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Abstract A computer program for advanced heart rate variability (HRV) analysis is presented. The program calculates all the commonly used time- and frequency-domain measures of HRV as well the nonlinear Poincaré plot and both parametric and nonparametric spectrum estimates. The program generates an informative printable report sheet which can be exported to various file formats including portable document format (PDF). Results can also be saved as an ASCII file from which they can be imported to a spreadsheet program such as Microsoft Excel®. Together with a modern heart rate monitor capable of recording RR intervals this freely distributed program forms a complete low-cost HRV measuring and analysis system.

Heart rate variability, Analysis software, Computer program, HRV

1 Introduction

Heart rate variability (HRV) describes the variations between consecutive heartbeats. The regulation mechanisms of HRV originate from sympathetic and parasympathetic nervous systems and thus HRV can be used as a quantitative marker of autonomic nervous system [1]. Stress, certain cardiac diseases, and other pathologic states affect on HRV. A good review of physiological origins and mechanisms of HRV can be found in [2].

In HRV analysis either the heart rate as a function of time or the intervals between successive QRS complexes need to be determined. In this paper when we talk about HRV we actually mean the variability of RR intervals (i.e. intervals between consecutive R peaks).

HRV analysis methods can be divided into time-domain, frequency-domain, and nonlinear methods. In the following these methods are discussed shortly. Denotions and definitions for HRV parameters in this paper and in the developed software follow the guidelines given in [1].

1.1 Time-domain methods

The time-domain parameters are the most simple ones calculated directly from the raw RR interval time series. The simplest time domain measures are the mean and standard deviation of the RR intervals. The standard deviation of RR intervals (SDNN) describes the overall variation in the RR interval signal whilst the standard deviation of the differences between consecutive RR intervals (SDSD) describes short-term variation. For a stationary time series SDSD equals to the root mean square (RMS) of the differences between consecutive RR intervals (RMSSD).

There are also other commonly used parameters like NN50 which is the number of consecutive RR intervals differing more than 50 ms. The pNN50 is the percentage value of NN50 intervals. The prefix NN stands for normal-to-normal intervals (i.e. intervals between consecutive QRS complexes resulting from sinus node depolarizations). In practice, RR and NN intervals usually appear to be same.

Furthermore, there are some geometric measures like the HRV triangular index and TINN that are determined from the histogram of RR intervals [1].

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1.2 Frequency domain methods

The RR interval time series is an irregularly time-sampled signal. This is not an issue in time-domain, but in the frequency-domain it has to be taken into account. If the spectrum estimate is calculated from this irregularly time-sampled signal, implicitly assuming it to be evenly sampled, additional harmonic components are generated in the spectrum. Therefore, the RR interval signal is usually interpolated before the spectral analysis to recover an evenly sampled signal from the irregularly sampled event series.

In the frequency-domain analysis power spectral density (PSD) of the RR series is calculated. Methods for calculating the PSD estimate may be divided into nonparametric [e.g. fast Fourier transform (FFT) based] and parametric [e.g. based on autoregressive (AR) models] methods [3]. The PSD is analyzed by calculating powers and peak frequencies for different frequency bands. The commonly used frequency bands are very low frequency (VLF, 0-0.04 Hz), low frequency (LF, 0.04-0.15 Hz), and high frequency (HF, 0.15-0.4 Hz). The most common frequency-domain parameters include the powers of VLF, LF, and HF bands in absolute and relative values, the normalized power of LF and HF bands, and the LF to HF ratio. Also the peak frequencies are determined for each frequency band. For the FFT based spectrum powers are calculated by integrating the spectrum over the frequency bands. The parametric spectrum, on the other hand, can be divided into components and the band powers are obtained as powers of these components. A detailed description of this can be found e.g. in [4]. This property of parametric spectrum estimation has made it popular in HRV analysis.

1.3 Nonlinear methods

It is realistic to presume that HRV also contains nonlinear properties because of the complex regulation mechanisms controlling it. The interpretation and understanding of many nonlinear methods is, however, still insufficient.

One simple and easy to comprehend nonlinear method is the so called Poincaré plot. It is a graphical presentation of the correlation between consecutive RR intervals. The geometry of the Poincaré plot is essential. A common way to describe the geometry is to fit an ellipse to the graph [5]. The ellipse is fitted onto the so called line-of-identity at 45° to the normal axis. The standard deviation of the points perpendicular to the line-of-identity denoted by SD1 describes short-term variability which is mainly caused by respiratory sinus arrhythmia (RSA). The standard deviation along the line-of-identity denoted by SD2 describes long-term variability.

1.4 Aim of this study

In this study we present a computer program for advanced HRV analysis for Windows operating systems. The program calculates all the commonly used time- and frequency-domain parameters of HRV as well the nonlinear Poincaré plot and both parametric and nonparametric spectrum estimates. It also features advanced detrending options for RR series and an informative printable report sheet which can also be exported to various file formats including portable document format (PDF). Combined with a modern heart rate monitor capable of recording RR intervals this freely distributed program forms a complete low-cost HRV measuring and analysis system.

2 Background

We have been developing a Matlab[1] based software package for event-related biosignal analysis in collaboration with the Kuopio University Hospital and the Brain@Work-Laboratory of the Finnish Institute of Occupational Health. The software package consists of a main browser for different biosignals and of various analysis tools. The presented HRV analysis software for Windows has originated from the HRV analysis tool of this software package.

The growing interest in HRV and the absence of free and professional HRV analysis programs have led us on to porting the existing Matlab based program to a standalone windows application. Our aim has been to develop a free and full-featured HRV analysis software for physicians and

[1]Matlab is a registered trademark of the Mathworks Inc. http://www.mathworks.com

other medical experts in research or clinical field. There are some commercial programs available for this kind of analysis, such as the Nevrokard® HRV System (Medistar Inc.), but their cost is sometimes too high for many applications.

Table I: Variables calculated by the program with short description

Variable	Units	Description
		Statistical Measures
Mean & STD RR	s	Mean and standard deviation of the selected RR interval series
Mean & STD HR	1/min	Mean and standard deviation of the selected heart rate series
RMSSD	ms	The root mean square of differences of successive RR intervals
NN50	count	Number of consecutive RR intervals that differ more than 50 ms
pNN50	%	The percentage value of consecutive RR intervals that differ more than 50 ms
		Geometric Measures
RR triangular index		The integral of the sample density distribution of RR intervals divided by the maximum of the density distribution
TINN	ms	Baseline width of the minimum square difference triangular interpolation of the maximum of the sample density distribution of RR intervals
		Nonlinear Measures (Poincaré plot)
SD1	ms	The standard deviation of poincaré plot perpendicular to the line-of-identity
SD2	ms	The standard deviation of poincaré plot along the line-of-identity
		Spectral Measures (parametric and nonparametric)
Peak frequency	Hz	Peak frequencies of the power spectral density estimate for VLF, LF, and HF frequency bands
Power	ms^2, % and n.u.	The powers for VLF, LF, and HF frequency bands in ms^2 and in percentage value. For LF and HF bands the power is also represented in normalized units (n.u.).
LF/HF	%	Ratio of LF and HF frequency band powers in [ms^2]

3 Program description

The program was originally developed using Matlab 6.1 (Release 12.1). The final version of the program has been compiled to a stand-alone C-language application using the Matlab Compiler Suite 2.3 and the free Borland C-Builder 5.5 compiler. Thus the program is now independent from Matlab and does not require Matlab installation to run.

The presented HRV analysis software calculates all the commonly used time- and frequency-domain measures of heart rate variability. All the calculated parameters are summarized in Table I. The emphasis in the development of the program has been on complete heart rate variability analysis combined with ease of use. Thus we have implemented an easy-to-use graphical user interface for the program (Fig. 1).

After the analysis the program generates an easy to interpret printable one-page report sheet (Fig. 3) which can also be exported to various file formats. The most important results of the analysis can also be saved as an ASCII text file from which they are easy to import to other programs for later analysis.

3.1 Input format for data

There are numerous different electrocardiogram (ECG) measuring devices with many more or less proprietary file formats. Thus writing a support for every program would be an endless job. However most of the ECG measuring programs can export the RR time series in some commonly used data format. One of these universal data formats is a simple ASCII text file. Hence we have chosen to have the RR interval data as a column vector in ASCII format.

Support for ASCII files opens new kind of possibilities since there exists some inexpensive and easily available products for heart rate monitoring[2].

[2]One of these products is the POLAR® S810 heart rate monitor used in the sample runs of this article.

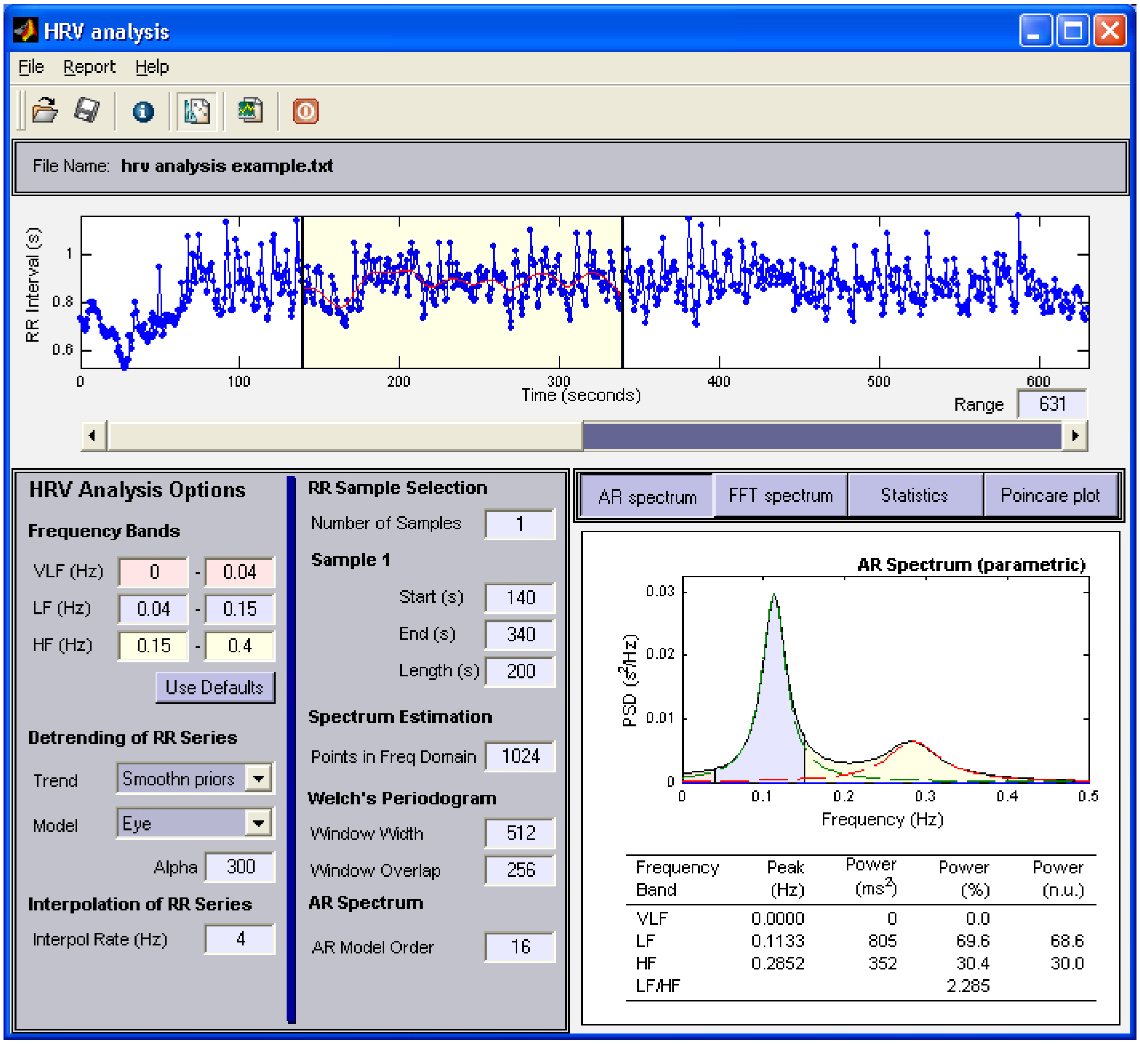


Fig. 1: The user interface of the program.

3.2 The user interface

The developed HRV analysis software is operated with a graphical user interface consisting of only one window shown in Fig. 1.

The user interface is divided into three segments: the data browser segment on the top of the user interface, analysis options segment on the lower left-hand side, and results view segment on the lower right-hand side of the user interface.

3.2.1 Data browser

The data browser segment displays the measured RR interval time series. The selected part or parts of the data are shown as a patch over the data. An estimate for trend in the selected part of the data is shown over the patch. The patch is movable and resizable with mouse. The x-axis limit of the data view can be changed by modifying the value beside the Range text. The name of the selected data-file is displayed over the data browser.

3.2.2 Analysis options

The analysis options segment of the program user interface has been divided into five subcategories. The left side of the segment contains *Frequency Bands*, *Detrending of RR series*, and *Interpolation of RR series* options. The right side contains *RR Sample Selection* and *Spectrum Estimation* options. Each of these options are described below.

Frequency Bands: The frequency limits for very low frequency (VLF), low frequency (LF), and high frequency (HF) bands are alterable. The Use Defaults button restores the frequency bands into their default values which are 0-0.04 Hz for VLF, 0.04-0.15 Hz for LF, and 0.15-0.4 Hz for HF band.

Detrending of RR Series: Sometimes the RR interval time series includes a disturbing low frequency baseline trend component. Detrending options can be used to remove this kind of trend components. Detrending options include removal of the first or second order linear trend or the trend can be removed using the so called smoothness priors method presented in [6].

Interpolation of RR Series: RR interval time series is an irregularly time-sampled series and should therefore be interpolated prior to spectrum estimation. The program uses cubic interpolation at the default rate of 4 Hz.

RR Sample Selection: The part of the RR series to be analyzed can be selected by editing the Start and End values or by just moving/resizing the patch over the RR series. The analyzed segment can also be formed by merging two or more smaller segments. The number of segments is limited to 20 segments.

Spectrum Estimation: This subcategory is divided into two parts: Welch's Periodogram (FFT based spectrum) and AR Spectrum (autoregressive modeling based spectrum). The number of points in frequency domain can be changed for both spectrum estimates. For Welch's periodogram also the width and overlap of the Hanning window can be adjusted in points [3], and for AR spectrum the order of the model can be changed. The so called FBLS-method (forward-backward linear least squares method) is used for the calculation of the AR-model parameters [3]. The default values of these options are set for the RR interpolation rate of 4 Hz.

All the default values for different tunable parameters in the analysis options segment can be customized, by editing a commented ASCII configuration file (named hrv_param.dat) located in the install directory of the program.

3.2.3 Results view

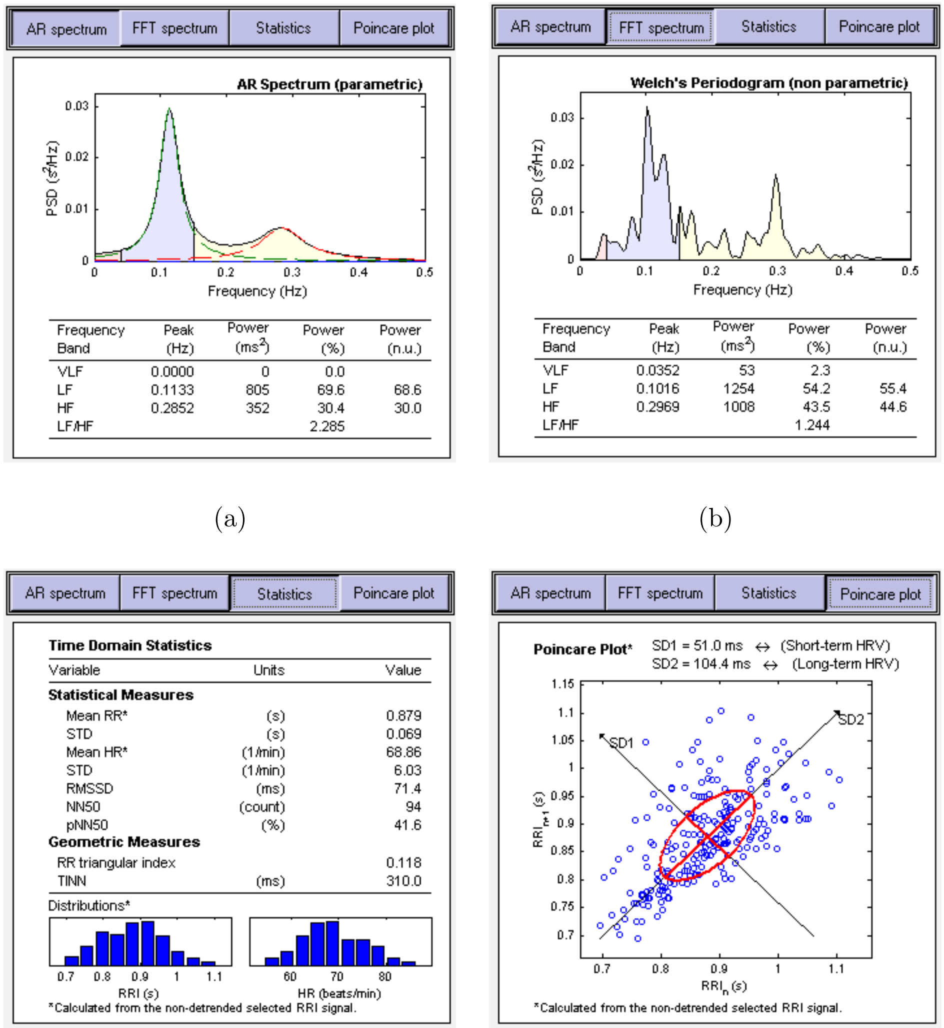
The results view section is for viewing calculated parameters and spectrums for prevailing options. It contains four buttons which control the displayed results (Fig. 2). Choosing the AR Spectrum option, the autoregressive spectrum estimate is displayed along with table of calculated parameters for the spectrum (Fig. 2(a)). The powers and peak frequencies for the AR spectrum are calculated from the distinct components. The FFT Spectrum button displays the Welch's periodogram and, correspondingly, a table of parameters calculated from the periodogram (Fig. 2(b)). The Statistics button displays a table of calculated time-domain parameters (Fig. 2(c)). Under the table RR interval and heart rate histograms are displayed. Choosing the Poincare plot option, the nonlinear Poincaré plot along with calculated parameters is displayed (Fig. 2(d)).

3.2.4 Menus and toolbar buttons

There are three user menus and six toolbar buttons located in the upper left-hand corner of the program interface window (Fig. 1). The File menu includes Open, Save, Save As, and Quit commands. The Save command saves the numeric results of the analysis to a file in ASCII format. Columns of the file are separated with commas so that the results could easily be imported to e.g. a spreadsheet program such as Microsoft Excel® for further inspection. Open, Save, and Quit commands are also available as toolbar buttons.

The Report menu has Report Sheet option which opens the printable report sheet window (Fig. 3). Report sheet window option is also included as a toolbar button.

The Help menu has About option which opens the about dialog. The about dialog contains the version number of the program and contact information. The about dialog can also be invoked



(a) (b)

(c) (d)

Fig. 2: Different options of the results view segment of the programs user interface. (a) AR spectrum estimation results, (b) FFT based spectrum estimation results, (c) time-domain parameters and distribution histograms, (d) Poincaré plot results.

with a toolbar button. There is also a toolbar button for showing/hiding the RR interval data markers.

3.3 The report sheet

The program generates an informative printable report sheet after the analysis has been made. The report includes in one page all the parameters calculated by the program. A screenshot of the report sheet is presented in Fig 3.

There are seven buttons in the report page toolbar. In order from left to right: Export, Print, Zoom In, Zoom Out, Restore original view, Move viewable area, and Close. The Print button opens the print dialog of the operating system and the Close button closes the report window. The Export button opens a specific export dialog. Supported file formats in the export dialog are summarized in Table II. Version 6.53 of the GNU Ghostscript is used for exporting the report sheet to some of the file formats and it is included in the program distribution. GNU Ghostscript

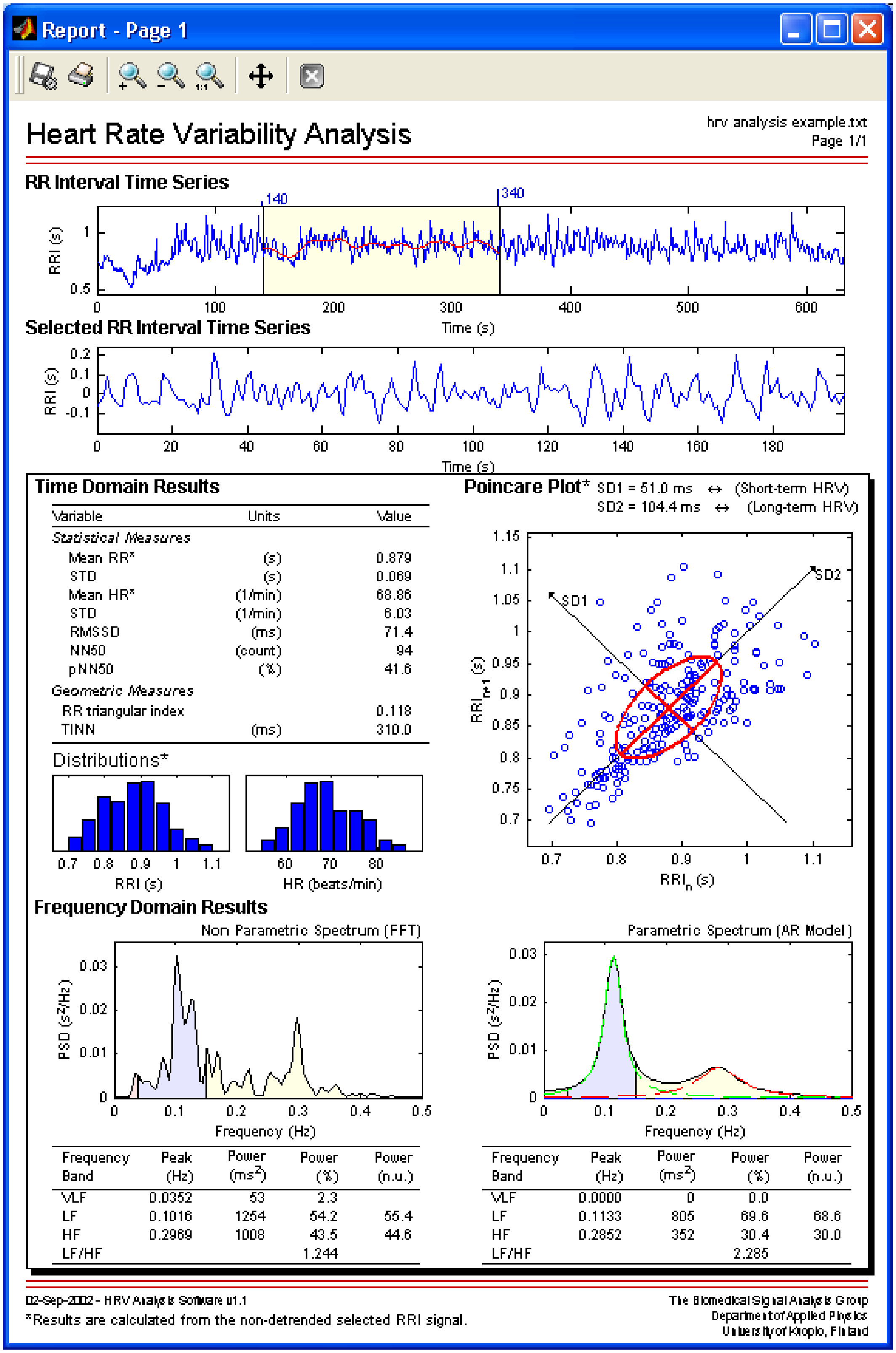


Fig. 3: Report sheet generated by the program.

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Table II: Supported file formats to export the report sheet

File Format	Extension
Portable Document Format	.pdf
Enhanced Metafile	.emf
Bitmap file	.bmp
Encapsulated Postscript	.eps
JPEG image file	.jpg
TIFF image file	.tif
Portable Network Graphics file	.png
Paintbrush 24-bit file	.pcx
Portable Bitmap file	.pbm
Portable Graymap file	.pgm
Portable Pixmap file	.ppm

3.4 Hardware specifications

HRV analysis software will run on all 32-bit windows operating systems (that is, windows 98/Me/NT/2000/XP). It should work also in windows 95 environment although it has not been tested. The program requires a PC system with about 30 MB of hard disk space, a Pentium class or higher processor with x86 architecture, minimum of 32 MB RAM and desktop resolution of 800x600 (although 1024x768 or higher is recommended for usability). For computations it uses mainly Matlab libraries which are included in the program distribution.

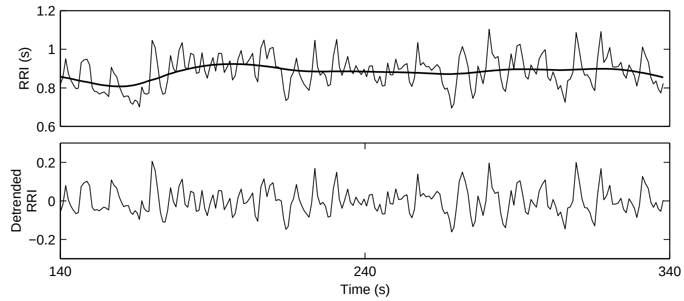
4 Sample runs

As a test case we measured HRV from a healthy young female at rest in a lying position. As a measuring device a POLAR S810 heart rate monitor was used. It is capable of automatically storing consecutive RR intervals and it is very inexpensive compared to other commercial ECG or RR interval measuring devices. The resolution of POLAR Vantage NV heart rate monitor, which is analogous to S810 but with lower memory capacity, was studied in [7]. The inaccuracy of the RR interval measurements was shown to be less than 3 ms which is sufficient for HRV analysis. The timing accuracy of the build-in QRS detection system was studied in [8].

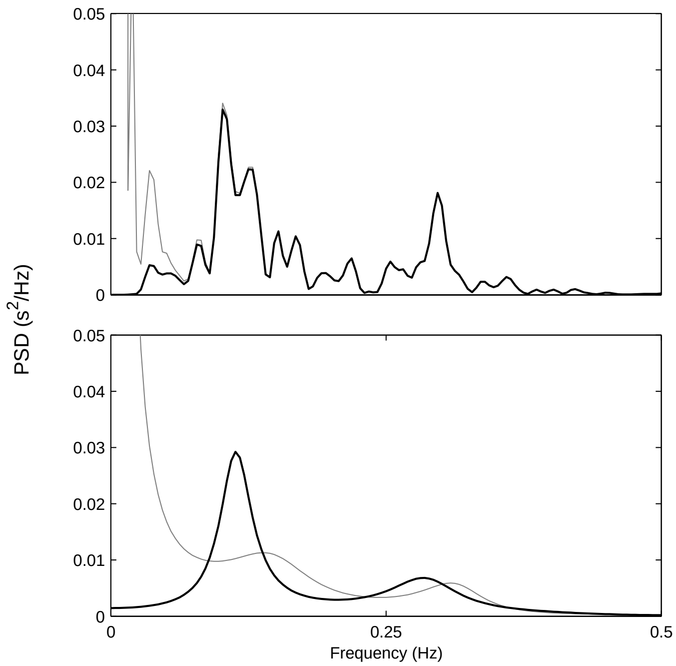
Prior to HRV analysis, the measured RR interval data was preprocessed for artifacts using the Polar Precision Performance™ software that came with the heart rate monitor. The measured preprocessed RR interval data can be seen in the data browser segment of the user interface in Fig. 1. For analysis a segment from 140 to 340 seconds was selected. Obtained results for the selected RR epoch are presented in the report sheet in Fig. 3. The low frequency trend component in the RR series was removed using the smoothness priors based approach. The smoothness priors method [9] operates like a time-varying finite impulse response (FIR) high-pass filter and it is easy to apply to different occasions, since it has only one adjustable parameter.

The effect of the detrending procedure on the spectrum estimates and on few popular time-domain parameters is presented in Fig. 4 and Table III. The spectrum estimates of the original and detrended RR series are compared in Fig. 4(b). For the Welch's periodogram method, the VLF component is properly removed while the higher frequency components are not significantly altered by the detrending. But when AR models of relatively low order are used, which is usually desirable in HRV analysis in order to enable distinct division of the spectrum into VLF, LF, and HF components, the effect of detrending is remarkable. In the AR spectrum of the original RR series the LF and HF components are almost entirely obscured by the strong VLF component. However, from the detrended RR series spectrum the LF and HF components are clearly evident and more congruent with the Welch's periodogram.

The effect of the detrending procedure on a few commonly used time-domain parameters is shown in Table III. The detrending has naturally a strong effect on SDNN and only a small effect on RMSSD and pNN50 which describe the short-term RR variability. Finally it should be emphasized that when using any detrending method one should make sure that the detrending does not lose any useful information from the lower frequency components.



(a)



(b)

Fig. 4: (a) The measured RR interval data with estimated trend (above) and detrended RR interval data (below). (b) PSD estimates for original (thin line) and detrended (bold line) RR interval data with Welch's periodogram method (above) and by using sixteenth-order AR model (below).

TABLE III: The effect of detrending to some time-domain parameters

Variable	**Units**	**Original**	**Detrended**
SDNN	(ms)	82.12	68.53
RMSSD	(ms)	71.90	71.40
pNN50	(%)	40.71	41.59

5 Future plans

In future versions we intend to add read-support for NeuroScan continuous CNT files (NeuroScan Inc.), Biopac AcqKnowledge files (Biopac Systems Inc.), and possibly for some other file formats. This will also include support for viewing raw ECG data and automatic detection of QRS-complexes for calculating RR intervals. These features are already implemented in the Matlab version of the software.

We are also planning to port the application to Linux and other Unix based systems.

6 Discussion

We have presented a computer program for advanced HRV analysis for Windows operating systems. The program calculates all the commonly used time- and frequency-domain parameters and the nonlinear Poincaré plot. Advanced spectrum estimation methods and detrending options are included as well. The program generates an informative and easy to interpret printable one-page report sheet that can be exported to various different file formats including the portable document format (PDF). The most important results of the analysis can also be saved as an ASCII text file from which they are easy to import to a spreadsheet program such as Microsoft Excel® for later analysis. The user interface of the program functions with only one window which simplifies the use of the program considerably. This software is aimed at physicians and other medical experts for clinical or research use and it is available free of charge upon request.

HRV analysis has a long time been considered only as a ”research toy”, but nowadays it has also gained growing interest in the clinical field as well. This has raised a need for inexpensive methods for advanced HRV analysis. The presented HRV analysis software for windows together with modern heart rate monitor able to record RR intervals creates a complete low-cost HRV measuring and analysis system.

7 Availability

The HRV analysis software for Windows is available free of charge upon request. If you are interested in downloading and using the software please visit *http://venda.uku.fi/research/biosignal* or email to *Pasi.Karjalainen@uku.fi* for further instructions.

Acknowledgments

This work has been done in collaboration with Kuopio University Hospital and the Brain@Work-Laboratory of the Finnish Institute of Occupational Health.

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