Kubios HRV – A Software for Advanced Heart Rate Variability Analysis

M.P. Tarvainen[1], J.-P. Niskanen[1,2], J.A. Lipponen[1], P.O. Ranta-aho[1] and P.A. Karjalainen[1]

[1] Department of Physics, University of Kuopio, Kuopio, Finland
[2] Department of Neurobiology, A.I. Virtanen Institute for Molecular Sciences, University of Kuopio, Kuopio, Finland

Abstract — **A software for advanced heart rate variability (HRV) analysis is presented. The software includes adaptable tools for correcting artifacts and for removing low frequency trend components. The analysis options of the software include all the commonly used time-domain, frequency-domain and nonlinear HRV parameters. Analysis results can be saved as a PDF report, ASCII text file or Matlab MAT file. The software is easy to use through its compact graphical user interface. Together with a high-quality heart rate monitor, capable of recording beat-to-beat RR intervals, this freely distributed software forms a complete system for HRV analysis.**

Keywords — **Heart rate variability, analysis software**

I. INTRODUCTION

Heart rate variability (HRV) is known to be affected e.g. by stress, certain cardiac diseases and pathological states. The variability of heart rate (HR) is a result of autonomic nervous system (ANS) regulation of the sinus node. The ANS can be divided into parasympathetic (vagal) and sympathetic branches. Roughly speaking, sympathetic activity tends to increase HR (HR↑) and parasympathetic tends to decrease it (HR↓) [1]. The most conspicuous periodic component of HRV is the respiratory sinus arrhythmia (RSA) which is considered to range from 0.15 to 0.4 Hz. This high frequency (HF) component is generally believed to be mediated predominately by parasympathetic activity [1]. Another widely studied component of HRV is the low frequency (LF) component ranging from 0.04 to 0.15 Hz. The rhythms within the LF band are considered to be both of sympathetic and parasympathetic origin [1]. Thus, HRV is commonly examined through spectral analysis and, e.g., the LF/HF ratio is considered as an index of sympatho-vagal balance.

In this paper, we present an advanced HRV analysis software – Kubios HRV (version 2.0), developed at Biosignal Analysis and Medical Imaging Group (BSAMIG), Department of Physics, University of Kuopio, Finland (http://bsamig.uku.fi). This freely distributed software is a considerable upgrade to the previous version of the software (described in [1]) which has been distributed to over 2700 users around the world so far. The developed software includes all the commonly used time- and frequency-domain parameters as described in [3]. In addition, the software includes a selection of popular nonlinear analysis methods.

II. ANALYSIS METHODS

In this section, the analysis methods included in the software are shortly described. Most of the methods are based on the guidelines given in [3]. In the following presentation, the methods are divided into time-domain, frequency-domain and nonlinear methods. All the methods included in the software are summarized in Table 1.

A. Time-domain methods

Time-domain methods are the simplest to perform since they are applied directly to the series of successive RR interval values. The most evident such measure is the mean value of RR intervals ($\overline{\mathrm{RR}}$) or, correspondingly, the mean HR ($\overline{\mathrm{HR}}$). In addition, several variables that measure the variability within the RR series exist. The standard deviation of RR intervals (SDNN) is defined as

$$\mathrm{SDNN} = \sqrt{\frac{1}{N-1}\sum_{j=1}^{N}\left(\mathrm{RR}_j - \overline{\mathrm{RR}}\right)^2} \qquad (1)$$

where RR_j denotes the value of j'th RR interval and N is the total number of successive intervals. The SDNN reflects the overall (both short-term and long-term) variation within the RR interval series, whereas the root mean square of successive differences (RMSSD) given by

$$\mathrm{RMSSD} = \sqrt{\frac{1}{N-1}\sum_{j=1}^{N-1}\left(\mathrm{RR}_{j+1} - \mathrm{RR}_j\right)^2} \qquad (2)$$

can be used as a measure of the short-term variability. Another measure calculated from successive RR interval differences is the NN50 (number of successive intervals differing more than 50 ms) and its relative value

$$\mathrm{pNN50} = \frac{\mathrm{NN50}}{N-1} \times 100\% \qquad (3)$$

J. Vander Sloten, P. Verdonck, M. Nyssen, J. Haueisen (Eds.): ECIFMBE 2008, IFMBE Proceedings 22, pp. 1022–1025, 2008

Table 1 Summary of the HRV measures calculated by Kubios HRV software

	Measure	Units	Description	References
Time-domain	$\overline{\mathrm{RR}}$	[ms]	The mean of RR intervals	
	STD RR (SDNN)	[ms]	Standard deviation of RR intervals	
	$\overline{\mathrm{HR}}$	[1/min]	The mean heart rate	
	STD HR	[1/min]	Standard deviation of instantaneous heart rate values	
	RMSSD	[ms]	Square root of the mean squared differences between successive RR intervals	
	NN50		Number of successive RR interval pairs that differ more than 50 ms	
	pNN50	[%]	NN50 divided by the total number of RR intervals	
	HRV triangular index		The integral of the RR interval histogram divided by the height of the histogram	[3]
	TINN	[ms]	Baseline width of the RR interval histogram	[3]
Frequency-domain	Peak frequency	[Hz]	VLF, LF and HF band peak frequencies	
	Absolute power	[ms^2]	Absolute powers of VLF, LF and HF bands	
	Relative power	[%]	Relative powers of VLF, LF and HF bands VLF [%] = VLF [ms^2] / total power [ms^2] × 100% LF [%] = LF [ms^2] / total power [ms^2] × 100% HF [%] = HF [ms^2] / total power [ms^2] × 100%	
	Normalized power	[n.u.]	Powers of LF and HF bands in normalized units LF [n.u.] = LF [ms^2] / (total power [ms^2] – VLF [ms^2]) HF [n.u.] = HF [ms^2] / (total power [ms^2] – VLF [ms^2])	
	LF/HF		Ratio between LF and HF band powers	
Nonlinear	SD1, SD2	[ms]	Standard deviation of the Poincaré plot	[4]
	ApEn		Approximate entropy	[5]
	SampEn		Sample entropy	[5]
	D_2		Correlation dimension	[6]
	α_1, α_2		Detrended fluctuation analysis (DFA): short-term and long-term fluctuations	[7]
	RPA		**Recurrence plot analysis**	[8]
	Lmean	[beats]	Mean line length	
	Lmax	[beats]	Maximum line length	
	REC	[%]	Recurrence rate	
	DET	[%]	Determinism	
	ShanEn		Shannon entropy	

In addition to the above statistical measures, there are some geometric measures that are calculated from the RR interval histogram. The HRV triangular index is obtained as the integral of the histogram (i.e. total number of RR intervals) divided by the height of the histogram which depends on the selected bin width. In order to obtain comparable results, a bin width of 1/128 seconds is recommended [3]. Another geometric measure is the TINN which is the baseline width of the RR histogram evaluated through triangular interpolation (see [3] for details).

B. Frequency-domain methods

In the frequency-domain methods, a spectrum estimate is calculated for the RR interval series. Prior to spectrum estimation, the RR interval series is converted to equidistantly sampled series by cubic spline interpolation. In the software, the spectrum is estimated with two different methods: Welch's periodogram and autoregressive (AR) modeling. In Welch's periodogram, the RR series is divided into overlapping segments, each segment is windowed to decrease the leakage effect, and the spectrum estimate is obtained by averaging the FFT spectra of these windowed segments. In the AR method, the RR series is modeled with an AR model of specific order and the spectrum estimate is obtained from the estimated model parameters.

The generalized frequency bands in case of short-term HRV recordings are the 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) bands. The typical frequency-domain measures extracted from the spectrum estimates include absolute and relative powers of VLF, LF and HF bands, LF and HF band powers in normalized units, the LF/HF power ratio, and peak frequencies for each band. The band powers can be computed by simply integrating the spectrum estimate over the frequency band limits. In the case of AR spectrum, the spectrum estimate can also be divided into distinct spectral components in which case the band powers are obtained as powers of the corresponding components. Even though it has been proposed that band powers can be evaluated more accurately by using such spectral decomposition [9], it should be performed with care because problems in the decomposition can yield highly distorted results.

C. Nonlinear methods

Considering the complex control systems of the heart, it is reasonable to assume that nonlinear mechanisms are involved in the genesis of HRV. The nonlinear properties of HRV have been analyzed using measures such as Poincaré plot [4], approximate and sample entropy [5], detrended fluctuations [7], correlation dimension [6] and recurrence plots [8].

Poincaré plot: One commonly used nonlinear method that is simple to interpret is the Poincaré plot. It is a graphical representation of the correlation between successive RR intervals, i.e. plot of RR_{j+1} as a function of RR_j. The shape of the plot is essential. A common approach to parameterize the shape is to fit an ellipse to the plot. The ellipse is oriented according to the line-of-identity (LOI) in which $RR_j = RR_{j+1}$. The standard deviation of points perpendicular to the LOI, denoted by SD1, describes short-term variability which is mainly caused by RSA [4]. The standard deviation along the LOI, on the other hand, is denoted by SD2 and it describes long-term variability [4].

Approximate and sample entropy: Approximate entropy (ApEn) and sample entropy (SampEn) both measure the complexity or irregularity of a signal [5]. Large values of ApEn or SampEn indicate high irregularity and smaller values indicate more regular signal. The difference between ApEn and SampEn is that in SampEn computation there is no self-comparison when computing the distances between embedding vectors extracted from the data. The two entropy estimates are however more or less comparable, especially with longer data samples.

Correlation dimension: Another method for measuring the complexity or strangeness of the time series is the correlation dimension [6]. The computation of correlation dimension has some similarities to ApEn and SampEn computation and it is expected to give information on the minimum number of dynamic variables needed to model the underlying system.

Detrended fluctuation analysis (DFA): DFA measures the correlation within the signal. The correlation is extracted for different time scales as described in [7]. Typically in DFA, the correlations are divided into short-term and long-term fluctuations. In the software, the short-term fluctuations (4-16 beats) are characterized by the slope value α_1 and the long-term fluctuations (16-64 beats) by the slope value α_2.

Recurrence plot (RP) analysis: Yet another approach, included in the software, for analyzing the complexity of the RR series is the RP analysis. In this approach, a symmetrical binary map, i.e. the RP, is formed by thresholding distances of time-lagged embedding vectors. The structure of the RP matrix usually shows short line segments of ones parallel to the main diagonal. These diagonal lines reflect recurrences. The RP can be quantified with various parameters such as recurrence rate (REC), determinism (DET), and mean and maximum line lengths (Lmean, Lmax).

III. SOFTWARE DESCRIPTION

The software was originally developed by using Matlab 7.6 (Release 2008a). The final version of the software has been compiled to a standalone application (Windows and Linux versions) by using the Matlab Compiler 4.8. The Matlab Compiler Runtime distributed with the software is required for running Kubios HRV.

A. Input data formats

Kubios HRV supports only RR interval data, and thus, either a HR monitor with beat-to-beat RR interval recording or an ECG system with RR interval export option is required. The supported RR interval file formats are Suunto SDF/STE, Polar HRM and plain RR interval ASCII files.

B. The user interface

Kubios HRV is operated using a graphical user interface shown in Fig. 1. The user interface can be divided into three segments: 1) RR data browser, 2) RR series preprocessing/analysis options and 3) results view.

RR data browser: The RR data browser segment displays the measured RR interval series. The part of RR data selected for analysis is indicated with a yellow patch. The patch can be re-sized with mouse and also new selections can be made by right-clicking the RR axis.

RR series preprocessing/analysis options: The RR series preprocessing options include artifact correction and trend removal options. In artifact correction, the effect of correction is illustrated in the RR axis, and thus, different correction levels can be easily compared. The detrending options include the smoothness priors approach presented in [14]. Within the preprocessing options, there are also options for modifying the RR samples selected for analysis.

The analysis options include frequency band settings (VLF, LF and HF band limits), adjustment of the RR data interpolation and several spectrum estimation options. Even more analysis options can be adjusted from the software preferences.

Results view: In the results view segment, different time-domain, frequency-domain, and nonlinear analysis results can be viewed. These results are updated automatically, whenever some of the analysis options or analyzed samples are modified.

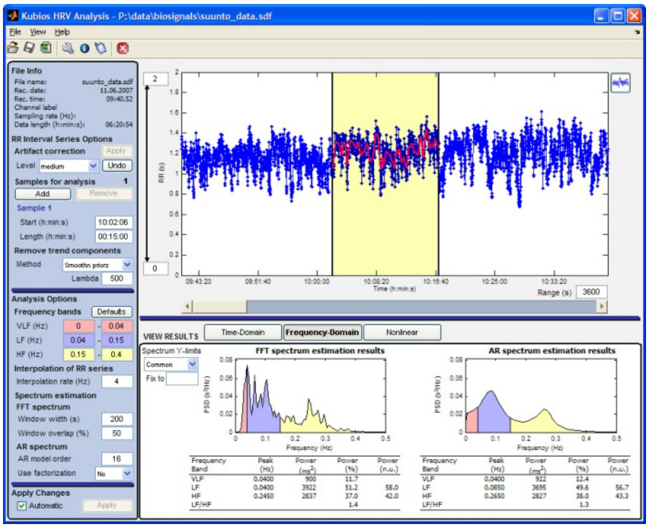

Fig. 1 The graphical user interface of Kubios HRV software.

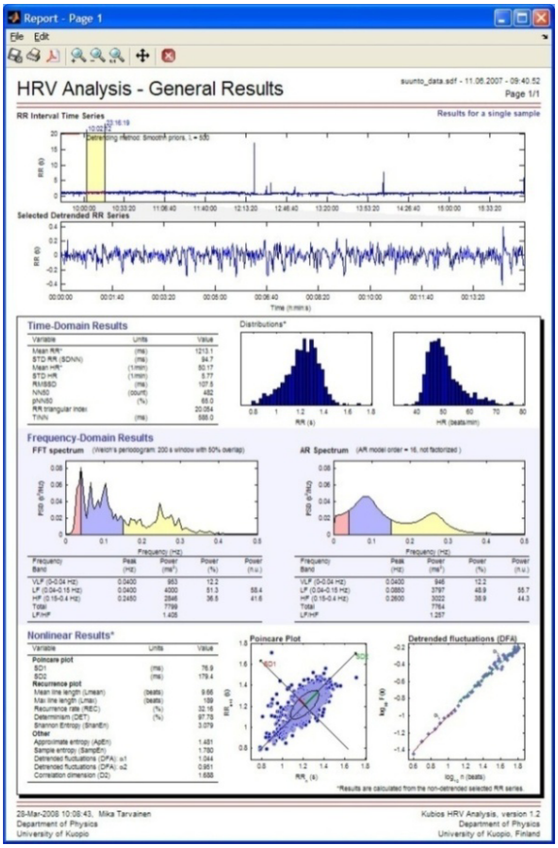

Fig. 2 Kubios HRV report sheet.

C. Saving the results

The analysis results can be saved in three different ways: 1) an ASCII text file which can be imported e.g. to MS Excel for further analysis, 2) a report sheet shown in Fig. 2 which can be printed or exported e.g. into PDF-format and 3) a MATLAB MAT-file.

IV. SUMMARY

The developed Kubios HRV software includes all the commonly used HRV analysis parameters and is available free of charge upon request. If you are interested in using the software, please visit http://bsamig.uku.fi.

REFERENCES

1. Berntson G, Eckberg JB Jr, Grossman P et al. (1997) Heart rate variability: Origins, methods, and interpretive caveats. Psychophysiol 34:623-648
2. Niskanen J-P, Tarvainen M, Ranta-aho P, Karjalainen P (2004) Software for advanced HRV analysis. Comput Meth Programs Biomed 76:73-81
3. Task force of the European society of cardiology and the North American society of pacing and electrophysiology (1996) Heart rate variability - standards of measurement, physiological interpretation, and clinical use. Circulation 93:1043–1065
4. Brennan M, Palaniswami M, Kamen P (2001) Do existing measures of Poincaré plot geometry reflect nonlinear features of heart rate variability. IEEE Trans Biomed Eng 48:1342–1347.
5. Richman J, Moorman J (2000) Physiological time-series analysis using approximate entropy and sample entropy. Am J Physiol 278:H2039-2049
6. Guzzetti S, Signorini M, Cogliati C et al. (1996) Non-linear dynamics and chaotic indices in heart rate variability of normal subjects and heart-transplanted patients. Cardiovascular Research 31:441–446
7. Peng C-K, Havlin S, Stanley H, Goldberger A (1995) Quantification of scaling exponents and crossover phenomena in nonstationary heartbeat time series. Chaos 5:82–87
8. Webber C Jr, Zbilut J (1994) Dynamical assessment of physiological systems and states using recurrence plot strategies. J Appl Physiol 76:965-973
9. Tarvainen MP, Georgiadis S, Ranta-aho PO, Karjalainen PA (2006) Time-varying analysis of heart rate variability signals with Kalman smoother algorithm. Physiol Meas 27:225-239
10. Tarvainen MP, Ranta-aho PO, Karjalainen PA (2002) An advanced detrending method with application to HRV analysis. IEEE Trans Biomed Eng 49: 172–175

Author: Mika P. Tarvainen
Institute: Department of Physics, University of Kuopio
Street: P.O. Box 1627
City: FI-70211, Kuopio
County: Finland
Email: mika.tarvainen@uku.fi