

Development of a Matlab Software for Analysis of Heart Rate Variability

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Abstract—The analysis of heart rate variability (HRV) signals is an important tool for studying the autonomic nervous system, as it allows the evaluation of the balance between the sympathetic and parasympathetic influences on heart rhythm. This paper presents a tool for analysis of HRV called ECGLab, which was developed in Matlab language in order to help research on HRV by making the analysis process faster and easier. The software obtains the HRV signal by using an automatic QRS detection algorithm. The user can inspect the ECG and correct mistakes in the detection process, and also identify ectopic beats. Importing RR intervals from previously typed ASCII files is also possible. Some of the most popular HRV analysis techniques were implemented: statistical and time series analysis, spectral analysis (using FFT, auto-regressive and Lomb methods), Poincaré plot analysis and sequential trend analysis.

I. INTRODUCTION

THIS paper presents a tool for analysis of heart rate variability (HRV) called ECGLab, which was developed for Matlab 5. The software was designed to help HRV researchers by making it easy to measure the RR intervals, generate statistics and obtain graphs.

This tool was developed in Matlab language because of the built-in functions provided by the Math Works Inc. software, which help in implementing the more complex algorithms, such as statistical measures, matrix operations and digital signal processing algorithms. Matlab is also a powerful system for plotting graphs and its open source nature allows one to adapt the software for his needs. The graphic user interface development is not as easy as on Borland C++ Builder or Delphi, but the availability of built-in DSP and statistics algorithms and graphic functions turned Matlab into the software of choice as the development environment for ECGLab.

Analysis of HRV signals is important when studying the autonomic nervous system because it helps in evaluating the equilibrium between the sympathetic and parasympathetic influences on the heart rhythm. The sympathetic branch of the nervous system increases the heart rhythm, resulting in shorter beat intervals. The

parasympathetic branch decelerates the heart rhythm, resulting in longer beat intervals. Thus the heart rate variability can be measured based on the beat intervals, which are more easily observed as RR intervals.

However, the manual measurement of RR intervals from ECG tapes is time-consuming, and a layman in the field of digital signal processing will find it very difficult to calculate all the parameters that are usually obtained from the HRV signal. There are software packages which implement some of the algorithms presented in ECGLab, but not all of them. Hence, cardiologists and nervous system specialists will find this tool useful for their research activities.

The ECGLab software is divided in modules, which implement different steps of the HRV signal attainment and analysis. The first one is the ECG filtering module, which removes 60 Hz noise, muscular noise and baseline fluctuations. Then, there is the QRS detection module, which allows the user to inspect the ECG and correct mistakes in the automatic detection process, and also to identify ectopic beats, which can be removed later on. Finally, there are four HRV analysis modules: statistics and time series analysis, spectral analysis, Poincaré plot analysis and sequential trend analysis. The analysis modules can be used with HRV signals obtained from ECGLab and also with RR interval series from previously typed ASCII files. Each one of the main modules is explained in the next sections.

II. QRS DETECTION MODULE

Heart rate variability signals describe either the time period elapsed between successive heartbeats or the "instantaneous heart rate" on each beat instant. Thus the first step of HRV analysis is the detection of the heartbeat time instants. The most precise way of doing that is through QRS detection.

The QRS complex can be detected with a bandpass filter centered at 17 Hz and using a Q factor of 3. The 17 Hz pass frequency gives maximum SNR and a Q of 3 yields an optimum ripple length for detection [1]. The digital

filter can be obtained with a bilinear transformation of equation (1), where k is the gain, Q is 3 and ω_o is 17 Hz. The value of k does not affect the detection.

$$H(s) = \frac{k\omega_o^2}{s^2 + \left(\frac{\omega_o}{Q}\right)s + \omega_o^2} \quad (1)$$

Once the QRS complex is isolated, it can be enriched with a derivative filter (2). An 8th order 30 Hz low-pass Butterworth filter is used in cascade to avoid high-frequency noise amplification.

$$y[n] = x[n] - x[n-1] \quad (2)$$

Before a threshold detector can be applied, it is necessary to compute the absolute value of each sample of the filtered signal so that every sample of the ripple becomes positive. The absolute value can be replaced by a square operation, which will magnify the segments with higher amplitude.

The result of these processes is a set of peaks every time a QRS complex occurs. These peaks can be gathered with an N -point moving average filter (3). The moving window should be 150 ms long [2]. N is the number of samples in the moving average.

$$y[n] = \frac{1}{N} \sum_{i=0}^{N-1} x[n-i] \quad (3)$$

As a result, there will be a wide peak every time a QRS occurs. An adaptive threshold detector should be used to identify those peaks. Care should be taken in order to avoid false negatives (threshold is too high) and false positives (threshold is too low). After a QRS complex is detected, the algorithm skips 350 ms to avoid false premature detections [2].

To correct the effect of the imprecision of the threshold detector and the phase distortion of the previous filters, a searchback algorithm is applied to the signal. This algorithm selects a small limited region of the ECG before each QRS-detection time instant, and identifies the sample with the highest absolute amplitude value as the peak of the R wave.

Due to baseline oscillation of the ECG, pre-processing of the original signal is necessary for accurate R wave time instant identification. A zero-phase 4th order 1 Hz high-pass Butterworth filter can be used. Zero-phase can be obtained with forward and reverse filtering. This way the absolute highest amplitude value on each region of the ECG can be marked as the R wave peak. The region length used in ECGLab is 70 ms and it begins 60 ms

before the first threshold detection instant [2]. This value of 60 ms is due to the nature of the adaptive threshold detection algorithm used. The result of the detection process is shown on Fig. 1.

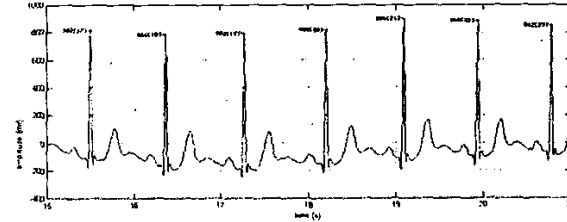


Fig. 1. Result of the QRS detection process. The dots indicate the detected peak of each R wave. The detection instants are used to generate the RR interval series. The numbers outside the brackets are the calculated RR interval values in milliseconds and the ones inside the brackets are the indexes of the intervals.

The heart period signal (also known as RR signal or HP signal) is obtained from those R wave peak time instants. Its graph shows the time interval between the heartbeat on a certain time instant and the previous beat (Fig. 2).

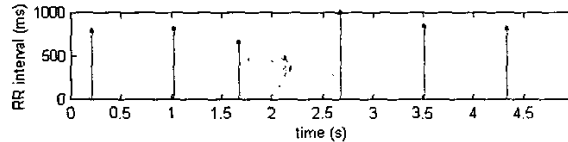


Fig. 2. Segment of the HP signal. Note that after the second beat there is a relatively small interval followed by a large interval. That indicates a premature contraction of the heart followed by a compensatory pause. The amplitude values of the third and fourth samples also indicate that, as the third sample has the lowest amplitude and the fourth sample has the highest amplitude of the ensemble. This peculiar event is called an ectopic beat and it must be removed from the RR interval series or replaced with a more appropriate value, or else the results of the analysis will be distorted. [3]

The QRS detection module of ECGLab also allows the user to inspect the ECG and correct mistakes in the detection process, and also to identify ectopic beats, which can be removed later on.

III. TIME SERIES ANALYSIS MODULE

In this module, the time series of RR intervals obtained on the previous module is evaluated. Importing RR interval series from previously typed ASCII files is also possible. The user will get the HP signal graph (Fig. 3) and the following statistics of the time series: total number of intervals; maximum amplitude value, minimum amplitude value and dynamic range; 25, 50 and 75 percentiles; average amplitude, standard deviation and variance coefficient; pNN50 and rMSSD [4]. It also presents a boxplot of the time series, in which ectopic beats will probably be shown as outliers.

This module also evaluates the stationarity of the signal, based on the amount of variation of its average and standard deviation. Thus signals with long term fluctuations or low-frequency modulations should be rejected, as well as signals presenting ectopic beats.

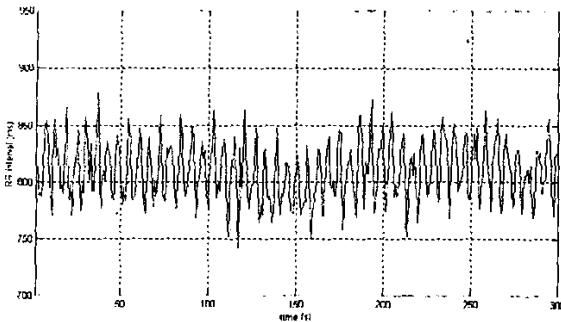


Fig. 3. HP signal graph obtained with ECGLab. It can be seen that the ectopic beats showed in Fig. 2 have been removed. Four ectopic beats were found in this RR interval series and they have all been removed before plotting.

If beats were identified during QRS detection as ectopic ones, in this module they can be either removed or replaced with more acceptable values. An appropriate method for replacing ectopic beats is used.

IV. SPECTRAL ANALYSIS MODULE

In this module, ECGLab presents a power spectrum density (PSD) graph of the HRV signal (Fig. 4), as well as some spectral parameters. The user defines three frequency bands: very low frequency (VLF), low frequency (LF) and high frequency (HF). Then the following parameters are calculated: absolute energy in each band and the total energy; normalized energy in each band (as a percentage of the total energy); relative energy in the LF and HF bands (in comparison to the total energy in both bands); LF/HF ratio.

Due to uneven sampling and ectopic beats, the user can choose one of three different techniques: removal of ectopic beats from the time series; replacement of ectopic beats with normal intervals; removal of ectopic beats and interpolation of the HRV signal using cubic splines. The user can also use the heart rate signal (HR) instead of the heart period signal (HP).

There are three different methods available for PSD estimation: Fast Fourier Transform (FFT), auto-regressive model (AR) and Lomb-Scargle periodogram [5]. The Lomb method estimates the PSD of the unevenly sampled time series without interpolation [6]. The splines interpolation sampling rate, the number of points of the FFT and the AR order can be defined. The user can plot the FFT estimated PSD and the AR estimation

simultaneously, and will be able to choose among three types of graph scale: normal, semi-log and log-log. There are also five different windows available for PSD estimation: rectangular, Bartlett, Hanning, Hamming or Blackman.

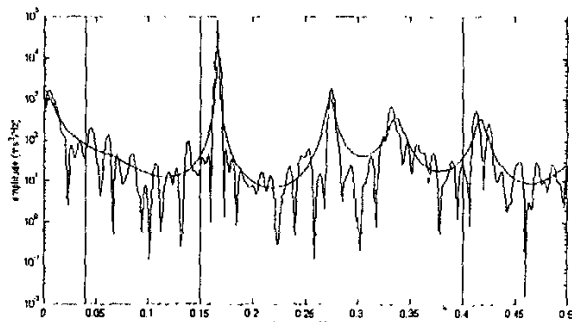


Fig. 4. Power Spectrum Density graph obtained with ECGLab. The peaky curve is the PSD calculated using Fast Fourier Transform. The smooth curve is the AR approximation. The vertical lines at 0.04 Hz, 0.15 Hz and 0.4 Hz indicate the boundaries of the frequency bands.

V. POINCARÉ PLOT ANALYSIS MODULE

A relatively recent tool for HRV signal analysis is the Poincaré plot, which does not require the HRV signal to be stationary. It allows the HRV researcher to measure the variability of heart rate from different points of view such as long-term variability, overall variability, variability on basal heart rate, variability on accelerated heart rate, and variability on decelerated heart rate, as well as the sympathetic-parasympathetic balance.

The Poincaré plot of the HRV signal is a diagram in which each RR interval is plotted against the previous interval (Fig. 5). The following parameters are extracted from it: centroid, vertical deviation (SD1), horizontal deviation (SD2), SD1/SD2 ratio, SD1xSD2 ellipse area, correlation coefficient, regression coefficient, equation of the regression line, and statistics of the series on percentiles 10, 25, 50, 75 and 90. The user can choose to calculate SD1 and SD2 based either on the regression line or on the identity line. Ectopic beats can be either removed from the time series or replaced by interpolated values.

VI. SEQUENTIAL TREND ANALYSIS MODULE

Another relatively little explored tool for HRV research is the sequential trend analysis of heart rate variability. It evaluates the sympathetic-parasympathetic balance as well as the spectral analysis, but has the advantage of being nondependent of the stationarity of the RR interval series.

The user will get a diagram of a ΔRR_n vs. ΔRR_{n+1} plot, where ΔRR_{n+1} is the difference between two successive

RR intervals and ΔRR_n , is the previous difference (Fig. 6). The parameters calculated are the number of points in each quadrant, on each quadrant boundary and on the origin, as well as the total number of points. It also shows those numbers as a percentage of the total number of points. The percentage and total number of null differences and non-null differences are also calculated.

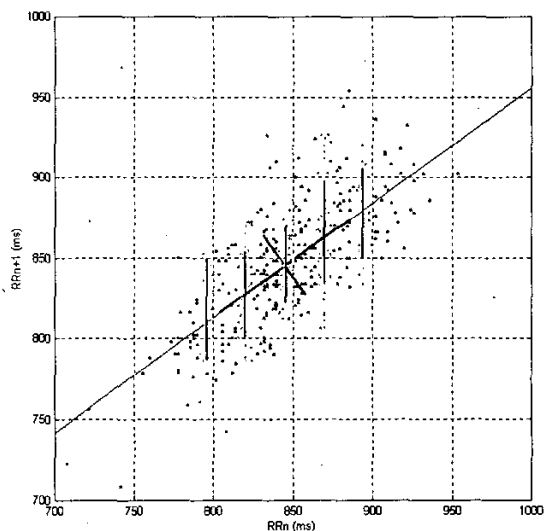


Fig. 5. Poincaré plot obtained with ECGLab. Each solid vertical line indicates the standard deviation of the series of intervals on each percentile (10, 25, 50, 75 and 90). The dashed lines on the percentiles indicate the dynamic range of each series. The inclined line that crosses the plot is the regression line. Its darker section indicates the SD2 and the perpendicular line indicates the SD1. [7]

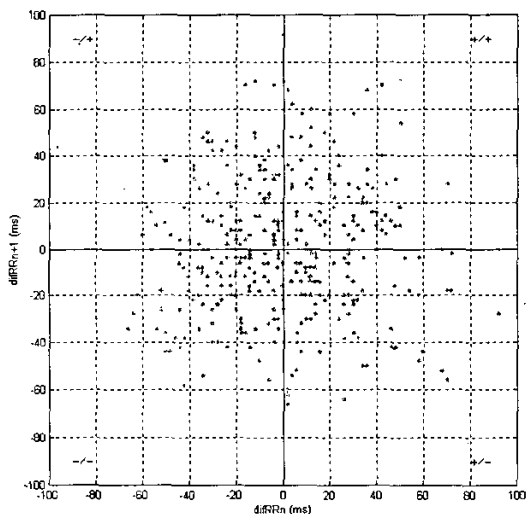


Fig. 6. ΔRR_n vs. ΔRR_{n+1} plot obtained with ECGLab. The graph is divided in four quadrants. The points located in the $+/+$ quadrant indicate two consecutive interval increments (heart rate is decreasing). The ones

in the $-/-$ quadrant indicate two consecutive interval decrements (heart rate is increasing). [8]

The sequential trend analysis is easily implemented and is an effective method for measurement of sympathetic and parasympathetic activities, which correspond to the concentration of points in the $-/-$ and $+/+$ quadrants, respectively.

VII. CONCLUSION

This paper presented a powerful tool for analysis of heart rate variability called ECGLab. This software, which was developed in Matlab 5, helps HRV researchers as it provides automatic QRS detection and RR interval measurement as well as four different analysis techniques: time series, spectral, Poincaré plot and sequential trend analysis. The choice of using Matlab will also allow others to modify and improve ECGLab, making it even more versatile.

ECGLab is already in use by the Cardiovascular Laboratory of the Department of Clinical Medicine, in the School of Health Sciences of the University of Brasilia. It is showing very good results according to the specialists that have been using it.

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