ECG Wiz Guide

BACKGROUND

An electrocardiogram (ECG) is a waveform signal characterizing the electrical activity of the heart over time. In human subjects, ECG is generally recorded using electrodes placed on the skin. Conventionally, to obtain comprehensive information about the heart, 12-lead ECG data (12 ECG signals) is acquired by attaching 10 electrodes at various positions on the chest and limbs.

In cardiology, acquisition and analysis of ECG data is routinely undertaken to diagnose and assess life-threatening conditions such as heart failure, atrial fibrillation (AF), and myocardial infarction (heart attack).

Normal heart rhythm produces three key ECG features: (i) a P-wave, (ii) a QRS-complex, and (iii) a T-wave. The R-wave or R-peak of the QRS complex is the most dominant feature in an ECG signal that characterizes the heartbeat and its rhythm.

The number of heartbeats per minute or heart rate (HR) in beats per minute (BPM) can be calculated by dividing 60 by the mean of consecutive R-peak to R-peak intervals or RR intervals measured in seconds. Similarly, in its simplest form, heart rate variability (HRV) can be computed in milliseconds (ms) by multiplying 1000 by the standard deviation of consecutive RR intervals measured in seconds. Thus, HRV is a measure of the variation in the time intervals between heartbeats. Research has shown that HRV characterizes the autonomic nervous system and cardiovascular system responses.

In human adults, a resting HR in the 60-100 BPM range is generally considered normal. This range may however vary for different individuals based on their overall physiology and fitness levels. Nonetheless, in cardiology, a HR lower than 60 BPM is flagged as abnormal and is referred to as bradycardia. Similarly, a resting HR of over 100 BPM is also flagged as abnormal and is referred to as tachycardia. The presence of bradycardia and/or tachycardia may point towards a number of conditions such as coronary artery disease, hypothyroidism, hyperthyroidism, and hypertension.

The issue of normal range of HRV in humans is more debatable. However, research studies report it to be roughly in the 10-60 ms range for normal subjects when measured via standard deviation. Abnormally low and/or high HRV could point to a variety of conditions such as mental stress, depression, onset of septicemia, and AF.

With advances in computing power and growing popularity of personal computers, tablets, and smartphones, more and more ECG data is being acquired by and analyzed on these devices. Therefore, these devices act as information extraction tools and decision support systems for a variety of individuals including scientists, students, biomedical engineers, physicians, and fitness enthusiasts.

The main challenge to the accurate analysis of ECG data on a computing device is the presence of noise in this data. Noise in ECG data could arise from a number of disparate sources including the type of electrodes employed (dry or gel), power line interface (50-60 Hz noise), motion artifacts, physiological noise (for example, AF), and other noise (for example, baseline wander). Thus, non-interactive and un-adjustable analysis algorithms running on these devices will often produce erroneous results for noisy ECG data.

ECG WIZ SUMMARY

ECG Wizard (Wiz) is a novel, versatile, robust, and fully interactive iOS App that enables visualization, digital signal processing (DSP), and analysis of high-frequency ECG waveform data. It allows users to transform, clean, and process ECG data based on individual characteristics of each recording. This enables ECG Wiz to achieve a high degree of accuracy in performing analysis tasks like R-peak detection and HR/HRV evaluation.

In the paid version, users can load their own digital ECG waveform data into the App via a digital signal file or via an input console where the ECG signal values can be typed in or pasted. They can then eyeball the data via scrollable/zoomable charts, change input data sampling frequency (re-sample the data), filter/clean the waveform data using various digital filters, detect ECG R-peaks by applying different thresholds, perform physiological and statistical cleaning of heartbeats, and evaluate HR and standard deviation-based HRV. Finally, users can send back processed data and results to themselves by email and/or save this information on their phones or cloud applications like Dropbox. The export feature allows users to transfer their data to other devices/platforms where they can review it and perform further analyses as required.

In the free version of the App, users can load, visualize, analyze, and export results for 20 sample ECG waveform datasets.

ECG WIZ DETAILS

Input Data: ECG Wiz only analyzes single-lead data. That is, users cannot analyze multi-lead ECG data simultaneously with the App. In principle, the App can be used for analyzing data from any one of the 12 ECG leads at a time.

Data Format: ECG Wiz can load, read, and parse tab-delimited and/or comma separated values (CSV) numeric data. That is, the App can work with digital ECG waveform data presented to it in a tabular form, whereby the delimiter is a tab and/or a comma. The App expects this data to consist of two fields: (i) time in seconds (X-values) and (ii) ECG value (Y-values). The first five entries of tab-delimited data would look like the following:

0.000 -6.5902
0.004 -12.359

0.008 -13.006
0.012 -19.095
0.016 -33.727

Since field (i) comprises the timestamp in seconds, the entries in it should be monotonically increasing as per the sampling rate of the digital ECG recording. For example, for a sampling frequency (Fs) of 250 Hz, the first five time-stamp entries in seconds would be [0.000, 0.004, 0.008, 0.012, 0.016]. The App will check that the time-stamp entries are increasing and contain no repeated values. In case, these conditions are not met, the App will throw an error and ask the user to check the time-stamp entries of their digital ECG data. Finally, the App will also throw an error for any data formats that it does not recognize and/or cannot parse.

Sample Files: In the App's free version, users can play with 20 sample ECG waveform data files. These files have been chosen from the PhysioBank ATM (https://physionet.org/cgi-bin/atm/ATM). Users can load any of these files into ECG Wiz and carry out all analyses including data export to fully understand the App's functionality.

User Data: In ECG Wiz's paid version, users can upload and analyze their own data. User data can be inputted into the App: (i) Via tab-delimited/CSV files with a .TXT/.CSV extension and (ii) Via a data input console where users can type in or paste signal values.

To load data from a user file, tap on the "Tap to load data…" button, then tap on the browse button on the right to browse and load the desired signal file. The App will load data from all correctly formatted files that have a .TXT and/or .CSV extension.

For typing or pasting user data, tap on the "Tap to load data…" button, then tap on the console button on the right to open the data input console. Enter signal values into the data input console as per the correct format and click on the "Done" button.

Please note that the App will check all incoming user data and proceed with the analysis only if the data format is correct (see Data Format section for details).

Input Data Sampling Frequency: The App will allow users to load ECG waveform data that have a sampling frequency range of 100-1000 Hz. That is, the App will check the sampling frequency of incoming ECG waveform data and throw an error if the signal sampling frequency is less than 100 Hz or more than 1000 Hz. This is done for optimizing the App's performance and because 100-1000 Hz is a reasonable sampling frequency range for ECG waveform data.

Input Data Duration: The App will allow users to load ECG waveform data that has a duration range of 5-75 seconds (s). The App will check the duration of incoming ECG waveform data and throw an error if the signal duration is less than 5 s or more than 75 s. Again, this is done for optimizing the App's performance and because 5-75 s is a reasonable timeframe for analyzing ECG waveform data.

Charting: ECG Wiz generates fully interactive charts for all waveform data. All charts are synchronized on the x-axis that displays data duration in seconds. Users can pinch the charts

horizontally to zoom in and zoom out from them. Users can also scroll the zoomed charts horizontally in both forward and backward directions. Finally, double tapping on any of the synchronized charts brings the charts to their original un-zoomed state. The interactive charting feature of the App allows a complete and comprehensive visualization and review of all data.

Smart Control Menu: ECG Wiz has a smart control menu that is movable and vertically pinchable to reduce and increase its height. This menu is also tappable whereby each double tap reduces and increases its height. The smart control menu thus never comes in the way of visualizing processed data on charts while various parameters are being changed and fine-tuned.

Data Re-Sampling: ECG Wiz employs the cubic spline interpolation method to change the sampling frequency of waveform data. Interpolating ECG waveform data with the cubic spline naturally smooths and augments QRS fiducial points, thus enabling more accurate R-peak detection.

With the Re-Sample slider in the control menu, users can change the signal sampling frequency in the 100-1000 Hz range in steps of 25 Hz.

The App, by default, re-samples all loaded ECG waveform data to 250 Hz.

Digital Filtering: The App enables users to clean ECG waveform data using Butterworth zero-lag infinite impulse response (IIR) second order digital filtering. This filtering technique ensures that there is no phase shift in the filtered signal relative to the original signal. Moreover, it also ensures that there is minimum boundary distortion in the filtered signal. These features are important and desirable in ECG processing and accurate R-peak detection.

Users can choose any of the three types of filters through the filter tab in the control menu: (i) band-pass filter (BPF), (ii) low-pass filter (LPF), and (iii) high-pass filter (HPF). Users can also enter the desired filter cut-off frequencies F_L (lower cut-off in Hz) and F_H (higher cut-off in Hz) in the text fields provided below the filter tab.

Users also have the option of not filtering the ECG signal by choosing NONE from the filter tab.

Default filtering is set to BPF with a passband of 2-25 Hz.

Data Trimming: Sometimes we encounter distortion or noise at the ECG signal boundaries. That is, distortion at the very beginning and/or at the very end of the ECG signal. This noise may arise because of several factors. For example, due to: (i) switching the ECG device ON or OFF, (ii) the point at which the signal is truncated, and (iii) signal filtering.

In view of the above difficulty, ECG Wiz allows users to trim or delete up to 25% of the signal starting samples (left trimming) and up to 25% of the signal ending samples (right trimming). For example, if a signal contains 100 samples, a left trimming of 10% will remove the first 10 samples, leaving a total of 90 samples. If this is followed by a right trimming of 10%, the last 9 samples will be removed, leaving a total of 81 samples.

With the Trim Left and/or Trim Right sliders in the control menu, users can choose the desired signal trimming in the 0-25% range in steps of 0.5%.

The App, by default, does not trim any data.

Signal Polarity: Sometimes, ECG signal polarity is reversed, that is, the QRS complexes are inverted. Such an inversion may arise due to factors like electrode configuration, electrode placement, and filtering. As a result, peak detection algorithms may not be able to detect the R-peaks accurately.

In view of the above difficulty, ECG Wiz allows users to reverse the polarity of the ECG waveform data via a simple ON/OFF switch. Switching ON the Reverse Polarity switch in the control menu reverses the polarity of the ECG signal. Switching OFF the Reverse Polarity switch restores the polarity of the ECG signal to its original state.

R-Peak Detector: The App uses proprietary algorithms based on the discrete Fourier transform (DFT) to generate a robust peak detector for the ECG signal. This peak detector augments only the QRS complexes in the ECG signal while suppressing other features and/or noise.

The peak detector plot is displayed below the interpolated and filtered ECG waveform data. A horizontal red line at Y = 0 is also displayed on this peak detector plot. The position of this red line on the peak detector plot helps in ECG R-peak detection. The peak detector plot moves closer to and/or farther away from the red horizontal line based on a variable called the peak detection threshold. That is, reducing this threshold moves the peak detector plot towards the horizontal red line while increasing this threshold moves the peak detector plot away from the horizontal red line.

With the Peak Threshold slider in the control menu, users can choose the desired peak detection threshold in the 0-1 range in steps of 0.01 for accurate R-peak detection.

Default peak detection threshold is set to 0.25.

R-Peak Detection: The App uses a zero-crossing algorithm on the peak detector signal for detecting the temporal locations of ECG R-peaks. Hence, it is important that the peak detector is set up correctly relative to the Y = 0 line (please see above).

RPa and RRi Time Series: The App plots the detected ECG R-peaks as red dots on the ECG waveform data. The amplitudes and temporal locations of the ECG R-peaks comprise the R-peak amplitude (RPa) time series.

The App also plots the intervals between consecutive R-peaks in seconds versus the temporal location of these intervals with a red line and dots. This comprises the RR interval (RRi) time series or the RR tachogram.

RPa Statistical Cleaning: Sometimes, due to transient and other noise in ECG waveform data, an R-peak detection algorithm might pick up erroneous peaks. These erroneous peaks could be too high

in amplitude relative to most of the detected peaks. Conversely, these erroneous peaks may be too low in amplitude relative to most of the detected peaks.

In view of the above difficulty, ECG Wiz allows users to find and remove R-peaks that are statistical outliers. First, the mean amplitude (Ma) of all detected R-peaks is computed. Then, the standard deviation of amplitudes (Sa) of all detected R-peaks is computed. Finally, based on a given threshold (Th, typical value = 3), R-peak amplitudes (RPa) that lie within the range [(Ma – Th*Sa) < RPa < (Ma + Th*Sa)] are retained while those outside this range are discarded. Lowering the value of Th will result in more and more R-peaks being discarded while increasing the value of Th will result in more and more R-peaks being retained.

The App also computes the number of samples in the RPa time series before amplitude cleaning and after cleaning. Based on this information, it generates a metric called percentage (%) of R-peaks lost due to cleaning. This gives users a quantification of the R-peaks they lost to cleaning. Generally, if % of R-peaks lost to cleaning is less than 3%, it is acceptable.

RPa cleaning can be enabled by switching ON the RPa Clean switch in the control menu. With the RPa Threshold slider, users can choose the desired R-peak amplitude cleaning threshold in the 0.1-7.0 range in steps of 0.1.

By default, R-peak amplitude cleaning is switched OFF and its threshold is set to 3.

RRi Physiological Cleaning: Because of RPa cleaning and/or other noise, RRi time series might have physiological outliers. That is, it may contain intervals corresponding to extremely high and/or low HRs.

In view of the above difficulty, ECG Wiz allows users to find and remove RR intervals that are physiological outliers. In terms of seconds, RR intervals (RRi) that lie within the range [0.25 < RRi < 2.50] are retained while those outside this range are discarded. That is, those RR intervals that correspond to a HR range of 24-240 BPM are retained, while others are discarded. For humans, a HR range of 24-240 BPM is reasonable. Any heartbeats or RR intervals outside this range can be regarded as physiological outliers and can thus be removed.

The App also computes the number of samples in the RRi time series before and after RR interval cleaning. Based on this information, it generates a metric called percentage (%) of RR intervals lost due to cleaning. This gives users a quantification of the RR intervals they lost to cleaning. Generally, if % of RR intervals lost to cleaning is less than 3%, it is acceptable.

RR interval cleaning can be turned OFF/ON with the RRi Clean switch in the control menu.

By default, RR interval cleaning is switched ON.

Heart Rate: ECG Wiz computes HR in BPM by dividing 60 by the mean of the RR interval (RRi) time series, whereby the unit of this times series is seconds.

Heart Rate Variability: ECG Wiz computes HRV in ms by multiplying 1000 by the standard deviation of the RR interval (RRi) time series, whereby the unit of this time series is seconds.

Results Summary: After HR ad HRV evaluation, ECG Wiz generates a tabular summary of all analyses displaying important parameters like raw/processed data sampling frequencies, type of filter employed, filter cut-offs, HR, and HRV.

Exporting Processed Data: Users have the option of emailing processed ECG data to themselves and or/saving this information on their phones or on third party systems like Dropbox. All processed data is exported via 4 text files: (i) Output.txt is a CSV file that contains processed ECG waveform data (time in seconds, ECG value), (ii) RPa.txt is a CSV file that contains ECG R-peak data (time in seconds, R-peak value), (iii) RRi.txt is a CSV file that contains ECG RR interval data (time in seconds, RR interval in seconds), and (iv) Summary.txt is a plain text file that contains a summary of all analyses.

App Orientation: During charting, all control menus will show only in the vertical (portrait) orientation while they will disappear in the horizontal (landscape) orientation. All charts will remain fully scrollable and zoomable in both orientations. In horizontal orientation, the charting area will increase, enabling a more detailed visualization and review of all data.

Analyzing Sample Files: To demonstrate the versatility, robustness, and accuracy of ECG Wiz, an analysis guide for all 20 sample files is presented below:

File Number: 1
Filename: chfdb_chf01.txt
Re-Sample: 250 Hz
Trim Left: 0.5%
Trim Right: 0.0%
Peak Threshold: 0.05
Reverse Polarity: Yes
Filter: BPF (1-16 Hz)
RPa Clean: OFF
RPa Threshold: N/A
RRi Clean: ON
HR: 67 BPM
HRV: 35 ms

File Number: 2
Filename: chfdb_chf09.txt
Re-Sample: 500 Hz
Trim Left: 0.0%
Trim Right: 0.0%
Peak Threshold: 0.25
Reverse Polarity: Yes
Filter: BPF (2-25 Hz)
RPa Clean: OFF

RPa Threshold: N/A
RRi Clean: ON
HR: 102 BPM
HRV: 19 ms

File Number: 3
Filename: chfdb_chf10.txt
Re-Sample: 650 Hz
Trim Left: 0.0%
Trim Right: 0.0%
Peak Threshold: 0.05
Reverse Polarity: Yes
Filter: LPF (15 Hz)
RPa Clean: OFF
RPa Threshold: N/A
RRi Clean: ON
HR: 122 BPM
HRV: 7 ms

File Number: 4
Filename: chfdb_chf13.txt
Re-Sample: 750 Hz
Trim Left: 0.0%
Trim Right: 0.0%
Peak Threshold: 0.25
Reverse Polarity: Yes
Filter: BPF (2-25 Hz)
RPa Clean: OFF
RPa Threshold: N/A
RRi Clean: ON
HR: 99 BPM
HRV: 4 ms

File Number: 5
Filename: chfdb_chf14.txt
Re-Sample: 350 Hz
Trim Left: 25.0%
Trim Right: 25.0%
Peak Threshold: 0.25
Reverse Polarity: Yes
Filter: BPF (1-35 Hz)
RPa Clean: OFF
RPa Threshold: N/A
RRi Clean: ON
HR: 75 BPM

HRV: 7 ms

File Number: 6
Filename: mghdb_mgh003.txt
Re-Sample: 250 Hz
Trim Left: 0.0%
Trim Right: 0.0%
Peak Threshold: 0.25
Reverse Polarity: Yes
Filter: BPF (2-25 Hz)
RPa Clean: OFF
RPa Threshold: N/A
RRi Clean: ON
HR: 128 BPM
HRV: 29 ms

File Number: 7
Filename: mghdb_mgh009.txt
Re-Sample: 250 Hz
Trim Left: 0.0%
Trim Right: 0.0%
Peak Threshold: 0.25
Reverse Polarity: No
Filter: BPF (2-25 Hz)
RPa Clean: OFF
RPa Threshold: N/A
RRi Clean: ON
HR: 116 BPM
HRV: 6 ms

File Number: 8
Filename: mghdb_mgh017.txt
Re-Sample: 1000 Hz
Trim Left: 6.5%
Trim Right: 5.0%
Peak Threshold: 0.25
Reverse Polarity: Yes
Filter: BPF (2-25 Hz)
RPa Clean: OFF
RPa Threshold: N/A
RRi Clean: ON
HR: 97 BPM
HRV: 3 ms

File Number: 9

Filename: mghdb_mgh181.txt
Re-Sample: 1000 Hz
Trim Left: 0.0%
Trim Right: 0.0%
Peak Threshold: 0.18
Reverse Polarity: Yes
Filter: BPF (1-15 Hz)
RPa Clean: OFF
RPa Threshold: N/A
RRi Clean: ON
HR: 81 BPM
HRV: 6 ms

File Number: 10
Filename: mghdb_mgh248.txt
Re-Sample: 800 Hz
Trim Left: 0.0%
Trim Right: 0.0%
Peak Threshold: 0.25
Reverse Polarity: Yes
Filter: BPF (1-20 Hz)
RPa Clean: OFF
RPa Threshold: N/A
RRi Clean: ON
HR: 65 BPM
HRV: 14 ms

File Number: 11
Filename: mitdb_100.txt
Re-Sample: 1000 Hz
Trim Left: 13.5%
Trim Right: 14.0%
Peak Threshold: 0.25
Reverse Polarity: No
Filter: BPF (2-25 Hz)
RPa Clean: OFF
RPa Threshold: N/A
RRi Clean: ON
HR: 74 BPM
HRV: 26 ms

File Number: 12
Filename: mitdb_115.txt
Re-Sample: 350 Hz
Trim Left: 0.0%

Trim Right: 0.0%
Peak Threshold: 0.08
Reverse Polarity: No
Filter: HPF (1 Hz)
RPa Clean: OFF
RPa Threshold: N/A
RRi Clean: ON
HR: 63 BPM
HRV: 59 ms

File Number: 13
Filename: mitdb_123.txt
Re-Sample: 700 Hz
Trim Left: 0.0%
Trim Right: 0.0%
Peak Threshold: 0.25
Reverse Polarity: No
Filter: BPF (2-25 Hz)
RPa Clean: OFF
RPa Threshold: N/A
RRi Clean: ON
HR: 48 BPM
HRV: 91 ms

File Number: 14
Filename: mitdb_124.txt
Re-Sample: 1000 Hz
Trim Left: 0.0%
Trim Right: 0.0%
Peak Threshold: 0.25
Reverse Polarity: No
Filter: LPF (25 Hz)
RPa Clean: OFF
RPa Threshold: N/A
RRi Clean: ON
HR: 49 BPM
HRV: 30 ms

File Number: 15
Filename: mitdb_209.txt
Re-Sample: 525 Hz
Trim Left: 0.0%
Trim Right: 0.0%
Peak Threshold: 0.25
Reverse Polarity: No

Filter: BPF (2-25 Hz)
RPa Clean: OFF
RPa Threshold: N/A
RRi Clean: ON
HR: 95 BPM
HRV: 34 ms

File Number: 16
Filename: nsrdb_16265.txt
Re-Sample: 1000 Hz
Trim Left: 0.0%
Trim Right: 0.0%
Peak Threshold: 0.16
Reverse Polarity: Yes
Filter: BPF (1-30 Hz)
RPa Clean: OFF
RPa Threshold: N/A
RRi Clean: ON
HR: 96 BPM
HRV: 18 ms

File Number: 17
Filename: nsrdb_16795.txt
Re-Sample: 250 Hz
Trim Left: 0.0%
Trim Right: 0.0%
Peak Threshold: 0.06
Reverse Polarity: Yes
Filter: BPF (0.5-22 Hz)
RPa Clean: ON
RPa Threshold: 2.7
RRi Clean: ON
HR: 69 BPM
HRV: 111

File Number: 18
Filename: nsrdb_17453.txt
Re-Sample: 250 Hz
Trim Left: 0.0%
Trim Right: 0.0%
Peak Threshold: 0.25
Reverse Polarity: No
Filter: BPF (2-25 Hz)
RPa Clean: OFF
RPa Threshold: N/A

RRi Clean: ON
HR: 83 BPM
HRV: 38 ms

File Number: 19
Filename: nsrdb_18184.txt
Re-Sample: 250 Hz
Trim Left: 0.0%
Trim Right: 0.0%
Peak Threshold: 0.25
Reverse Polarity: No
Filter: BPF (2-25 Hz)
RPa Clean: OFF
RPa Threshold: N/A
RRi Clean: ON
HR: 88 BPM
HRV: 64 ms

File Number: 20
Filename: nsrdb_19093.txt
Re-Sample: 250 Hz
Trim Left: 0.0%
Trim Right: 0.0%
Peak Threshold: 0.25
Reverse Polarity: No
Filter: BPF (2-25 Hz)
RPa Clean: OFF
RPa Threshold: N/A
RRi Clean: ON
HR: 69 BPM
HRV: 47 ms

DISCLAIMER

Please note that ECG Wiz is not suited for clinical and/or medical use. It is a useful tool for researchers, scientists, biomedical engineers, DSP practitioners, students, and fitness enthusiasts who want to learn more about ECG analysis and analyze/transform their own data. Please do not use this App for monitoring and/or treatment of any medical conditions. If you think you have medical problems, consult your doctor directly.