Available Online at http://www.recentscientific.com

ISSN: 0976-3031

International Journal of Recent Scientific Research
Vol. 6, Issue, 4, pp.3501-3506, April, 2015

International Journal of Recent Scientific Research

RESEARCH ARTICLE

SOFTWARE TOOLS FOR HEART RATE VARIABILITY ANALYSIS

Butta Singh and Nisha Bharti

Department of Electronics and Communication Engineering, Guru Nanak Dev University, Regional Campus, Jalandhar, India

ARTICLE INFO

Article History:

Received 5th, March, 2015
Received in revised form 12th, March, 2015
Accepted 6th, April, 2015
Published online 28th, April, 2015

Key words:

ECG; Heart rate variability; HRV; Kubios; gHRV; ARTiiFACT; KARDIA; RHRV POLYAN; aHRV.

ABSTRACT

Heart rate variability (HRV) refers to beat to beat variation in heart rate (R-R intervals) of electrocardiogram (ECG) that quantifies the interplay between sympathetic and parasympathetic activity of autonomic nervous system (ANS). HRV parameters can be categorized in time domain, frequency domain, time-frequency and non-linear methods. Commercially available ECG acquisition equipment does not usually include HRV functionalities due to the lack of standard diagnostic protocols. As an alternative to commercial softwares, many simple, online free, device-independent and portable software tools are developed for HRV analysis and cardiovascular research. This paper briefly reviews the state of the art in the field of HRV analysis softwares. Features of various freely available HRV analysis tools are described in depth.

INTRODUCTION

In earlier days, the physicians believed that the heart beats regularly with a fixed rate. It was after the technology development and the more precise measurement of heart rate (HR) that some amount of variability was discovered[1]. The HR defined as the number of heart-beats per unit of time, usually minutes. At rest, the normal HR for adult ranges from 60 to 100 beats/min at regular rhythmic intervals[2]. However, HR is not constant, and presents variations as a means to adapt internal and external stress factors. Heart rate variability (HRV) is a noninvasive marker to expresses the total amount of variations of both instantaneous HR and RR intervals (intervals between QRS complexes) [3-5]. HRV analysis reflects the interplay of the sympathetic and vagal components of the autonomic nervous system (ANS) on the sinus node of the heart. This analysis can be performed by time-domain, frequency-domain, and non-linear indices of the HR signals. Time domain methods include estimation of variables such as the standard deviation of the normal-to-normal (NN) intervals (SDNN), square root of the mean of the sum of the squares of differences between adjacent NN intervals (rMSSD), percent of the number of pairs of adjacent NN intervals differing by more than 50 ms (pNN50). Time domain HRV parameters lack the ability to discriminate between sympathetic and parasympathetic contribution of HRV, due to this limitation, spectral analysis methods are introduced[1, 3, 6]. Cardiovascular system consist multiple subsystems that show nonlinear deterministic and stochastic properties[4, 5]. As a result, RR interval time series are often highly nonlinear, random and complex. Due to which time and frequency measures of HRV may not be able to detect subtle, but important changes in the HRV. Therefore, nonlinear methods have been developed to quantify the dynamics of HR fluctuations. Now days, monitoring equipment have expanded their capabilities and specific software tools for HRV analysis are emerging[6-8]. Mostly free software tools offer HRV analysis in time and frequency domain analyses. Some of them include a graphical user interface, and can be used by a wide spectrum of users. Some developers describe their tools without specifying the implementation platform or language. Among the few specific environments for HRV analysis, many tools are proprietary and not made available in the public domain for research purposes. In this paper an attempt has been made to explore the features and limitations of freely online available software tools for HRV analysis in time domain, frequency domain and non-linear domain.

HRV Quantification

Although patterns of HRV hold considerable promise for clarifying issues in clinical applications, the inappropriate quantification and interpretation of these patterns may obscure

Corresponding author:* **Butta Singh
Department of Electronics and Communication Engineering, Guru Nanak Dev University, Regional Campus, Jalandhar, India

critical issues or relationships and may impede rather than foster the development of clinical applications. Task Force was created and charged with reviewing the problems of HRV measurement, physiologic interpretation, and clinical use[1]. There are several methods for the measurement of HRV but Commonly HRV is analyzed by four methods; time-domain, frequency-domain, time- frequency domain and non-linear methods.

Time-domain measures

HR fluctuations are quantified by number of methods. Perhaps the simplest to perform are the time domain measures. These measures of HRV are based on either statistical or geometrical analysis of the HR or RR intervals between successive normal-normal QRS complexes[1, 9]. With these methods HR at any point in time or between successive normal complexes can be estimated.

The statistical indices are recommended by the Task Force of the European Society of Cardiology and North American Society of Pacing Electrophysiology[1] includes: i) SDNN ii) SDANN iii) RMSSD iv) SDNN v) SDSD vi) NN50 count vii) NN50 %. Another time-domain measure of HRV is the triangular index; a geometric measure obtained by dividing the total number of all NN intervals by the height of histogram of all NN intervals on a discrete scale with bins of 7.8125 ms. (Goldberger *et al*., 1996) suggests that the time-domain measures cannot detect subtle changes in HR dynamics and are suitable only for long-term recordings[10]. In recent studies, low SDNN has shown to predict mortality in post AMI patients[11, 12].

Frequency-domain measures

The time-domain measures convey the information about the overall variability in time series or the maximum amplitude of variability but not contain any information about the periodic fluctuations of the HR. Frequency-domain analysis provides information of how power distributes as a function of frequency. As per the recommendations of Task Force[1] the power spectrum of a healthy subject can usually be divided into four major frequency bands. The range of the spectral components usually used is: HF component 0.15-0.4 Hz, LF component 0.04-0.15 Hz, VLF component 0.003-0.04 Hz, and ULF component < 0.003 Hz. The total power in autonomic band from 0-0.5 Hz is represented by the total area under the power spectral curve, and the power of individual frequency bands are represented by the area under the proportion of the curve related to each band. The ratio between the LF and HF components (LF/HF ratio) has been found to reflect the sympatho-vagal balance of the HR fluctuation[13, 14].

Time-frequency-domain measures

The HRV metric which were discussed earlier are based on frequency-domain methods. The main difficulty in frequency-domain processing of RR-intervals series is non-stationary behaviour of heart beats. The heart beats of even a normal healthy person tend to be time variant. This non-stationarity becomes more severe in abnormal cardiac rhythms. Thus the conventional spectral estimation techniques are not suitable for analyzing heart beat signal whose frequency components change rapidly with time. The problem concerning the estimation of such time varying signal has become now a days a source of an active research. In this regard the Wigner-Ville distribution and wavelet transform are powerful time-frequency distribution that gives excellent time- and frequency- resolution and other properties, so that it is extensively used in many areas of signal processing, such as speech, seismic, and biomedical signals[15, 16]. These methods provide localized time and frequency descriptions of HRV to characterize the changing autonomic regulation. Wiklund *et al.* [15] characterized the HRV signal using wavelet transform as a time-frequency analysis method to characterize HRV. Unser[16] presents a detailed summary on the applications of wavelet transform in biomedical signal processing.

Non-linear measures

Conventionally used time- and frequency-domain parameters of HRV are not always suitable for analysis because of the presence of nonlinear phenomena in the physiological signal's parameter variability. Therefore the application of nonlinear techniques is appropriate[17]. Pincus developed approximate entropy (ApEn), a non-linear complexity index, to quantify the randomness of physiological time-series[18]. Richman and Moorman developed and characterized sample entropy (SampEn), a new family of statistics, measuring complexity and regularity of clinical and experimental time-series data and compared it with ApEn[19].

The long-term variability of HRV (SD1) derived from Poincaré plots[20] was considered as the marker of vagal activity as SD1 was also found to be decreased with upright posture and further decreased during exercise in healthy subjects[21]. The short-term variability (SD2) decreased during atropine administration, and further decreased during exercise after complete parasympathetic blockade, which indicated that the SD2 was influenced by both sympathetic as well as parasympathetic activity.

Features and Performance Comparison of Software Tools

The HRV analysis has lead to development of several commercial and non-commercial software tools. Mostly commercial ECG monitoring and HR analysis equipment include device dependent software for HRV, but there are also few device-independent HRV software tools. In addition to commercial tools, several non-commercial freely available HRV software tools have also been developed [7, 8].

Kubios

Kubios HRV (ver 2.1) is a freely available HRV software tool for non-commercial use for researchers and clinicians (http://kubios.uef.fi)[7]. The software may analyze HRV in time-domain, frequency-domain and nonlinear indices. The software is a complete solution compatible with Windows and Linux operating systems with support for both ECG and RR interval data formats and performs the necessary pre-processing operations of QRS detection and artefact correction. The input signal formats supported by the kubios are binary files (biopac acknowledge (.acq), European data format (.edf), general data format (.gdf)) and ASCII text files. The HRV analysis results can be saved as an ASCII text file (importable into MS Excel or SPSS), Matlab MAT-file or PDF format.

An illustrative example of a HRV analysis with Kubios software package is presented in Fig. 1 on data record (100) from the MIT-BIH Arrhythmia Database (http://ecg.mit.edu). Graphical user interface of Kubios HRV for MIT-BIH arrhythmia database Record 100 is shown in Fig. 1 with report sheet in Fig. 2.

GHRV

gHRV, Python programming language based an open source, perform frame-based HRV analysis for an interval, window and a time shift[8]. Software tool can be easily executed on Windows, GNU Linux or Apple OS X operating systems. The input file formats supported by gHRV are heart beat positions in WFDB and ASCII formats, IBI (InterBeat Intervals) ASCII files, Polar and Suunto heart rate monitors. The preprocessing stage includes outliers removal and interpolation. Updated versions of gHRV are freely available on http://ghrv.milegroup.net. gHRV quantifies HRV in time, frequency and non-linear domain. Fig. 3 shows the GUI of HRV analysis for record 100 of sinus arrhythmia database. Frame based evaluation with frame length= 50 sec, frame shift= 10 sec and 47 frames of record is shown in Fig.4.

KARDIA

KARDIA (from Greek meaning “heart”) is a Matlab scripting language based open source for HRV analysis. All functions are written within a single program (kardia.m), freely available at http://sourceforge.net/projects/mykardia/ [22].The execution of m-file require Matlab 7.0 or updated version with Matlab Signal Processing Toolbox. KARDIA can calculate HR at any user defined sampling rate with different interpolation: constant, linear or spline methods. Linear HRV parameters in time- and frequency- domain, non-linear parameters with detrended fluctuation analysis can be quantified.

VARVI

Variability of the he Art Rate in response to Visual stImuli (VARVI) is an open source application designed in python language to analyze the HRV in response to different visual stimuli through a sequence of videos. Software has a wide range of applications in psychiatry and psychological studies.

VARVI software is available open source at varvi.milegroup.net. It requires no software installation but following preinstalled applications are required: Linux platform, mplayer (http://www.mplayerhq.hu/) for videos, PyBluez libraries (http://pybluez.googlecode.com/) for communication with the Polar WearLink band.

RHRV

It is an R language based open software for the statistical computing of HRV[24]. This R language is basically the implementation of the S language and compatible with windows and MacOSX platforms. The software has the advantage of highly customized plots. It imports data files containing heart beat positions both in WFDB and ASCII format. The software package is available to downloaded and installation, following third party procedures for the R platform.

ARTiiFACT

ARTiiFACT is a MATLAB® 2009b based tool with MATLAB® compiler 4.13 for artifacts processing and HRV analyses. Although it was written in the proprietary environment of Matlab but license of Matlab is not a prerequisite for software execution[6]. Software, tutorial and user manual are freely available upon request (Email tobias.kaufmann@uni-wuerzburg.de) and also available to download at http://www.artiifact.de/download/C_ARTiiFACT/ARTiiFACT_V2.01/. ARTiiFACT includes options for batch processing, HRV analysis by autoregressive models and nonlinear domain, treatment of respiration related issues. It provides a possibility to low pass or high pass filter the raw ECG data at a adjustable cut-off frequency.

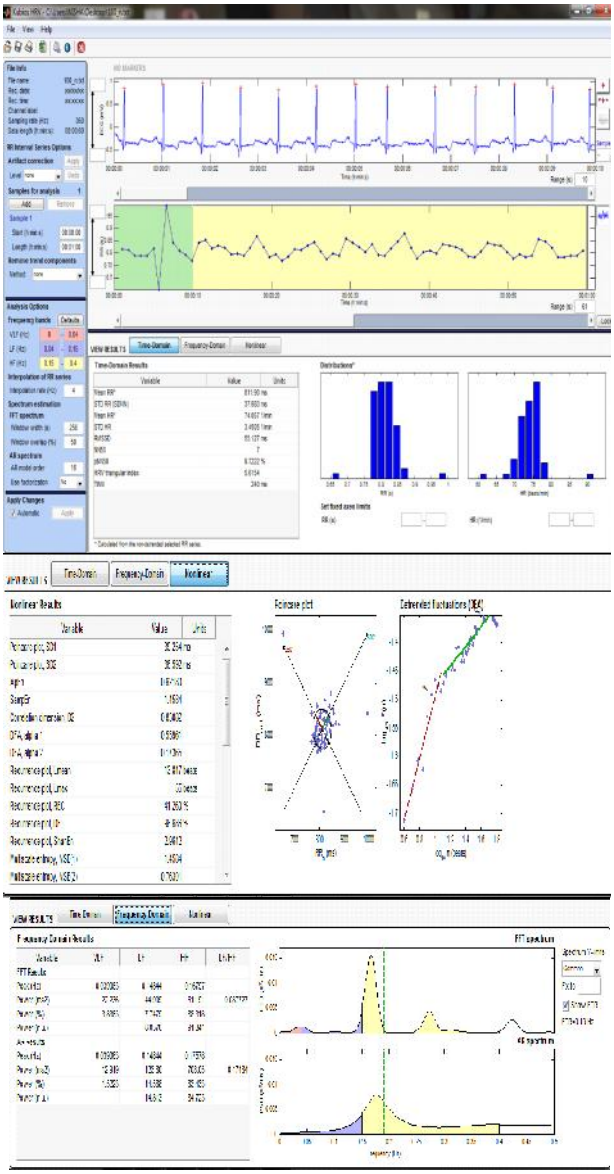

Fig.1 GUI of Kubios for MIT-BIH sinus arrhythmia data record 100

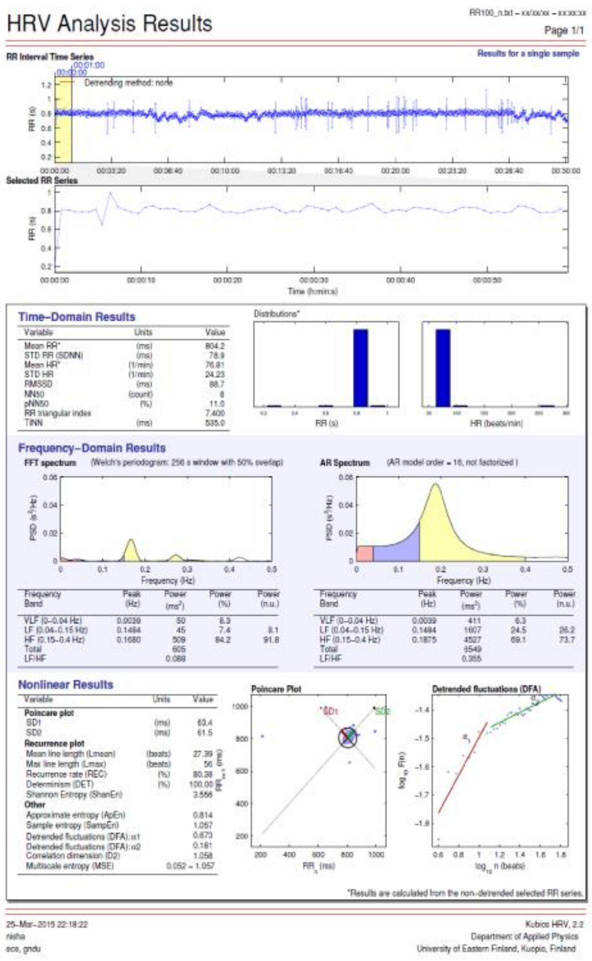

Fig. 2 Report sheet of HRV analysis of MIT-BIH sinus arrhythmia data record 100 by Kubios

It imports various text file formats (.txt, .hdf, .xls) and also matlab files (.mat). Software tool provides adequate and efficient artifact detection, artifact removal and HRV computation. The MATLAB® component runtime 7.13 (MCR) is packaged along with the software. ARTiiFACT It is compatible with all 32-bit Windows (XP, Vista and 7) operating systems. The required desktop resolution is atleast 1280 × 768 pixels.

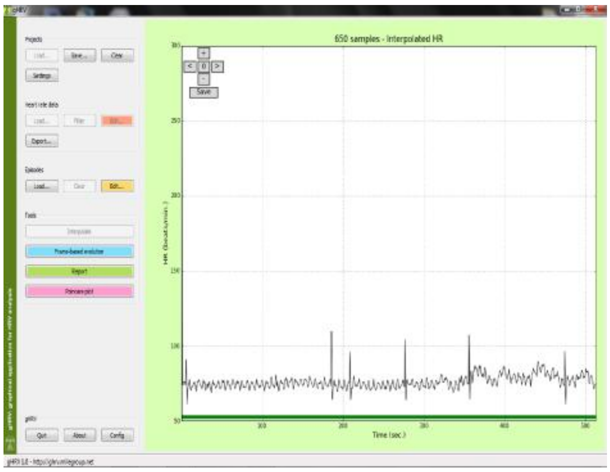

Fig. 3 GUI of gHRV software for MIT-BIH sinus arrhythmia data record 100

GUI with data flags of ARTiiFACT for first 650 samples of record 100 of MIT-BIH sinus arrhythmia data base is displayed in Fig. 5.

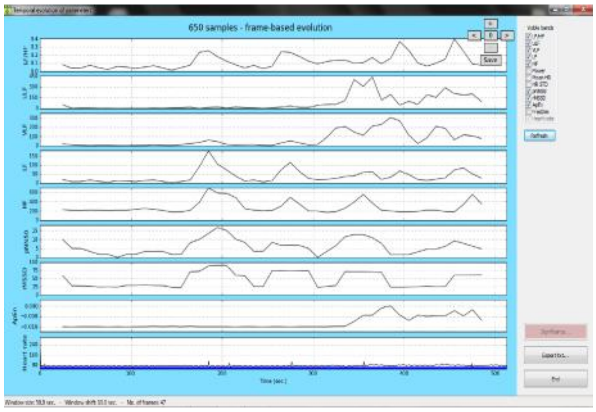

Fig .4 Frame based evaluation of sinus arrhythmia record 100 by gHRV

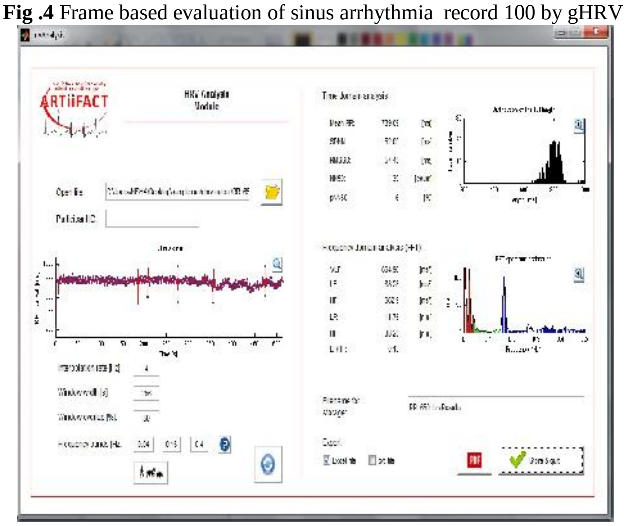

Fig. 5 ArtiiFact GUI for HRV analysis of record 100 of sinus arrhythmia database

LabVIEW

Laboratory Virtual Instrument Engineering Workbench (LabVIEW) is a proprietary system-design platform that provide development environment. This tool can also be used for HRV analysis[25]. LabVIEW is focused to system designers (hardware and software) and it includes signal processing functionalities that make it possible to create custom HRV analysis applications.

POLYAN

POLYparametric Analysis (POLYAN) is written in Matlab 4.2, a computing environment for high performance numeric computation and visualization. It is compatible with MS Windows 3.11 or Windows 95. It is available to researchers interested in sharing research protocols with developer group[26]. POLYAN is an open source designed specifically for the simultaneous analysis of multiple signals (polyparametric approach) for autonomic function testing. It can quantify HRV in both time and frequency domain and facilitate the understanding and interpretation of results by elaborated graphs. The use of matlab language allows a flexibility and ease to expand the package.

Table 1 Features of various HRV software tools

Software	Features	Data format (signal)	Data format (output)	Time domain	Frequency domain	Non-linear domain	Free available	Platform
Kubios[7]	QRS detection, artefact correction, Spectral factorization and respiratory frequency estimation.	.edf, .pdf, .txt, .acq, polar .mat and .gdf	MAT files, ASCII files, .pdf file,	Yes (Mean RR, SDNN, RMSSD, NN50, pNN50, TINN, RR Triangular index.	Fourier, AR(VLF, LF, HF), LF/HF	Yes (Poincaré plots, SD1, SD2, DFA, ApEn, Recurrence plot, SampEn, Multiscale entropy)	Yes	Linux, windows (Matlab)
gHRV[8]	Frame based evaluation, outlier removal, automatic and manual filtering, artifact removal, portable tool developed in python.	WFDB, ASCII files, IBI ASCII files, polar and suunto heart rate monitors(HRM and SDF/STE files)	.txt file	Yes	Yes	Yes (Poincaré plot, ApEn, FracDim)	Yes	Linux, windows OS X (Matlab)
LabView [25]	Appearance of virtual instruments imitates the actual instruments, interactive user interface and source code, creates custom HRV analysis applications.	IBI data type	Create program in flow chart lform called block diagram.	Yes	Fourier, AR	Poincaré plot, Detrended fluctuation.	Yes	Linux, windows
RHRV [24]	Statistical calculation, R-programming language.	ASCII and WFDB	.txt files	Yes	Fourier, wavelet	ApEn, fracDim	Yes	Linux, windows OS X (R)
ARTiiFACT[6]	Batch processing, artifact removal, Independent modules for various import and export opportunities	.txt, .hdf,.xls, .mat	Matlab files, spreadsheet format.	Yes	Fourier	No	Yes	Window (Matlab)
KARDIA[22]	User defined sampling, load data from many subjects simultaneously and calculates average PCRs and HRV statistics, IBI analysis.	.txt files, .mat files.	Matlab file	Yes	Fourier and AR	Detrended fluctuation	Yes	Linux, Window (Matlab)
VARVI[23]	Allow the analysis of HRV while the subject watching a series of videos (Visual stimuli)	Compatible with gHRV and RHRV	.txt files	Yes	Fourier	Yes	Yes	Linux, mPlayer, PyBlueZ
aHRV[24]	Segmented ECG analysis, Advanced detrending options, informative printable report sheet.	ASCII text file, .txt, .pdf, .mat, binary files, .edf	.pdf, .emf, .bmp, .jpg, .tif, .eps, .png, .pgm, .pcx, .pbm, .ppm	Yes	Fourier, AR	Poincaré plot	Yes	Window
POLYAN[26]	Analysis of several simultaneous signals, non-invasive technique, used for neurovegetative assessment, baroreflex sensitivity, flexible	Raw time series (heart period, systolic and diastolic arterial pressure, instantaneous lung volume).	.mat	Yes	Fourier , AR	Yes	Yes	Window(Matlab)

aHRV

aHRV is a commercial software, developed by Nevrokard for HRV analysis[27]. This tool can import data in ASCII files, binary files in European Data Format and many proprietary formats also. Advanced aHRV versions also include: segmented ECG analysis by LT-HRV or sleep apnea screening by OSAS. Software provides a user friendly interface for time and frequency domain analysis.

The emergence in HRV application and the absence of professional HRV analysis tools have led the researchers to develop free to available and device independent softwares. A detailed comparison of various features of these software tools is shown in Table 1.

CONCLUSION

HRV has significant potential to evaluate the role of ANS fluctuations in healthy and cardiac subjects and enhance the understanding of disease mechanisms and physiological phenomena. Currently, commercial or semi-commercial equipment exists which enables simultaneous recording of ECG, respiration, blood pressure, etc. Each signal can be analyzed separately and the results of the analysis can be compared.

Commercially available ECG acquisition systems do not usually embedded with the functionalities for HRV analysis. This is due to the reason that software developers have not considered this a priority because HRV has not been yet included in the standard diagnostic protocols. However various developers and research groups develop their own software tools adapted to their specific requirements.

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