Philips XML files (extension .xml) use `format = 'philips_xml'` and load via the file `load_philipsxml.m`. Sampling frequency is 500 Hz and is encoded in the XML. Lead data are stored in the relevant XML sections in base64 encoding followed by LZW compression, in units where 1 unit = 5 μ V which is also encoded in the XML. Files that have not been deidentified or had identifies removed include age and gender encoded in the XML.

HL7 .xml

HL7 XML files (extension .xml) use `format = 'hl7_xml'` and load via the file `load_hl7xml.m`. Sampling frequency, units per mV, and leads are all encoded within the XML file. Details of the HL7 format standards can be found at
https://www.amps-llc.com/uploads/2017-12-7/aECG_Implementation_Guide.pdf [12].

DICOM .dcm

DICOM files (extension .dcm) use `format = 'DICOM'` and load via the file `load_dicom.m`. Sampling frequency, units per mV, and leads are all encoded in the DICOM file. Details of the DICOM format standards can be found at
<https://www.dicomstandard.org/News-dir/ftsup/docs/sups/sup30.pdf> [13].
Note: `load_dicom.m` requires the MATLAB Image Processing Toolbox. If this toolbox is not available you will need to write your own function to load DICOM files.

ISHNE .ecg

International Society for Holter and Noninvasive Electrocardiology (ISHNE) files (extension .ecg) use `format = 'ISHNE'` and load via the file `load_ISHNE.m`. Sampling rate, signal resolution, and lead data are all encoded in the file. Details of the format can be found at
<http://thew-project.org/papers/Badilini.ISHNE.Holter.Standard.pdf> [14].

GE .mrq

GE Marquee ASCII files (extension .mrq) use `format = 'mrq_ascii'` and load via the file `load_mrq.m`. Sampling frequency is 500 Hz and is not encoded in the file. Units are in μ V.

Unformatted .csv

Unformatted comma separated value files (extension .csv) use `format = 'generic_csv'` and load via the file `load_generic_csv.m`. These files contain 12 columns with data in the order of lead I, II, III, avR, avL, avF, V1, V2, V3, V4, V5, and V6. Sampling frequency and units are not encoded in the file and must be specified in `ECG12.m` after loading.

22 Result Class Variables

Variables and their definitions for the 3 results classes are presented here. Detailed mathematical explanations and associated equations are available in the Methods Manuscript.

22.1 VCG Morphology Class (**VCG_Morphology.m**)

Variable	Description	Units
TCRT	Total Cosine R to T (range 0 - 1)	-
TCRT_angle	Angle from TCRT = $\text{acos}(\text{TCRT})$	deg
qrsloop_residual	SVD variance from fitting QRS loop to a plane (0 = perfect fit) = qrs_S3^2	-
qrsloop_rmse	RMSE for fit of QRS loop to best fit plane (0 = perfect fit)	mV
qrsloop_roundness	QRS loop roundness. 1 = perfect circle, larger values are increasingly elliptical = $\text{qrs_S1}/\text{qrs_S2}$	-
qrsloop_area	Area of QRS loop	mV
qrsloop_perimeter	Length of QRS loop projected into best fit plane	mV^2
tloop_residual	SVD variance from fitting T loop to a plane (0 = perfect fit) = t_S3^2	-
tloop_rmse	RMSE for fit of T loop to best fit plane (0 = perfect fit)	mV
tloop_roundness	T loop roundness. 1 = perfect circle, larger values are increasingly elliptical = $\text{t_S1}/\text{t_S2}$	-
tloop_area	Area of T loop	mV
tloop_perimeter	Length of T loop projected into best fit plane	mV^2
qrs_loop_normal	Unit vector normal to best fit QRS loop plane	-
t_loop_normal	Unit vector normal to best fit T loop plane	-
qrst_dihedral_ang	Dihedral angle between best fit QRS loop and T loop planes	deg
qrs_S1	1st singular value of QRS loop	-
qrs_S2	2nd singular value of QRS loop	-
qrs_S3	3rd singular value of QRS loop	-
t_S1	1st singular value of T loop	-
t_S2	2nd singular value of T loop	-
t_S3	3rd singular value of T loop	-
qrs_var_s1_total	% of total variance made up by 1st QRS singular value	%
qrs_var_s2_total	% of total variance made up by 2nd QRS singular value	%
qrs_var_s3_total	% of total variance made up by 3rd QRS singular value	%
t_var_s1_total	% of total variance made up by 1st T singular value	%
t_var_s2_total	% of total variance made up by 2nd T singular value	%
t_var_s3_total	% of total variance made up by 3rd T singular value	%

22.2 VCG Calculation Class (**VCG_Calc.m**)

Variable	Description	Units
qrs_int	QRS duration	ms
qt_int	QT interval	ms
svg_x	X component of SVG = XQ_area + XT_area	mV·ms
svg_y	Y component of SVG = YQ_area + YT_area	mV·ms
svg_z	Z component of SVG = ZQ_area + ZT_area	mV·ms
sai_x	Area under the absolute value of the median X QRST complex	mV·ms
sai_y	Area under the absolute value of the median Y QRST complex	mV·ms
sai_z	Area under the absolute value of the median Z QRST complex	mV·ms
sai_qrst	SAI QRST = sai_x + sai_y + sai_z	mV·ms
sai_vm	Area under the absolute value of the median VM QRST complex	mV·ms
q_peak_mag	Magnitude of peak QRS vector	mV
q_peak_az	Azimuth of peak QRS vector	deg
q_peak_el	Elevation of peak QRS vector	deg
t_peak_mag	Magnitude of peak T wave vector	mV
t_peak_az	Azimuth of peak T wave vector	deg
t_peak_el	Elevation of peak T wave vector	deg
svg_peak_mag	Magnitude of the sum of peak QRS and peak T vectors ("peak SVG")	mV
svg_peak_az	Azimuth of the "peak SVG" vector	deg
svg_peak_el	Elevation of the "peak SVG" vector	deg
q_area_mag	Magnitude of QRS area vector ([XQ_area, YQ_area, ZQ_area])	mV·ms
q_area_az	Azimuth of QRS area vector	deg
q_area_el	Elevation of QRS area vector	deg
t_area_mag	Magnitude of T-wave area vector [XT_area, YT_area, ZT_area]	mV·ms
t_area_az	Azimuth of T-wave area vector	deg
t_area_el	Elevation of T-wave area vector	deg
svg_area_mag	Magnitude of the SVG vector [svg_x, svg_z, svg_z]	mV·ms
svg_area_az	Azimuth of the SVG vector	deg
svg_area_el	Elevation of the SVG vector	deg
qrst_angle_area	Area QRST angle: 3D angle between area QRS and area T wave vectors	deg
qrst_angle_peak	Peak QRST angle: 3D angle between peak QRS and peak T wave vectors	deg
qrst_angle_peak_frontal	Projection of area QRST angle into frontal plane	deg
qrst_angle_area_frontal	Projection of peak QRST angle into frontal plane	deg
XQ_area	Area under median X QRS complex	mV·ms
YQ_area	Area under median Y QRS complex	mV·ms
ZQ_area	Area under median Z QRS complex	mV·ms
XT_area	Area under median X T wave	mV·ms
YT_area	Area under median Y T wave	mV·ms
ZT_area	Area under median Z T wave	mV·ms

Variable	Description	Units
XQ_peak	Value of median X QRS complex at time of maximum distance from origin	mV
YQ_peak	Value of median Y QRS complex at time of maximum distance from origin	mV
ZQ_peak	Value of median Z QRS complex at time of maximum distance from origin	mV
XT_peak	Value of median X T wave at time of maximum distance from origin	mV
YT_peak	Value of median Y T wave at time of maximum distance from origin	mV
ZT_peak	Value of median Z T wave at time of maximum distance from origin	mV
speed_max	Maximum speed across the entire VCG loop	mV/ms
speed_min	Minimum speed across the entire VCG loop	mV/ms
speed_med	Median speed across the entire VCG loop	mV/ms
time_speed_max	Time after QRS onset of maximum VCG speed	ms
time_speed_min	Time after QRS onset of minimum VCG speed	ms
speed_qrs_max	Maximum speed across the QRS VCG loop	mV/ms
speed_qrs_min	Minimum speed across the QRS VCG loop	mV/ms
speed_qrs_med	Median speed across the QRS VCG loop	mV/ms
time_speed_qrs_max	Time after QRS onset of maximum QRS speed	ms
time_speed_qrs_min	Time after QRS onset of minimum QRS speed	ms
speed_t_max	Maximum speed across the T wave loop	mV/ms
speed_t_min	Minimum speed across the T wave loop	mV/ms
speed_t_med	Median speed across the T wave loop	mV/ms
time_speed_t_max	Time after QRS onset of maximum T-wave speed	ms
time_speed_t_min	Time after QRS onset of minimum T-wave speed	ms
qrst_distance_area	Distance between the area QRS and area T vectors	mV
qrst_distance_peak	Distance between the area QRS and area T vectors	mV
vcg_length_qrs	Length of QRS VCG loop	mV
vcg_length_t	Length of T wave VCG loop	mV
vcg_length_qrst	Length of QRST VCG loop = vcg_length_qrs + vcg_length_t	mV
vm_tpeak_time	Time after QRS onset of peak of median VM Twave	ms
vm_tpeak_tend_abs_diff	Time difference between T wave peak and T wave end in median VM lead	ms
vm_tpeak_tend_ratio	Ratio between time of T wave peak and time of T wave end in median VM lead	–

22.3 Lead Morphology Class (**Lead_Morphology.m**)

[lead] refers to any of the 16 leads (L1, L2, L3, avR, avL, avF, V1-V6, X, Y, Z, VM)

Variable	Description	Units
[lead]_r_wave	Magnitude of R wave on median beat of [lead]	mV
[lead]_s_wave	Magnitude of S wave on median beat of [lead]	mV
[lead]_rs_wave	Magnitude of entire QRS complex = [lead]_r_wave + abs([lead]_s_wave)	mV
[lead]_rs_ratio	Ratio of R wave to magnitude of entire QRS complex = [lead]_r_wave / [lead]_rs_wave	–
[lead]_sr_ratio	Ratio of S wave to magnitude of entire QRS complex = [lead]_s_wave / [lead]_rs_wave	–
[lead]_t_max	Maximum magnitude of T wave in [lead]	mV
[lead]_t_max_loc	Timing of T wave maximum (after QRS onset) in [lead]	ms

23 Annotation Parameter Links with GUI

This section contains the links between parameters in `Annoparams.m` and where the parameter value is editable in the BRAVHEART GUI.

- `maxBPM` ↔ GUI item **1.6** textbox
- `pkthresh` ↔ GUI item **1.7** textbox
- `lowpass` ↔ GUI item **1.3** checkbox
- `highpass` ↔ GUI item **1.4** checkbox
- `wavelet_level_lowpass` ↔ GUI item **1.3** dropdown
- `wavelet_level_highpass` ↔ GUI item **1.4** dropdown
- `wavelet_name_lowpass` ↔ GUI item **1.3** dropdown
- `wavelet_name_highpass` ↔ GUI item **1.4** dropdown
- `baseline_correct_flag` ↔ GUI item **1.5** checkbox
- `transform_matrix_str` ↔ GUI item **1.2** dropdown
- `baseline_flag` ↔ GUI item **3.12** dropdown
- `origin_flag` ↔ GUI item **3.13** dropdown
- `autoMF` ↔ GUI item **3.1** checkbox
- `autoMF_thresh` ↔ GUI item **3.1** textbox
- `MF_width` ↔ NA
- `QRwidth` ↔ GUI item **3.2** textbox
- `RSwidth` ↔ GUI item **3.2** textbox
- `STstart` ↔ GUI item **3.2** textbox
- `STend` ↔ GUI item **3.2** textbox
- `spike_removal` ↔ GUI item **1.8** checkbox
- `pacer_spike_width` ↔ GUI item **1.8** textbox
- `pacer_mf` ↔ NA
- `pacer_thresh` ↔ GUI item **1.8** textbox
- `align_flag` ↔ GUI item **3.4** dropdown
- `cov_mf` ↔ NA
- `cov_thresh` ↔ NA
- `shiftq` ↔ NA
- `shifttt` ↔ NA
- `Tendstr` ↔ GUI item **3.3** dropdown
- `median_reanno_method` ↔ GUI item **3.15** dropdown
- `outlier_removal` ↔ GUI item **9.4** checkbox
- `modz_cutoff` ↔ GUI item **9.3** textbox
- `pvc_removal` ↔ GUI item **9.10** checkbox
- `pvcthresh` ↔ GUI item **9.5** textbod
- `rmse_pvcthresh` ↔ GUI item **9.6** textbox
- `keep_pvc` ↔ GUI item **9.7** radio button
- `blanking_samples` ↔ GUI item **6.5.1** textbox
- `debug` ↔ GUI item **3.10** checkbox

NA = Parameter cannot be adjusted via GUI

24 Testing Framework

It is important to be certain that any changes to the BRAVEHEART source code have not broken or otherwise adversely affected the main functions of the software, including ECG processing/filtering, annotation, PVC/outlier removal, manual beat removal/editing, and calculations. In order to ensure that any changes have not inadvertently affected critical parts of the BRAVEHEART source code, we have provided a testing framework that can be used to validate any changes that are made. The testing framework is located in `test_braveheart.m`. This is a very long file that contains a multitude of tests designed to determine if there are any errors in any parts of the BRAVEHEART ECG/VCG processing pipeline.

The testing framework can be run by opening the `test_braveheart.m` file and clicking the “Run Tests” icon in the Editor toolbar, or by typing `runtests("test_braveheart")` in the MATLAB command line. The testing functions will run and at the end you will get a report about how many functions passed or failed. If the software is functioning properly, all tests should pass. If a test fails, MATLAB provides information on the error that can be used to troubleshoot.

If you make changes to some of the BRAVEHEART core functions such as signal filtering or annotation, it is possible that the tests may fail even though BRAVEHEART is functioning properly within the parameters of this new code. This is because functions like filtering and annotation affect all downstream processing and measurements. The testing framework assumes that the **current** filtering and annotation functions are being used, and the measurements that are checked as part of testing will therefore generate errors if alternate filtering/annotation functions are used. If such changes are made, the testing framework expected outputs can be updated.

The testing framework will not automatically update if new parameters are added to the BRAVEHEART results classes (see **Chapter 9**), but adding new parameters will not break the testing framework.

The BRAVEHEART Github automatically runs the testing framework for all commits to ensure that the most up-to-date version of code in the Github repository will function accurately and without errors.

25 Troubleshooting/Help/FAQs

25.1 My ECG Won't Load

If an ECG won't load, first check that the correct file format is selected, and try to load another ECG of the same format to ensure that the format is set correctly.

The most common reason for an ECG not loading is significant noise or artifact that interferes with QRS peak localization (because QRS peak localization depends on thresholding the full VM signal, large, focal artifacts can result in almost all of the ECG being below the percentile value set by `pkthresh`). By enabling **Safe Mode** (see **Chapter 25.2** below) in the GUI

Utilities section (GUI item **6.6.7**), after the ECG signals are loaded you can view the 12-lead ECG by clicking on the **12L ECG** (GUI item **7.1**). This may reveal a large area of noise/artifact, or significant baseline wander.

The first thing to try is to decrease the value of `pkthresh` by lowering the value in the 'Peak Threshold' textbox in GUI section **1.6** to a very low value around 10. In fact, if the ECG throws an error but loads in Safe Mode (GUI item **6.6.7**), without changing any other settings, the value of `pkthresh` is likely the cause of the error, as Safe Mode also automatically lowers `pkthresh` to 10 in addition to disabling processing that occurs after filtering. If this resolves the error, you may need to increase `pkthresh` somewhat to avoid overcalling QRS peaks. Use of the **Threshold** button (GUI item **1.15** – see **Chapter 13.1** and **Figure 22**) can help visualize what the QRS peak detector is doing.

If adjusting `pkthresh` does not resolve the issue, next try to lower the the high-pass filtering level (GUI item **1.4**) by 1-2 levels. This often helps remove any low-frequency wander by increasing the high-pass filter cutoff frequency. However, lowering the high-pass filtering level (and therefore increasing the high-pass filter cutoff frequency) too much can adversely affect measurements by distorting the QRST complex. If filtering is removing frequencies between 0.5-40 Hz there will be some concern that the QRST complex may be distorted by filtering [2].

If there is a focal section of the ECG that is causing errors, another option is to load the ECG in Safe Mode and then use the **ECG Splitter** button/function in the **Utilities** section (GUI item **6.6.5**). The abnormal area of the ECG can be cut out and the remainder of the ECG without the severe artifact can be analyzed. It should be noted that using a shortened ECG will likely affect the measured values slightly because baseline correction depends on the calculated HR.

25.2 Safe Mode

Safe mode can help in cases where an ECG will not load. As noted above, this is often due to significant noise and artifact that cause problems with initial R peak detection. Clicking ‘Safe Mode’ in GUI item **6.6.7** disables all processing after filtering and decreases the value of `pkthresh` to 10 to increase the chances that the ECG can load without an error. This can allow you to visualize the ECG/VCG using GUI section 7.

25.3 The ECG Loads but I get an Error When Press Calculate

This is usually due to an issue with first pass or median beat annotation. Attempt to troubleshoot this issue in the same was as shown above when dealing with ECGs that won’t load. Checking the ‘Debug’ figures (see **Chapter 25.6**) can also help.

25.4 A Measured Parameter Returns as NaN

This error is usually due to noise/artifact which can be dealt with as noted above. The other reason that this may occur is if a median beat fiducial point was not found. This most commonly occurs if the median beat annotater did not find a T_{off} . This can occur if the ECG is very noisy, or in good quality ECGs if the QT interval is long or if the QRS morphology is atypical to the point where the QRS width and/or QT search windows are too short. If this occurs, using the `Debug` option (see **Chapter 25.6**) can help troubleshoot, and often adjusting the annotation parameters will allow the annotater to find all fiducial points. In rare occasions when the neural network median beat annotater fails but the ECG quality is reasonable, switching `median_reanno_method` from `'NNNet'` to `'Std'` may be useful. The overall accuracy of the `'Std'` median beat annotater is significantly lower than the `'NNNet'` median beat annotater, especially for low amplitude T waves or atypical QRST morphologies.

25.5 Error Logs

When using the GUI, under **Utilities** there is an option for **Error Logging** (GUI item **6.6.3**). If this is checked, loading an ECG will generate a text file called `braveheart_error_log_<date_time>.txt` which includes information on the file, annotations parameters, and any errors that are generated. Note that logging is started during ECG loading, so to start logging errors you will need to load/reload the ECG after checking **Error Logging**. We are happy to assist with interpretation of error logs if needed - contact us at braveheart.ecg@gmail.com.

25.6 Debugging Annotation Figures

The **Debug** checkbox (GUI item 4.9) enables graphical display of both first pass and median beat annotation, and can be helpful when troubleshooting ECGs that cause errors or do not annotate properly. Debug figures can help determine how to adjust annotation parameters to allow the ECG to successfully process. When **Debug** is checked and **Calculate** is pressed, figures showing annotation windows for first pass annotation and neural network predicted fiducial point probabilities are displayed. See **Chapter 16**, **Chapter 16.3**, **Figure 30**, and **Figure 49** for further details. These figures can often help you determine if adjustment of annotation parameters will resolve any errors.

25.7 Frequently Asked Questions

1. Can BRAVEHEART use scanned ECGs in **.jpg** or **.pdf** format?

No – BRAVEHEART requires ECG data to be in some raw, digitized format. The formats that are included with BRAVEHEART are described in **Chapter 21**, and new formats can be added as needed as described in **Chapter 7**. Construction of VCGs also requires simultaneous recording of the 8 independent ECGs leads (I, II, V1–V6), but if you have printed ECGs of decent quality that have simultaneous rhythm strips of at least the 8 independent leads, consider using a program to digitize your ECG [15] and then import the digitized version into BRAVEHEART.

2. How should I cite use of the BRAVEHEART software?

Please site our methods manuscript as methods manuscript [1].

3. Can BRAVEHEART annotate or measure parameters from P waves?

Not currently, although we are in the process of adding P wave annotation which will allow assessment of P wave parameters. P wave annotation/processing is more complex than QRST annotation due to the fact that a cardiac cycle always has a single QRST complex in a predictable order, but atrial activity can be completely dissociated from ventricular activity (or absent completely) and, in general, P waves are lower amplitude signals with a lower signal to noise ratio.

4. I don't have MATLAB, but I need to add a new ECG format, transformation matrix, or parameter. What can I do?

Contact us at braveheart.ecg@gmail.com and we will try to assist you.

5. I found a bug/error. How can I tell you whats wrong?

Contact us at `braveheart.ecg@gmail.com` with as many details as possible (and possibly an error log – see **Chapter 25.5**) and we will try to resolve the issue.

26 External Code/Files

BRAVEHEART uses some existing open-source code which includes:

- draggable – Francois Bouffard (2023)
<https://www.mathworks.com/matlabcentral/fileexchange/4179-draggable>,
MATLAB Central File Exchange. Retrieved February 5, 2020.
- LZW Compression Algorithm – Giuseppe Ridinò (2023)
<https://www.mathworks.com/matlabcentral/fileexchange/4899-lzw-compression-algorithm>,
MATLAB Central File Exchange. Retrieved June 1, 2022.
- Sierra ECG Tools – David D. Salcido and Christopher A. Watford (2014).
<https://github.com/sixlettervariables/sierra-ecg-tools>,
Retrieved June 1, 2022.

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- [12] HL7 aECG Implementation Guide.
[https://www.amps-llc.com/uploads/2017-12-7/aecg_implementation_guide\(1\).pdf](https://www.amps-llc.com/uploads/2017-12-7/aecg_implementation_guide(1).pdf) [Accessed Dec. 6, 2022].
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