Kubios HRV
(ver. 3.2)

USER'S GUIDE

- ✓ HRV Standard
- ✓ HRV Premium

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kubios

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Abbrevations

ACQ	AcqKnowledge data file format (Biopac Inc.)
ANS	Autonomic nervous system
ApEn	Approximate Entropy
AR	Autoregressive (model or process)
ASCII	Text file using the ASCII character set, which is the most common format for English-language text files
CSV	Comma separated value (file format)
DFA	Detrended fluctuation analysis
ECG	Electrocardiogram
EDF	European data format (file format)
EDR	ECG derived respiration
FFT	Fast Fourier transform
GDF	General data format (file format)
GUI	Graphical user interface
HF	High frequency (refers to HRV frequency band, by default 0.15-0.4 Hz)
HR	Heart rate
HRV	Heart rate variability
IBI	Inter-beat-interval (same as RR interval)
LF	Low frequency (refers to HRV frequency band, by default 0.04-0.15 Hz)
MAT	MATLAB data file format (Mathworks Inc.)
MSE	Multiscale entropy
NNxx	Number of successive RR interval pairs that differ more than xx msec
PDF	Portable document format (file format)
pNNxx	Relative number of successive RR interval pairs that differ more than xx msec
PNS	Parasympathetic nervous system
PPG	Photoplethysmogram (measurement of blood volume changes)
QRS	QRS complex of electrocardiogram
RMSSD	Root mean square of successive RR interval differences
RPA	Recurrence plot analysis
RR	Time interval between successive ECG R-waves (RR interval, same as IBI)
SampEn	Sample entropy
ShanEn	Shannon entropy
SDANN	Standard deviation of the averages of RR intervals in 5-min segments
SDNN	Standard deviation of normal-to-normal RR intervals
SDNNI	Mean of the standard deviations of RR intervals in 5-min segments
SI	Stress index
SNS	Sympathetic nervous system
SPSS	Statistical analysis software package(IBM Corp.)
TINN	Triangular interpolation of normal-to-normal intervals
VLF	Very low frequency (refers to HRV frequency band, by default 0-0.04 Hz)

1 Overview

1.1 About Kubios HRV

Kubios HRV is a powerful heart rate variability (HRV) analysis software. With Kubios HRV, you can turn your ECG or HR monitor into a powerful tool to probe the cardiovascular system or to evaluate the effect of stress and recovery on heart health. The software is suitable for clinical and public health researchers, professionals working on human well-being, or sports enthusiasts for anybody who want to perform detailed analyses on heart rate variability, e.g. to examine autonomic nervous system function.

The first versions of the Kubios HRV were developed as part of academic research work carried out at the Department of Applied Physics, University of Eastern Finland, Kuopio, Finland. Earlier versions of Kubios HRV has been described in two scientific publications [15, 23]:

> Niskanen J-P, Tarvainen MP, Ranta-aho PO, and Karjalainen PA. Software for advanced HRV analysis. *Comp Meth Programs Biomed*, 76(1):73-81, 2004.
>
> Tarvainen MP, Niskanen J-P, Lipponen JA, Ranta-aho PO, and Karjalainen PA. Kubios HRV – Heart rate variability analysis software. *Comp Meth Programs Biomed*, 113(1):210-220, 2014.

Kubios HRV is a scientifically validated software and the most commonly used HRV analysis software for scientific research. This is evidenced by the fact that the two publications listed above have attracted over 1 000 citations.

Kubios HRV is currently available as two alternative products:

> **Kubios HRV Standard:** Freeware HRV analysis software for non-commercial research and personal use. Supports HR data from most common HR monitor manufacturers and computes most commonly used time- and frequency-domain HRV parameters. Software is operated through an easy-to-use GUI and analysis results can be saved as PDF report or text file.
> **Product page:** https://www.kubios.com/hrv-standard.
>
> **Kubios HRV Premium:** Full featured HRV analysis software for scientific research and professional use. Supports wide range of ECG, PPG and HR data and computes all commonly used time-domain, frequency-domain and nonlinear HRV parameters. In addition, Kubios HRV Premium includes improved pre-processing, ECG derived respiration, time-varying analysis and extended exporting options. Analysis results can be saved as illustrative PDF reports, CSV text file, MATLAB MAT file and also in a ”SPSS friendly” batch file.
> **Product page:** https://www.kubios.com/hrv-premium.

A summary of the features is given in Table 1.

Please visit at https://www.kubios.com/, where you can find current information on the software, download updates, find tutorials and information about HRV and how to use the software. **If you have any trouble or questions regarding the software, please check first if your particular problem or question has an answer in the FAQ/troubleshooting section at the software homepage!** You can also follow us on Facebook, LinkedIn, and YouTube.

1.2 System requirements

Kubios HRV was developed using MATLAB®[1] and was compiled to a standalone application with the Matlab Compiler. Therefore, in addition to Kubios HRV the MATLAB Runtime also needs to be installed. The latest installers for Kubios HRV and MATLAB Runtime can be downloaded from https://www.kubios.com/download. Please note that the MATLAB Runtime is free and does not require the user to have a Matlab license. System requirements for running Kubios HRV are similar to those

[1] MATLAB®. ©1984-2019 The Mathworks, Inc.

Table 1: Summary of Kubios HRV Standard and Kubios HRV Premium features

FEATURES	Standard	Premium
Data support		
• IBI or RR interval data files: Garmin and Suunto FIT files, Polar TXT files, custom formatted text and CSV files	✓	✓
• ECG/PPG data files: EDF/EDF+, GDF, Biopac ACQ3, Cardiology XML, ISHNE Holter ECG, and custom formatted text and CSV files	–	✓
• Supported HR monitors: ActiHeart, emWave, Firstbeat Bodyguard, Garmin (Forerunner and Fenix series), Polar (V800), Suunto (Ambit and Spartan series), Zephyr BioHarness	✓	✓
→ Direct export from Polar Flow (RR/IBI data from all Polar Flow compatible monitors when H6, H7 or H10 heart rate sensor is used in measurement)	–	✓
• Supported ECG/PPG devices: Actiwave Cardio, AliveCor Kardia, Biopac, Bittium Faros, Empatica E4, Mindfield MindMaster, Shimmer and several clinical Holter and ECG monitors	–	✓
Pre-processing		
• Built-in QRS detector for accurate detection of ECG R-waves and pulse wave detector for PPG data	–	✓
• Artefact correction methods: Threshold based RR correction algorithm / Automatic RR correction algorithm / ECG based R-wave correction	✓ / – / –	✓ / ✓ / ✓
• Smoothness priors method for removing very low frequency trend components when performing short-term HRV analysis	✓	✓
Analysis options		
• Automatic analysis sample generation (based on predefined CSV file)	–	✓
• Stress index, PNS index and SNS index	✓	✓
• Time-domain parameters: Mean RR and HR, min/max HR, SDNN, RMSSD, pNN50, HRV triangular index, TINN etc.	✓	✓
• Frequency-domain parameters: VLF, LF and HF band powers (in absolute, relative and normalised units), peak frequencies and LF/HF ratio	✓	✓
• Spectrum estimation methods: Welch's periodogram / Lomb-Scargle periodogram / AR spectrum estimate	✓ / – / ✓	✓ / ✓ / ✓
• Basic nonlinear parameters: Poincaré plot, approximate entropy (ApEn), sample entropy (SampEn) and detrended fluctuation analysis (DFA)	✓	✓
• Additional nonlinear parameters: correlation dimension (D_2), recurrence plot analysis (RPA), multiscale entropy (MSE)	–	✓
• Built-in algorithm for ECG derived respiration (EDR) providing an accurate estimate of respiratory rate, which is needed in reliable RSA component estimation	–	✓
• Time-varying analysis: time trends for stress and PNS/SNS indexes, time-domain and frequency-domain parameters, spectrogram and Kalman smoother based time-varying spectrum estimates	–	✓
Reports and results export		
• HRV reports (PDF reports) including: time-domain, frequency-domain and nonlinear results / Time-varying analysis results	✓ / –	✓ / ✓
• ECG print (PDF report) showing the raw ECG trace for selected time period	–	✓
• HRV analysis results export options: PDF file / Text file / MATLAB MAT file	✓ / ✓ / –	✓ / ✓ / ✓
• "SPSS friendly" batch file export (ideal for group analyses or repeated measurements)	–	✓

of Matlab (see https://www.mathworks.com/support/sysreq/) and only 64-bit operating systems are supported. Please note that **correct version of MATLAB Runtime (available at Kubios download page) must be installed** in order to run Kubios HRV.

Windows (7 SP1 or 10, 64-bit) operating system with 4 GB of RAM, 3-5 GB of disk space, screen resolution of 1024×768 or higher, and the MATLAB Runtime installation.

Mac OS X (Sierra, High Sierra or Mojave) operating system with 4 GB of RAM, 3-5 GB of disk space, screen resolution of 1024×768 or higher, and the MATLAB Runtime installation

Linux distribution (see qualified distribution at Mathworks site) with 4 GB of RAM, Intel or AMD x86-64 processor, 4-6 GB of disk space, screen resolution of 1024×768 or higher, hardware accelerated graphics card supporting OpenGL 3.3 with 1GB GPU memory, graphical desktop environment, and the MATLAB Runtime installation.

1.3 Release notes

The version history of the most significant updates and changes made in Kubios HRV is given in the release notes. Going though the latest release notes is recommended always before updating to a new version. Up-to-date and detailed release notes can be found from https://www.kubios.com/release-notes.

1.4 Installation

In order to run Kubios HRV, you need to install Kubios HRV and MATLAB Runtime on your computer. Installers can be download from https://www.kubios.com/download. The first time you launch Kubios HRV, you will be prompted to activate the software for the the current computer using your personal License key. In order to get the License key, fill in the order form at https://www.kubios.com/. A short description of the installation process at different operating systems is given below.

Windows: Make sure that you have administrative privileges (you will need them to install Kubios HRV). In order to install Kubios HRV on a Windows computer, you need to first install the MATLAB Runtime on your computer. After you have installed the MATLAB Runtime, run the Kubios HRV installer file and follow the instructions given in the setup wizard to complete installation. You can launch Kubios HRV by using the Desktop icon (if created) or by selecting it from the Start Menu. Please note that Kubios HRV also starts the MATLAB Runtime and may take some time especially with older computers. The first time you start Kubios HRV, you also need to activate the software using your personal license key.

Mac OS: Download the the MATLAB Runtime and the Kubios HRV application bundle. First install the MATLAB Runtime on your computer. After you have installed the MATLAB Runtime, move the Kubios HRV application bundle into Applications on your computer. Kubios HRV is then ready to be launched.

Linux: Install the MATLAB Runtime by extracting the MATLAB Runtime zip package and executing the installer command `./install` as root. Do not change the default MATLAB Runtime install directory if you do not have a special need to change it. Kubios HRV assumes that MATLAB Runtime is installed in the default directory. Otherwise the MATLAB Runtime directory has to be given as an argument to the `run_kubioshrv` script. Kubios HRV can be installed using the deb (Ubuntu/Debian) or rpm (Fedora/SUSE/RedHat) package using your package manager. Furthermore, Kubios HRV can also be installed without a package manager by extracting the tar.gz file to a directory of your choosing. To run Kubios HRV, select it from the menu of your desktop environment or run the command `kubioshrv-standard` or `kubioshrv-premium` in the terminal. If you have installed Kubios HRV using the tar.gz package, go to the directory you extracted the package and run `./run_kubioshrv` in the terminal.

1.5 Uninstallation

Windows: The software can be uninstalled using the "Windows Settings > System > Apps & Features" (Windows 10) or "Control Panel > Programs and Features" (Windows 8 and 7). However, the uninstaller does not remove your preferences settings or license file. These have to be deleted manually and can be found in the following folders:

Kubios HRV Standard
`C:\Users\<username>\AppData\Roaming\Kubios\KubiosHRVStandard`
`C:\ProgramData\Kubios\KubiosHRVStandard`

Kubios HRV Premium
`C:\Users\<username>\AppData\Roaming\Kubios\KubiosHRVPremium`
`C:\ProgramData\Kubios\KubiosHRVPremium`

Mac OS: Move the installed applications (MATLAB Runtime and Kubios HRV application) to trash.

Linux: Remove the MATLAB Runtime by deleting the directory it was installed in (default `/usr/local/MATLAB/MATLAB_Runtime/v91`). If you have installed Kubios HRV using a deb or rpm package, use your package manager to uninstall the kubioshrv package. If you have installed Kubios HRV using the tar.gz package, just delete the directory it was extracted in. However, the preferences and license file have to be deleted manually from the `~/.kubios` directory.

2 Supported data formats and devices

The different file formats and devices that are compatible with Kubios HRV are described here. Features available only in the Premium version are indicated in the text and an overview of differences between these versions is given in Table 1.

Kubios HRV supports the following data formats:

1.	Polar TXT and HRM files (Polar Electro Ltd.)	(*.txt,*.hrm)
2.	Suunto FIT files (Suunto Ltd.)	(*.fit)
	Suunto SDF, STE and XML files (older formats)	(*.sdf,*.ste,*.xml)
3.	Garmin FIT files (Garmin Ltd.)	(*.fit)
4.	RR interval text files	(*.txt,*.dat,*.csv)
5.	Custom text data files (only RR data)	(*.txt,*.dat,*.csv)
Available only in Premium version:		
6.	Direct export from Polar Flow (in FIT format)	(*.fit)
7.	ECG and PPG data text files	(*.txt,*.dat,*.csv)
8.	Custom text data files (RR, ECG and PPG data)	(*.txt,*.dat,*.csv)
9.	Biopac ACQ3 files (Biopac Systems Inc.)	(*.acq)
10.	Cardiology XML files	(*.xml)
11.	European data format (EDF and EDF+) files	(*.edf)
12.	General data format (GDF) files	(*.gdf)
13.	ISHNE Holter ECG data format files	(*.ecg)
14.	Zephyr BioHarness ECG and RR data files	(*.csv)
15.	Kubios HRV Matlab MAT files	(*.mat)

When using Polar, Suunto or Garmin HR monitors, **make sure that your device can measure and store RR intervals in beat-to-beat**. From averaged data (e.g. HR values at every 5 seconds) you are not able to analyse HRV. In addition to standardized HR monitor file formats, a support for plain RR interval text files (ASCII files) is provided. The input text file can include RR interval values in one or two column format, i.e. the RR interval values can be given as:

Type 1	Type 2	
0.759	0.759	0.759
0.690	1.449	0.690
0.702	2.151	0.702
0.712	2.863	0.712
0.773	3.636	0.773
⋮	⋮	⋮

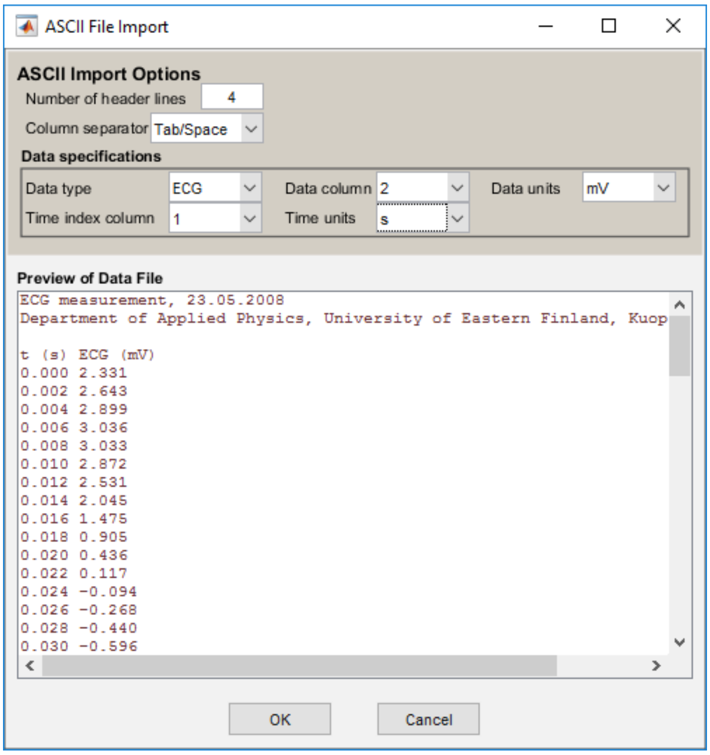
In Type 2 format, the first column includes the time indexes of R wave detections (zero time for the first detection in this example) and second column the RR interval values. The RR interval values above are given above in seconds, but also millisecond values can be used.

Similarly, ECG data can be given as input in text file formatted as shown below

Type 1	Type 2	
-0.173	0	-0.173
-0.119	0.002	-0.119
-0.025	0.004	-0.025
0.091	0.006	0.091
0.218	0.008	0.218
⋮	⋮	⋮

where the first column on Type 2 format is the time scale in seconds for the ECG data. The sampling rate of this example file is thus 500 Hz (samples per second). If ECG data is given according to the Type 1 format, user is prompted to enter the sampling rate manually.

In addition to above text file formats, a custom text file option is also provided. Using this option you can import text files including header lines and/or several data columns. Once you have selected an input file, an interface for importing the file into Kubios HRV is opened. This interface and the options that you need to set according to your data file are shown in Fig. 1.



Options to be set based on the data file:

- Number of header lines
- Column separator (tab/space, comma, or semicolon)
- Data type (ECG, PPG or RR)
- Data column (the ordinal number of data column)
- Data units (μV, V or mV for ECG / ms or s for RR)
- Time index column (the ordinal number of time indexes)
- Time units (units of time indexes in ms, s or date/time format)
- ECG sampling rate in Hz (if no time index column is defined for ECG)

Once you have specified the above values for your file, press OK to proceed to opening the file.

Figure 1: The interface for importing custom text data files into Kubios HRV.

In addition to above text file formats, Kubios HRV supports the Zephyr BioHarness file format (CSV file), Cardiology XML, and four binary data formats (Biopac ACQ3, EDF, GDF and ISHNE ECG). The EDF/EDF+ are open file formats quite generally used for storing biomedical signal data. The ISHNE ECG is a standard output format for Holter ECG data described in [1]. When any of these binary files are read to the software, Kubios HRV automatically tries to determine the ECG channel from the channel labels. If the ECG channel cannot be determined (or more than one channels are identified as ECG channels), the software prompts the user to select the appropriate channel.

A list of commonly used devices, which are known to be compatible with Kubios HRV is given in Table 2. Please note that this is not a complete list, many other devices may also support exporting the data in Kubios HRV compatible format.

Finally, the software supports also MATLAB MAT files saved by Kubios HRV. When you are using Kubios HRV, you can save the analysis session into a MATLAB MAT file as described in Section 5.3. The MAT files include all the analysis results and settings as well as the raw data (ECG, PPG or RR data). Therefore, you are able to reopen the analysis session by opening the saved MAT file again in Kubios HRV.

Table 2: Commonly used ECG or HR measurement devices known to be compatible with Kubios HRV.

Devices	Data type	Kubios HRV input option
Actiheart (CamNtech Ltd.)	IBI	RR text file
Actiwave Cardio (CamNtech Ltd.)	ECG	EDF
Biopac system with ECG module (Biopac Systems Inc.)	ECG	Biopac ACQ3
Cortium C3** (Cortrium Ltd.)	ECG	EDF
Faros (Bittium)	ECG/IBI	EDF
Empatica E4 (Empatica Inc.)	PPG	Custom text file
emWave (HeartMath Inc.)	IBI	Custom text file
Firstbeat Bodyguard (Firstbeat Technologies Ltd.)	IBI	SDF file
Garmin (Forerunner and Fenix) HR monitors* (Garmin Ltd.)	IBI	FIT file
GE CardioSoft and CASE systems (GE Healthcare)	ECG	Cardiology XML
Kardia** (AliveCor Inc.)	ECG	EDF
Mindfield MindMaster (Mindfield Biosystems Ltd.)	ECG	EDF
Polar HR monitors* (Polar Electro Ltd.)	IBI	FIT file or HRM/RR text file
Shimmer ECG and PPG systems (Shimmer Sensing)	ECG/PPG	Custom text file
Suunto (Ambit and Spartan) HR monitors* (Suunto Ltd.)	IBI	FIT/SDF/STE/XML files
Zephyr BioHarness (Zephyr Tech. Corp.)	ECG/IBI	Zephyr BioHarness CSV

* Make sure that the model supports beat-to-beat data export (IBI data). A direct export from Polar Flow is available in Premium version (supports any Polar Flow compatible monitor with H6, H7 or H10 heart rate sensor).

** Requires converter available from device manufacturer

3 Beat detection and pre-processing

3.1 Beat detection algorithms

Kubios HRV Premium has a built-in accurate QRS and pulse wave detectors for detecting heart beats from ECG and PPG data, respectively.

In case ECG data is imported into Kubios HRV Premium, the R-wave time instants are automatically detected by applying the built-in QRS detection algorithm. This in-house developed detection algorithm is based on the Pan–Tompkins algorithm [17]. The detector consists of a preprocessing part followed by decision rules. The preprocessing part includes bandpass filtering of the ECG (to reduce power line noise, baseline wander and other noise components), squaring of the data samples (to highlight peaks) and moving average filtering (to smooth close-by peaks). The decision rules include amplitude threshold and comparison to expected value between adjacent R-waves. Both of these rules are adjusted adaptively every time a new R-wave is acceptably detected. Before R-wave time instant extraction, the R-wave is interpolated at 2000 Hz to improve the time resolution of the detection. This up-sampling will significantly improve the time resolution of R-wave detection when the sampling rate of the ECG is relatively low (200 Hz or higher recommended).

The pulse wave detector is based on matched filtering approach. Firstly maximum of 1st derivative representing the steepest part of the pulse wave is used for initial pulse location estimation. Secondly, template for the pulse wave (and matched filter) is constructed using the initial pulses. Decision of the final pulse wave locations are defined by comparing the filtered signal against varying threshold and comparing normalized error between the template and PPG signal. Allowed normalized error between template and pulse wave under inspection can be adjusted in software preferences. That is, the smaller the acceptance threshold percent is the more similar the pulse wave have to be with the template in order to be accepted.

The accuracy of the pulse wave detection algorithm is shown in Fig 2. The left panel showing the Bland-Altman plot illustrating the agreement between detected PP intervals and corresponding RR intervals during a resting measurement. The right panel shows error percentages of commonly used HRV parameters estimated from PP interval compared to RR interval time series. Used dataset contains 20 healthy volunteers with wide age scale (20 to 50 years). Error between the RR and PP time series is -0.01$\pm$5.16 ms (mean $\pm$ SD). This $\pm$5 ms error in heart beat detection produces approximately $\pm$10% maximum errors to the HRV parameters.

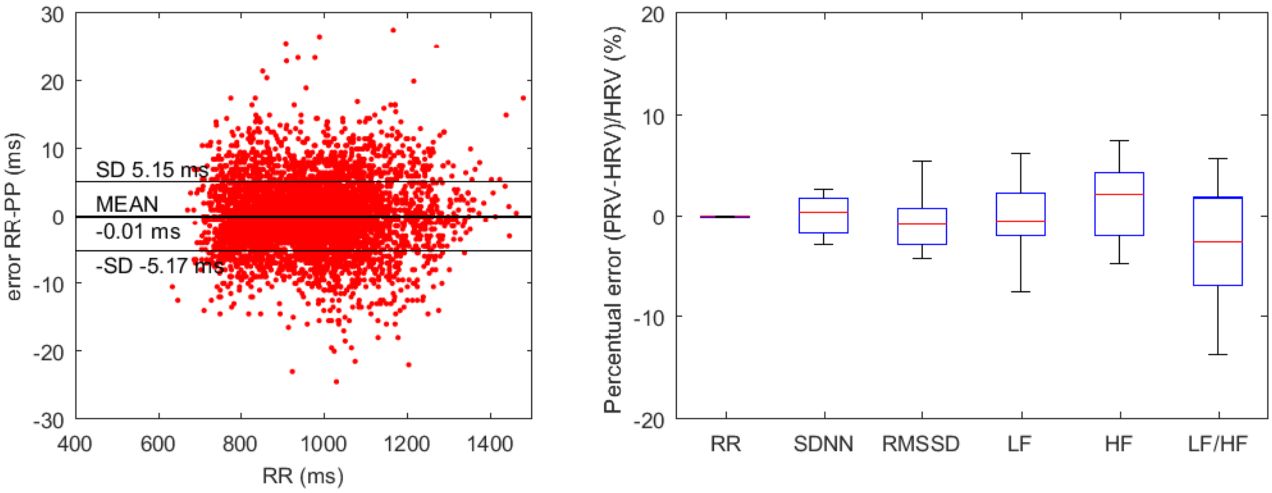


Figure 2: Accuracy of the PP interval vs. RR interval during resting measurement is presented on left panel. In right panel, errors between the PRV and HRV parameters are presented. Blue box indicates region between the 25-75 percentile and black lines are maximum and minimum value.

3.2 Artefact correction algorithms

Artefacts in the IBI time series can cause significant distortion to HRV analysis results, and thus, all artefacts should be either corrected or excluded from analysis as recommended also in [25]. Typical artefacts include missing, extra or misaligned beat detections as well as ectopic beats such as premature ventricular contractions (PVC) or other arrhythmias.

Kubios HRV includes two methods for correcting artefacts and ectopic beats present in the IBI data: 1) Threshold based correction, in which the artefacts and ectopic beats are simply corrected by comparing every RR interval value against a local average interval 2) Automatic correction (only available in Premium), in which artefacts are detected from a time series consisting of differences between successive RR intervals. In addition to these IBI data based correction methods, the beat detections can be corrected manually when ECG data is used for analysis (see Section 4.2).

The **threshold based artefact correction algorithm** compares every IBI value against a local average interval. The local average is obtained by median filtering the IBI time series, and thus, the local average is not affected by single outliers in IBI time series. If an IBI differs from the locale average more than a specified threshold value, the interval is identified as an artefact and is marked for correction. The threshold value can be selected from:

- Very low: 0.45 sec (threshold in seconds)
- Low: 0.35 sec
- Medium: 0.25 sec
- Strong: 0.15 sec
- Very strong: 0.05 sec
- Custom, for setting a custom threshold in seconds

For example, the “Medium” correction level will identify all IBIs that are larger/smaller than 0.25 seconds compared to the local average. The correction is made by replacing the identified artefacts with interpolated values using a cubic spline interpolation. Please note that the thresholds shown above are when 60 bpm hear rate and are adjusted according to mean heart rate (i.e. lower thresholds for higher heart rate). The correction level should be adjusted individually, because inter-individual difference in HRV are quite significant and therefore a fixed threshold does not work optimally for all subjects. The optimal threshold is the lowest correction level which identifies all artefacts but does not identify too many normal RR intervals as artefacts.

In the **automatic artefact correction algorithm**, artefacts are detected from dRR series, which is a time series consisting of differences between successive RR intervals. The dRR series provides a robust way to separate ectopic and misplaced beats from the normal sinus rhythm. To separate ectopic and normal beats, time varying threshold (Th) is used. To ensure adaptation to different HRV levels, the threshold is estimated from the time varying distribution of the dRR series. For each beat, quartile deviation of the 90 surrounding beats is calculated and multiplied by factor 5.2. Beats within this range cover 99.95% of all beats if RR series is normally distributed. However, RR interval series is not often normally distributed, and thus, also some of the normal beats exceed the threshold. Therefore, decision algorithm is needed to detect artefact beats.

Ectopic beats form negative-positive-negative (NPN) or positive-negative-positive (PNP) patterns to the dRR series. Similarly long beats form positive-negative (PN) and short beats negative-positive (NP) patterns to the dRR series. Only dRR segments containing these patterns are classified as artefact beats. Missed or extra beats are detected by comparing current RR value with median of the surrounding 10 RR interval values (medRR). A missed beat is detected if current RR interval (RR(i)) satisfies condition

$$\left|\frac{RR(i)}{2} - medRR(i)\right| < 2Th \tag{1}$$

and an extra beat is detected if two successive RR intervals (RR(i) and RR(i+1)) satisfy condition

$$|RR(i) + RR(i+1) - medRR(i)| < 2Th. \tag{2}$$

Detected ectopic beats are corrected by replacing corrupted RR times by interpolated RR values. Similarly too long and short beats are corrected by interpolating new values to the RR time series. Missed beats are corrected by adding new R-wave occurrence time and extra beats are simply corrected by removing extra R-wave detection and recalculating RR interval series.

3.3 IBI time series trend removal

Another common feature that can alter the analysis significantly are the slow linear or more complex trends within the analysed time series. Such slow nonstationarities are characteristic for HRV signals and should be considered before the analysis. The origins of nonstationarities in HRV are discussed, e.g., in [3]. Two kinds of methods have been used to get around the nonstationarity problem. In [27], it was suggested that HRV data should be systematically tested for nonstationarities and that only stationary segments should be analysed. Representativeness of these segments in comparison with the whole HRV signal was, however, questioned in [9]. Other methods try to remove the slow nonstationary trends from the HRV signal before analysis. The detrending is usually based on first order [13, 14] or higher order polynomial [20, 14] models. In addition, Kubios HRV software includes an advanced detrending method originally presented in [24]. This method is based on smoothness priors regularisation and is suitable also for more complex trends of the time series. The method works like a time-varying highpass filter, smoothing the data according to the value of the smoothing parameter. The bigger the smoothing parameter is the lower is the cutoff frequency of the filter. We recommend using the smoothness priors method for removing IBI time series nonstationarities. The cutoff frequency should be below the low frequency band (< 0.04 Hz) not to remove any parts of the normal short term HRV.

4 Kubios HRV user interface

In this section, the graphical user interface (GUI) of Kubios HRV analysis software explained. Please note that functionalities available in the GUI depend on the version you are using (Standard or Premium). All the screen captures shown in this documentation are taken from the Kubios HRV Premium. Features available only in Premium are mentioned in the text.

The user interface window of Kubios HRV is shown in Fig. 3. The user interface is divided into three segments: 1) the RR interval series options segment on the top left corner, 2) the data browser segment on the top right corner, and 3) the results view segment on the bottom. These segments are described in Sections 4.1, 4.2 and 4.3, respectively.

Figure 3: The graphical user interface of Kubios HRV analysis software.

4.1 RR interval series options

The RR interval series options shown in Fig. 4 includes two functions: 1)*Artifact correction* and 2) *Samples for analysis*. The artifact correction options can be used to correct artifacts from a corrupted RR interval series. The user can select between two methods: 1) Automatic correction (available only in Premium) and 2) Threshold correction. The automatic correction is an accurate algorithm for detecting artifacts (missed, extra and misaligned beat detections) as well as ectopic beats. The threshold correction simply compares every beat interval against a local mean RR, and identifies the beat as artifact if it exceeds the specified threshold. The threshold should be selected individually, because normal variability in RR intervals can be quite different between individuals, and therefore, a fixed threshold could over or under correct the RR data. For details on these correction algorithms, see Section 3.2.

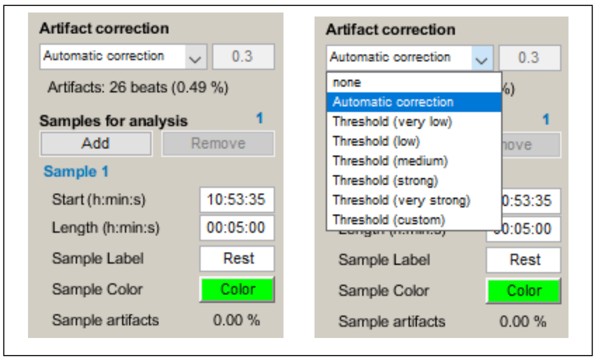


Figure 4: The RR interval series options segment of the user interface.

When using any of the correction methods, Kubios HRV displays on the RR data axis the corrected RR interval time series in blue and original uncorrected data in light grey as shown in Fig. 5 A. In this case, the RR interval data includes two clear artifacts: 1) a simulated ectopic beat at 10:13:40 (short interval followed by longer interval) and 2) a simulated missed beat detection at 10:15:30, which are both nicely corrected by using the automatic correction. The number of corrected artifacts in the whole recording is given under the Artifact correction controls and the number of artifacts corrected from the analysis sample is given under Samples for analysis controls. A piecewise cubic spline interpolation method is used in the corrections.

The importance of artifact correction is highlighted in Figs. 5 B-C. Please observe that having only two artifacts within the 5-min analysis segment has a significant effect on the time-domain HRV parameters, especially on SDNN, RMSSD and TINN. Thus, even single artifacts should always be either corrected or excluded from analysis. On the other hand, the number of corrected beats should not be too high (preferably <5%) not to cause significant distortion (suppressed variability) to analysis results. Finally, if ECG is measured, you should first try to directly correct the R-wave detections shown in the ECG data axis as described in Section 4.2.

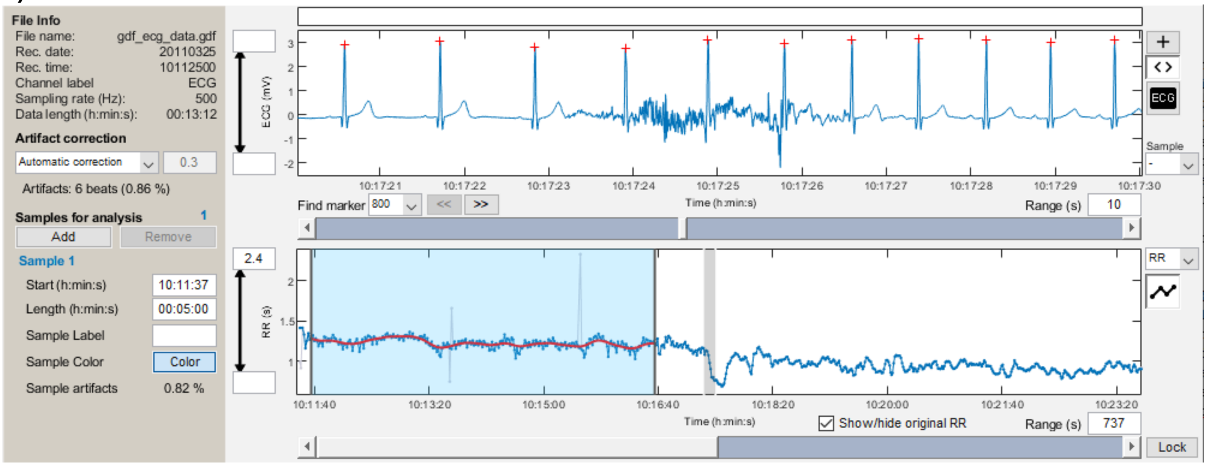
Using the *Samples for analysis* options, you can add as many analysis samples that you want (the number of samples is not limited) and you can easily modify the positioning and length of these samples. You can edit the samples using the Add (adding a new sample), Remove (removing the active sample), Start (changing sample onset), Length (changing sample length), Sample Label (an illustrative name for the sample), and Sample Color (e.g. color-code different types of samples) controls. In addition, you can also edit the samples using mouse directly on the RR data axis as described in Section 4.2. Sample Label and Color are optional. By default, Kubios HRV computes analysis results for every selected sample, but you can also choose to merge all samples into one longer sample before analysis using the Sample analysis type control under the RR data axis.

NOTE: In Kubios HRV Premium, you can automatically generate analysis samples by editing desired sample information within a structured CSV file ("`Kubios_Samples.csv`" found from the Sample Data folder). In the CSV file you can can define Sample Label, Color, Start time and End time for as many samples as necessary. Analysis samples can be defined differently for every file in the folder or you can also define general sample definitions that will be used for every file in the folder. More information about editing the CSV file is provided on the file header. If the CSV file is placed in the same folder with the data files and sample definitions for a given data file are found, the analysis samples will be automatically imported into Kubios HRV. This feature will make analysis of larger data sets with known sample times much easier.

4.2 Data browser

The data browser segment shown in Fig. 6 displays the measured ECG signal and the extracted RR interval series. If RR interval data is given as input (no ECG data), then only the RR data axis will be

A) RR artifact correction in Kubios HRV



B) Without artifact correction

Time-Domain Results

Variable	Value	Units
Mean RR*	1228.9	ms
STD RR (SDNN)	93.462	ms
Mean HR*	49.099	beats/min
STD HR	3.4995	beats/min
Min HR	44.851	beats/min
Max HR	55.089	beats/min
RMSSD	136.38	ms
NNxx	108	
pNNxx	44.444	%
HRV triangular index	9.7600	
TINN	989.00	ms

C) Artifacts corrected

Time-Domain Results

Variable	Value	Units
Mean RR*	1225.0	ms
STD RR (SDNN)	49.300	ms
Mean HR*	49.114	beats/min
STD HR	2.4390	beats/min
Min HR	45.358	beats/min
Max HR	54.298	beats/min
RMSSD	58.785	ms
NNxx	104	
pNNxx	42.798	%
HRV triangular index	11.619	
TINN	231.00	ms

Figure 5: RR interval artifact correction. A) The artifact corrected series is visualized on top of the raw RR interval series, summary of corrected beats within the recording is given on the right side of RR data axis. Time-domain analysis results B) before artifact correction and C) after the artifacts have been corrected.

displayed in bigger size. The ECG and RR interval data axes can be controlled by using Sliders (scrolling the data), Range edit boxes (to change data range shown on the axes), and Y-limit edit boxes (to change the y-axis scaling). The range of the ECG axis is displayed as a grey patch on the RR axis, which can be moved with left mouse button. ECG and RR axes can also be locked (Lock toggle button) and scrolled together.

The main functionalities of the data browser segment are described below.

Correcting beat detections – If ECG (or PPG) data is available, each detected beat is marked in the ECG axis with a "+" mark. Each mark can be moved or removed by right clicking it with the mouse (NOTE: By selecting Remove several, you can remove all detections after or before the current beat, or to remove beat detections within given interval. These options are useful for removing beat detections from noisy signal segments). In addition, new beat markers can be added by either right clicking some other marker and selecting "Add", or by pressing the (+) button on the right hand side of the ECG axis. Moved or added beat markers are by default snapped to closest ECG maximum, but manual positioning can also be achieved by pressing the (<>) button on the right hand side of the ECG axis (manual positioning should be used in case of PPG data). The changes made in beat detection markers will be automatically updated to RR interval series.

ECG printout – A printout of the ECG (or PPG) is generated when pressing (ECG). An example of the ECG printout is shown in Fig. 16. When clicking on the button for displaying a printout of the ECG recording, a popup window will appear in which you can select the range for the ECG to be printed (e.g. the whole recording or the range of the analysed sample). In addition, you can adjust

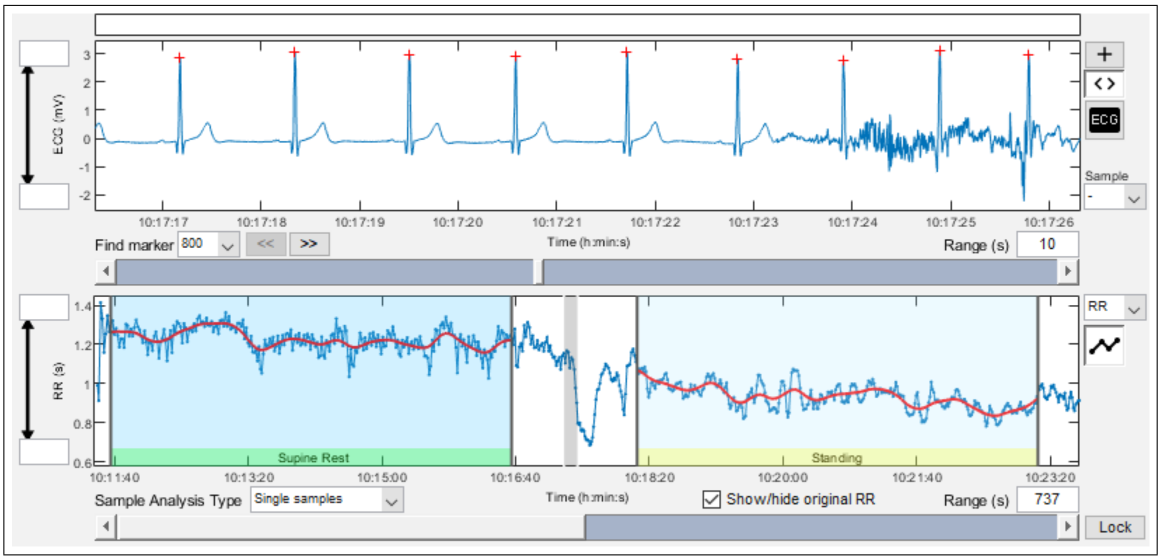


Figure 6: The data browser segment of the user interface.

"print speed" in mm/sec of the ECG in this popup window. Once you have defined the range for ECG printout and clicked the OK button, the ECG signal is displayed in a preview window where it can be easily printed or saved into a PDF file (see Section 5.2 for details on the preview window functionalities).

Data markers – Below the ECG (or PPG) data axis, you find controls for scrolling the markers of the recording session. These controls are hidden if marker data is not available.

Mouse gestures/shortcuts

- Pan (scroll, SHIFT + scroll) and zoom (CTRL + scroll) data on RR and ECG data views by using mouse scroll wheel.
- Pan both RR and ECG data views by dragging with middle mouse button.
- Add a new analysis sample (right mouse button + drag) and delete sample (CTRL + right mouse button).
- Move or resize analysis samples by dragging them with left mouse button from the middle of the sample (to move) or from the left or right edge (to resize).
- Center ECG data view to current cursor position in RR data view (CTRL + left mouse click).

4.3 Results view

The results for the selected RR interval sample are displayed in the results view segment (see Fig. 3, which shows results for a maximal cardiopulmonary exercise test). The results are divided into 1) Overview, 2) Time-domain, 3) Frequency-domain, 4) Nonlinear, and 5) Time-varying (available only in Premium) categories. The results of each category are displayed by pressing the corresponding button on the top of the results view segment. The results are by default updated automatically whenever analysis samples or analysis settings are changed. The processing time for computing all the analysis results depends on the length of measurement and number of analysis samples. If the updating of the results takes too much time, you can disable the automatic update by unchecking the "Auto-refresh results" check box on top of the results view segment. When unchecked, you can do all the changes to the analysis samples and settings at once, and then press the "Refresh" button when you want to update the results.

4.3.1 Results overview

The results overview section shown in Fig. 7 displays 1) a comparison between HRV parameters of selected analysis segment and normal resting values and 2) an overview of recording. The normal values for the HRV parameters (Mean RR, Mean HR, RMSSD, SD1 (%) and SD2 (%)) are obtained or derived from the quantitative systematic review by Nunan et al. 2010 [16]. The Stress index is the square root (to make the index normally distributed) of the Baevsky's stress index proposed in [2] and values of Baevsky's stress index between 50 and 150 are considered normal. The six HRV parameters divided into those reflecting paramsympathetic nervous system (PNS) tone (Mean RR, RMSSD and SD1 (%)) and those reflecting sympathetic nervous system (SNS) tone (Mean HR, Stress index and SD2 (%)) are illustrated on top of the normal value distributions. These graphs give a quick view about the level of subject's HRV with respect to normal values. NOTE: the normal values are from rest measurements, thus exercise or stressful situations are expected to produce higher heart rate and lower HRV. PNS and SNS indexes are computed to provide an overall measures of these nervous system activities as compared to normal resting values.

The overview of the recording includes an illustration of HR, RMSSD and Stress index time trends HR zones graph (time spent in each zone) stress zones (time spent in each stress zone) and energy expenditure (basal metabolic rate and activity related energy expenditure). These information are also provided in the time-varying report sheet (see Section 5.2), where also RMSSD zones are illustrated. HR, Stress index and RMSSD zones are defined as follows:

	HR zones (of HR_{max})		Stress zones ($\sqrt{SI}$)	(Baevsky's SI)		RMSSD zones
MAXIMUM:	90–100%	VERY HIGH:	$\geq$30	($\geq$900)	VERY LOW:	<5 ms
HARD:	80–90%	HIGH:	22.4–30	(500–900)	LOW:	5–12 ms
MODERATE:	70–80%	ELEVATED:	12.2–22.4	(150–500)	LOWERED:	12–27 ms
LIGHT:	60–70%	NORMAL:	7.1–12.2	(50-150)	NORMAL:	27–72 ms
VERY LIGHT:	50–60%	LOW:	<7.1	(<50)	HIGH:	$\geq$72 ms
INACTIVE:	<50 %					

The total energy expenditure is divided into three components: 1) Basal metabolic rate (BMR), 2) Diet Induced Thermogenesis (DIT), and 3) Activity related energy expenditure. Energy expenditure (EE) is computed using the Keytel's model without a measure of fitness (VO_2, max)according to [12]. The energy expenditure computations are based on heart rate, body weight, height and age, which can be defined in Preferences. In Kubios HRV Premium, these settings can also be changed by clicking the Change Personal Data button (to enable a quick way to update personal details for the current recording). DIT is the energy expenditure related to digestion of food and is estimated to be 10% of total energy expenditure within 24 hours. The BMR is estimated using the Mifflin-St Jeor equations, which have been found to be the most accurate.

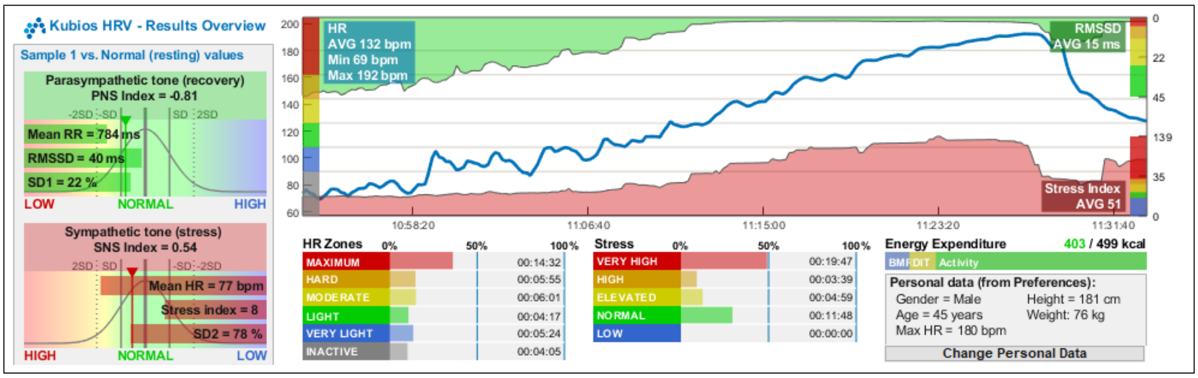


Figure 7: Results overview segment of Kubios HRV.

4.3.2 Time-domain results view

The time-domain results view shown in Fig. 8 A) displays the time-domain HRV parameters in a table and the RR interval and HR histograms in the two axes. All HRV parameters are calculated from the detrended RR interval data (if detrending is applied), but mean RR, mean HR as well as min and max HR values are exceptions (marked with the $*$ symbol). In the edit boxes below the histograms, you can define fixed lower and upper limits for RR and HR values. These limits are saved in software preferences, so you only need to enter them once. These limits have effect on how the RR and HR histograms are displayed, not only in the results view segment but also in the report figure described in Section 5.2. If you leave the edit boxes empty, the histograms are auto-scaled according to the minimum and maximum values of the data.

4.3.3 Frequency-domain results view

The frequency-domain results view shown in Fig. 8 B) displays the results for both FFT and AR spectrum estimation methods. Both methods are applied to the detrended RR series. The spectra of the two methods are presented in the two axes (FFT spectrum on the left and AR spectrum on the right). In Premium version, user can choose in software preferences (see. Section 6) to use Lomb-Scargle periodogram instead of FFT based Welch's periodogram. The frequency axes of the spectra are fixed to range from 0 Hz to the upper limit of HF band plus 0.1 Hz. Thus, for the default frequency band settings the frequency axis range is 0–0.5 Hz. The results for both spectra are displayed in the table on the left. If ECG is measured, an estimate of the respiration frequency is also computed. This estimate, i.e. electrocardiogram derived respiration (EDR) is shown as a vertical line in both spectrum estimates. The EDR value is also shown below the spectrum Y-limit options.

The frequency-domain results view includes the following settings. The power axes limits, can be adjusted with the options below the spectrum axes. The power axes can be selected to have either common (same limits for FFT/Lomb and AR spectra) or separate upper Y-limits. If common Y-limit is selected, it can also be entered manually into the edit box beside the selection button. The selected power axis options apply also for the report sheet. Below the spectrum Y-limits options, there is a checkbox, which can be used to show/hide the EDR. In addition, you can find settings for the very low frequency (VLF), low frequency (LF), and high frequency (HF) bands limits. The default values for the bands are VLF: 0–0.04 Hz, LF: 0.04–0.15 Hz, and HF: 0.15–0.4 Hz according to [25]. The default values for the bands can be restored by pressing the Defaults button. Adjustments to the frequency bands here apply only for the current session, if you want to change these settings permanently, you need to do it by editing software preferences (see Section 6).

4.3.4 Nonlinear results view

The nonlinear results view shown in Fig. 8 C) displays all the calculated nonlinear variables in one table. The Poincaré plot and the DFA results are also presented graphically in the two axes. In the Poincaré plot (left hand axis), the successive RR intervals are plotted as blue dots and the SD1 and SD2 variables obtained from the ellipse fitting technique are presented. In the DFA plot (right hand axis), the detrended fluctuations $F(n)$ are presented as a function of n in a log-log scale and the slopes for the short term and long term fluctuations α_1 and α_2, respectively, are indicated.

4.3.5 Time-varying results view

The time-varying results view shown in Fig. 8 D) displays the time-varying trend of the selected variable. Time-varying analysis is by default applied to the whole measurement, but you can also change Preferences to perform time-varying analysis for every analysis sample (see Section 6). The variable is selected using the two dropdown buttons on the top left corner of the view. Selectable variables are divided into Overview, Time-domain, Frequency-domain, and Nonlinear categories. The trend of the

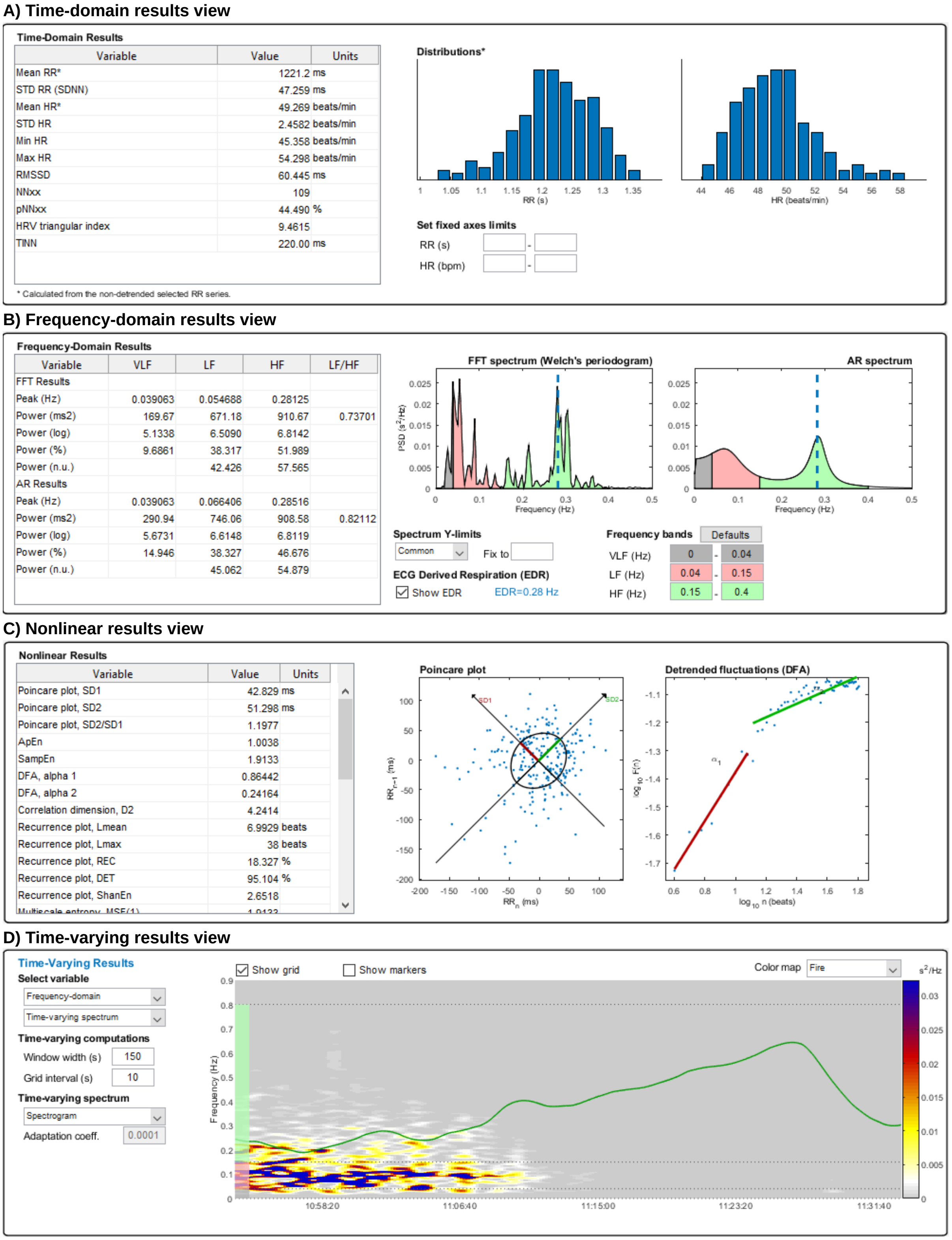


Figure 8: Results view segments of Kubios HRV: A) Time-domain results, B) Frequency-domain results, C) Nonlinear results and D) Time-varying results (available only in Premium).

selected variable will appear immediately in the axis. Trend lines can be plotted with or without backgroung grid and markers (checkboxes above the axis). When the time-varying spectrum is selected for view, a color bar indicating the power values is also shown on the right. The color map of the spectrum can be changed with the Color map dropdown button. The adjustable options for the time-varying analysis include the window width and grid interval for the moving window, which is used to calculate the results. In addition, the time-varying spectrum can be estimated using either the spectrogram method or the Kalman smoother method. The latter one is a parametric approach where the time-varying AR parameters are solved with a Kalman smoother algorithm as described in [22]. The adaptation speed of the algorithm can be adjusted manually by changing the Adaptation coeff. value (default 0.0001 bigger the value the faster the algorithm adapts to changes in the signal).

4.4 Menus and toolbar buttons

The user menus and toolbar buttons are located on the upper left hand corner of the user interface. There are all together four user menus and eight toolbar buttons. The toolbar button icons and their actions are explained below

- **Open new data file** button is for opening a new data file for analysis. If the results of the current analysis have not been saved, user is prompted to do so.
- **Save results** button is for saving the analysis results. The results can be saved in ASCII, PDF, and MATLAB MAT file format (see Section 5 for details).
- **Append results to "SPSS friendly" batch file** (available only in Premium) button is for adding the current analysis session results into an existing (or creating a new) "SPSS friendly" batch file (see Section 5 for details).
- **Print results** button is for printing the current results without opening report sheet windows.
- **Report preview** button opens the report sheet preview window which include all the analysis results (see Section 5.2 for details).
- **Edit preferences** button opens a preferences window in which you can, e.g., change the default values for analysis options (see Section 6 for details).
- **About Kubios HRV** button opens the about dialog of the software, which includes the version number and contact information. Also the Kubios HRV End User License Agreement can be viewed in the about dialog.
- **Zoom in/out** buttons can be used to zoom in or out on the ECG and RR data axes (please note that in other axes zooming is not enabled).
- **Close file** button closes the current data file. If the results of the current analysis have not been saved, user is prompted to do so.

All the above actions are also available on the user menus. The **File menu** includes Open, Save Results, Save Results As, Append Results to "SPSS friendly" Batch File, Print Results, Edit Preferences, Close, and Quit commands. The Quit command of the File menu is for exiting from the software. The File menu also displays the last nine opened data files. The **View menu** includes Markers menu and Report preview command. The Markers menu is for displaying possible stimuli or event markers presented in the experimental procedure and stored in the data file. If no markers are found from the data file the Markers menu will be disabled. The **Tools menu** includes Polar Flow Export option, which provides an easy way to export all your Polar Flow measurements into your computer in FIT file format to be analyzed in Kubios HRV (see Appendix A for details). Finally, the **Help menu** includes links to Kubios HRV User's guide, Kubios home page, Kubios Support pages, Contact us by e-mail, License information, and the About Kubios HRV dialog.

5 Saving the results

The analysis results can be saved by selecting Save Results or Save Results As from the File menu or by pressing the save button on the toolbar. This will open a file save dialog in which the saving type can be selected. There are three different types in which the results can be saved: 1) the results can be written in an ASCII text file for further inspection, 2) the report sheets generated from the results can be saved in a PDF-file, and 3) the results can be saved in a MATLAB MAT-file (available only in Premium). In addition to these, Kubios HRV Premium includes the Append to "SPSS friendly" batch file option to save session results into existing batch file (ideal for saving group results).

5.1 ASCII text file

When the ASCII text file is selected for the saving type, the numeric results of the analysis will be written in an CSV formatted text file. The resulting text file includes the following information in the enumerated order.

1. Software, user, and data file informations
2. Used analysis parameters
3. Samples selected for analysis
4. Results overview
5. Time-domain results
6. Frequency-domain results
7. Nonlinear results
8. Time-varying results
9. RR interval data and spectrum estimates

The columns of the file are separated with comma or semicolon (can be adjusted in software preferences) so that the results could easily be imported to, e.g., spreadsheet programs such as the Microsoft Excel® for further inspection. A preview of the CSV formatted text file showing standard analysis results is presented in Fig. 17 and showing time-varying results in Fig. 18.

5.2 PDF report

The PDF report includes all the analysis results for the current session. The report pages opens in a preview window where they can be easily printed or saved into a PDF file. Kubios HRV produces one report page for every analysis sample including all the time-domain, frequency-domain, and nonlinear analysis results as shown in Fig. 19. In addition, Kubios HRV Premium produces one page (or several pages if time-varying analysis has been set to apply into analysis samples in Preferences) including time-varying analysis results as shown in Fig. 20. The RR interval data and the sample selected for analysis are presented on top of all report pages and the analysis results below them.

When Save Results have been selected, the report page(s) can be saved in a single PDF-file by selecting Report figure as the saving type in the save dialog. In this case, the report page(s) will not be displayed, but just saved in the selected PDF-file. If you wish to view the report page(s), choose Report preview from the View menu or just press the corresponding toolbar button.

The report preview window includes 11 toolbar buttons and File and Page menus on the upper left hand corners of the windows. The toolbar buttons are explained below

Print button opens a print dialog from which the report page(s) (all pages, pages in certain range or current page) can be sent to the selected printer.

Save all pages as PDF-file button is for saving all report page(s) into a single PDF-file.

Zoom in button if for zooming in (magnifying) the report page.

Zoom out button is for zooming out the report page.

Reset to original size button can be used to restore the original zoom level. This also resets the size of the corresponding report preview window to its original size.

Move visible area button is for moving the visible area of the zoomed report page in the report preview window (just grab the sheet with mouse and drag it to the desired direction).

Close button is for closing the report preview.

Go to first page button is for displaying the first report page in the preview.

Go to previous page button is for displaying the previous report page in the preview.

Go to next page button is for displaying the next report page in the preview.

Go to last page button is for displaying the last report page in the preview.

The File menu includes Save All Pages as PDF, Print and Close commands, which are also given as toolbar buttons described above. The Page menu includes commands for changing the page that is displayed in the preview window (First page, Previous page, Next page, Last page), which are all also given as toolbar buttons.

5.3 Matlab MAT-file (available in Premium)

In addition to saving the numeric results into an ASCII text file or saving the report sheet(s) in a PDF-file, the analysis results can also be saved in a MATLAB MAT-file (compatible with MATLAB® R2006b or later). The MAT-file include all the analysis results and analysis parameters, exactly as they where when you saved the results. In addition, these files include the raw data (ECG or RR data). This saving option has two purposes:

1. The main purpose of the MAT-file is that by opening the MAT-file in Kubios HRV, you can return to the previously performed analyses session as it was (all settings and analysis samples are presented as they were) when the analysis was originally performed. Thus, the MAT file makes it easy for you to change something in the analysis (e.g. add a new analysis sample or change some settings) and re-analyse the data. Thus, we recommend that you save the analysis results always as a MAT-file, just in case if something needs to be done differently.
2. In addition, the MAT files are useful for anyone working with MATLAB (further analysis or processing can be performed easily by loading the MAT-files into MATLAB).

The MAT files include a single structured array variable named `Res`. The `Res` variable includes the numeric results as well as the RR interval data and all the analysis options. The `Res` structure includes four fields which are shortly described as follows

`f_name`: File name of the analysed data file
`f_path`: Full path for the analysed data file
`CNT`: Basic information of the data file (the field name refers to Neuroscan CNT-file for historical reasons)
`HRV`: Used analysis options, RR interval data, and all analysis results.

The `HRV` field is the most essential one of these fields. The `HRV` field includes six fields the contents of which are shortly described as follows

`Param:`	The analysis options used in the calculation of the results
`Data:`	The RR interval data
`Summary:`	Results overview including PNS and SNS indexes
`Statistics:`	Time-domain analysis results
`Frequency:`	Frequency-domain analysis results
`NonLinear:`	Nonlinear analysis results
`TimeVar:`	Time-varying analysis results

The variable names of the different fields are more or less self-descriptive and are not documented here.

5.4 ”SPSS friendly” batch file (available in Premium)

In Kubios HRV Premium, you can also save the analysis results into a ”SPSS friendly” batch file. This saving options is ideal for saving group results, for example if you need to analyse HRV data of several subjects and want to be able to have the group results easily available for statistical testing e.g. in MS Excel or SPSS. Alternatively, you can use the batch file saving option for saving HRV results of repeated personal recordings, e.g. to monitor training effect or daily stress levels. Kubios uses Comma Separated Values (CSV) file format for the batch file, which can be easily imported into many spreadsheet and statistical software packages (MS Excel, SPSS).

The Append to ”SPSS friendly” batch file functions as follows:

1. When saving the analysis results of the first subject (i.e. when you want to initialise a new CSV file), select the destination and file name for the new CSV file from the file dialog. In this case, Kubios HRV will initialise the CSV file by writing the column labels and add the analysis results into the first row below the column labels.

2. When saving the analysis results of other subjects, simply select the previously saved CSV file. In this case, Kubios HRV will add the results of the current analysis session into the last row of the file.

The structure of the ”SPSS friendly” batch file is presented in Fig. 21. Every row of the batch file consists of the file name string and used analysis parameters values ([1x18] array) followed by the following information for every analysis sample: sample info consisting of sample onset/offset time and artifact correction statistics ([1x2] array), and HRV analysis results ([1x82] array). For more details on the different HRV analysis variables please see Table 3.

6 Kubios HRV preferences

Kubios HRV includes several settings related to how the ECG or RR interval data is processed and analysed. The default values for these settings are designed to be suitable for short-term (normal human) HRV recordings, but may sometimes need to be redefined. Some of these settings can be adjusted in the user interface to apply for the current analysis session, but in order to make permanent changes into these settings you need to edit them at software preferences. Preferences can be edited by selecting Edit Preferences from the File menu or by pressing the corresponding toolbar button. This will open the preferences window in which the preference values can be redefined. The preferences are divided into four categories: 1) User information, 2) Input data & pre-processing, 3) Analysis options (divided into time/frequency-domain, nonlinear and time-varying subcategories), and 4) Report settings.

In the **User information** settings shown in Fig. 9 you can set up your personal contact information (Name, Department, and Organization). This information will only be included in the bottom left corner of the report sheet and in the beginning of the ASCII text file including the analysis results. That is, the user information is meant just for indicating the person/organisation that has carried out the analysis. The values given for Gender, Date of birth, Height, Weight and Max HR are used in HR zones and energy expenditure computations.

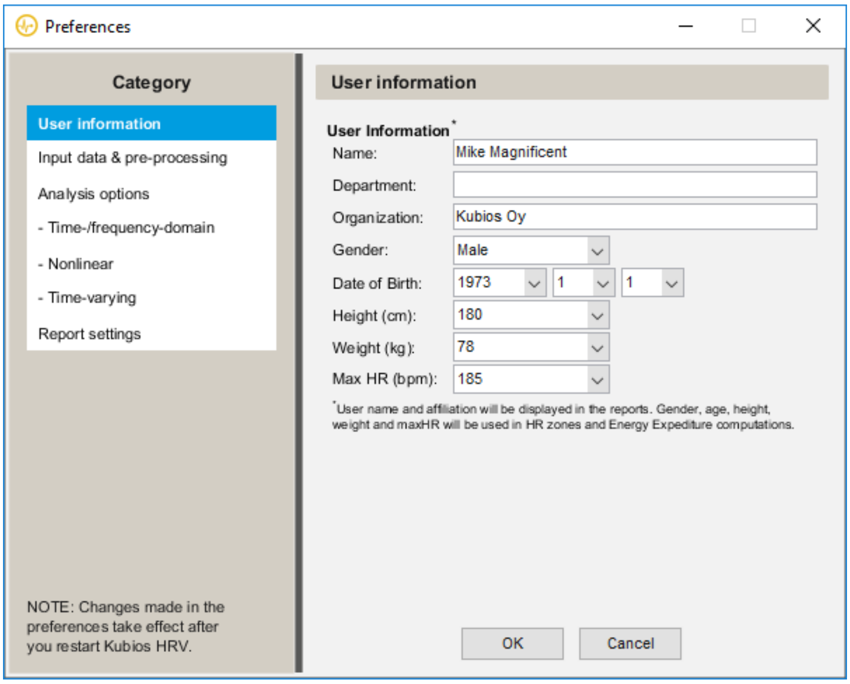


Figure 9: Set up preferences window of the software – User information settings.

From the **Input data & pre-processing** settings shown in Fig. 10, you can change the default input data type into any of the file formats mentioned in Section 2. The selected input data type is used as the default data type every time a new data file is opened, so you can save one additional click by defining the data type you usually work on as the default. The default artifact correction method and acceptance threshold can be modified here (see Section 3.2). By default the acceptance threshold is set to 5%, meaning that analysis samples having more than 5% trigger a warning of low quality data. Under Signal type you can specify if you are using ECG or PPG data for HRV analysis (this has effect on the algorithm applied in beat detection). If you are using RR or IBI data, this selection does not have any effect. When ECG is selected as signal type, you can modify QRS detection settings. You can force Kubios to look for the R-waves either from positive of negative amplitudes, or let Kubios to decide (R-wave polarity=Automatic). Also, you can manually fix the prior guess for the average RR interval (used by the QRS detector as initial value), or let Kubios try to estimate it automatically. By default the QRS detection settings are set to automatic and there is no reason to change them unless you are experiencing problems in R-wave detection. If PPG is selected as signal type, you can modify the pulse acceptance threshold (not visible in Fig. 10 because ECG selected as signal type), which adjusts the sensitivity of the pulse detector algorithm. In addition, the interpolation rate (by default a 4 Hz cubic spline interpolation is applied to form equidistantly sampled time series from the IBI data) and detrending method (by default smoothness priors method is used to remove very low frequency trend components) can be adjusted here. The default detrending settings will remove most of the very low frequency components (frequencies below 0.04 Hz) from the RR interval series prior to analysis. By doing so the HRV analysis results are not affected by the slow changes in HR level and are more sensitive to the short-term HRV regulated by the autonomic nervous system. We recommend removing the trend using the Smoothness priors method which was proposed in [24]. The default settings of the method are optimised for human HRV, but if needed you can change the smoothness of the removed trend by editing the Lambda value. The estimated cut-off frequency for the given Lambda value is presented next to the Lambda value edit box. In the user interface, the trend removed from the RR interval data is shown as a red line over the analysed RR data sample.

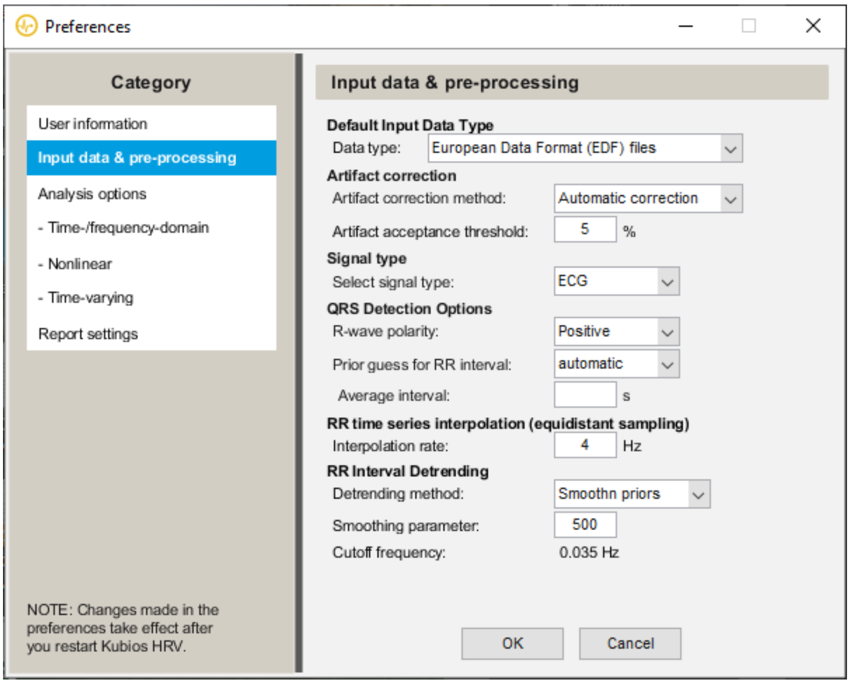


Figure 10: Set up preferences window of the software – Input data & pre-processing settings.

The **Analysis options** settings include some general analysis options, and detailed settings of different analysis methods under three sections: 1) Time/frequency-domain, 2) Nonlinear and 3) Time-varying. The general analysis settings shown in Fig. 11 includes selection of analysis to be performed: 1) Standard analysis (all time-domain, frequency-domain and nonlinear analysis for selected stationary samples), and 2) Time-varying analysis. Only selected analysis will be performed and thus un-checking unnecessary analysis type will speed up the computations. Using the settings for RR interval samples, you can define how many analysis samples are generated by default and what is the length of these samples. In case of several samples, you can choose the analysis type between Single samples (in this case, Kubios will perform analysis for every sample separately) and Merge samples (the samples are merged into one longer sample for which analysis is then performed). Finally, the Update mode can be changed between Automatic (analysis results are refreshed automatically) and Manual (you need to refresh results manually).

The time and frequency-domain analysis settings are shown in Fig. 12. For time-domain analysis methods, you can adjust the window width of the moving average filter (default 5 beats), which is used to extract minimum and maximum HR values. Also, you can adjust the threshold used in the computation of NNxx and pNNxx parameters (default 50 ms → NN50 and pNN50). Under HRV frequency bands, the very low frequency (VLF), low frequency (LF), and high frequency (HF) bands of HRV frequency-domain analysis can be adjusted. The default values for these frequency bands are VLF: 0–0.04 Hz, LF: 0.04–0.15 Hz, and HF: 0.15–0.4 Hz according to [25]. The rest of the settings relate to spectrum

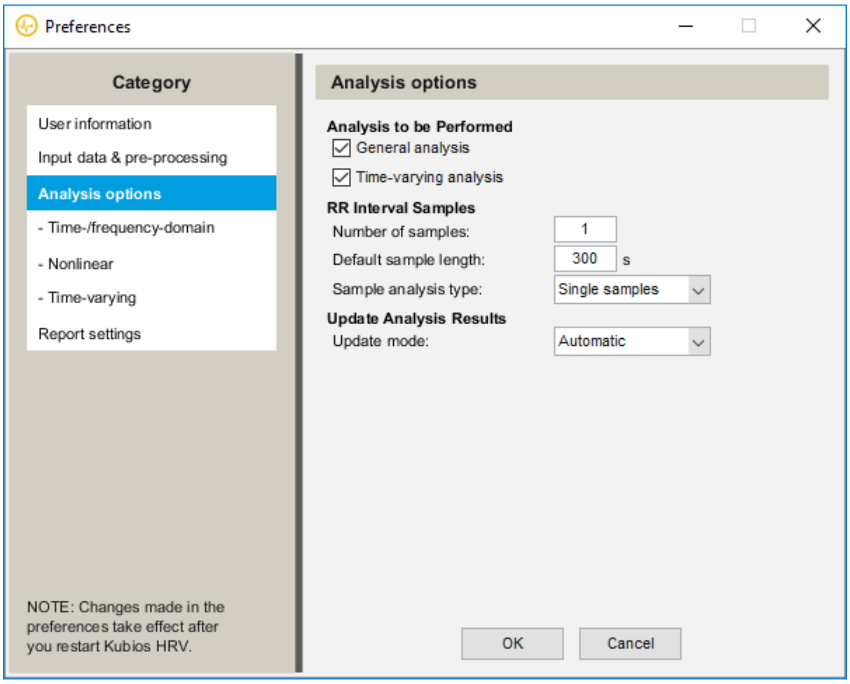


Figure 11: Set up preferences window of the software – Analysis options settings.

estimation methods. The points in frequency-domain is given as points/Hz and corresponds by default to the window width of the FFT spectrum. If spectrum interpolation is desired the points in frequency-domain can be increased. The spectrum for the selected RR interval sample is calculated both with Welch's periodogram method (FFT spectrum) and with an autoregressive modeling based method (AR spectrum). In the Welch's periodogram method, the used window width and window overlap can be adjusted by editing the corresponding value. The default value for window width is 300 seconds and the default overlap is 50 % (corresponding to 150 seconds), which produce three overlapping windows for a 10-min (600 sec) analysis sample. As an alternative to FFT spectrum, you can select to use the Lomb-Scargle periodogram, which does not assume equidistant sampling and has been recommended for HRV spectral analysis in some studies. The default smoothing window for this spectrum estimate is 0.02 Hz. For the AR spectrum, there are two options that can be selected. First, the order of the used AR model can be selected. The default value for the model order is 16. The second option is whether or not to use spectral factorization in the AR spectrum estimation. In the factorization the AR spectrum is divided into separate components and the power estimates of each component are used for the band powers. Spectral factorisation has been shown to provide some advantage especially when e.g. the HF component is partially overlapping with the LF band [22].

The nonlinear analysis settings are shown in Fig. 13. As the first option, you can choose if the nonlinear parameters are also computed from the detrended RR interval data or not (by default computations are made from detrended data). If you uncheck this option, then all nonlinear parameters are always computed from non-detrended RR interval data. The embedding dimension m (default 2 beats) and the tolerance value r (default 0.2 times SD) used in for the computation of Approximate entropy (ApEn) and Sample entropy (SampEn) can be modified. Note that the tolerance value is adjusted in relation to the standard deviation of the RR interval data. Next, limits of the short-term (N1) and long-term fluctuations used in the Detrended fluctuation analysis (DFA) can be modified (defaults 4-12 and 13-64 beats, respectively). Finally, the embedding dimension (default 10 beats) used both in the computation of the Correlation dimension (D_2) and in the Recurrence plot analysis (RPA), and the threshold level (default $\sqrt{10}$) used in RPA, can be modified.

The time-varying analysis settings are shown in Fig. 14. You can choose to apply time-varying analysis (analysis mode) on the whole measurement (default) or for analysis samples. You can adjust the width (default 300 sec) and grid interval (default 60 sec) of the moving window used for time-varying analysis. The grid interval defined how much the window is moved at every step, and analysis results

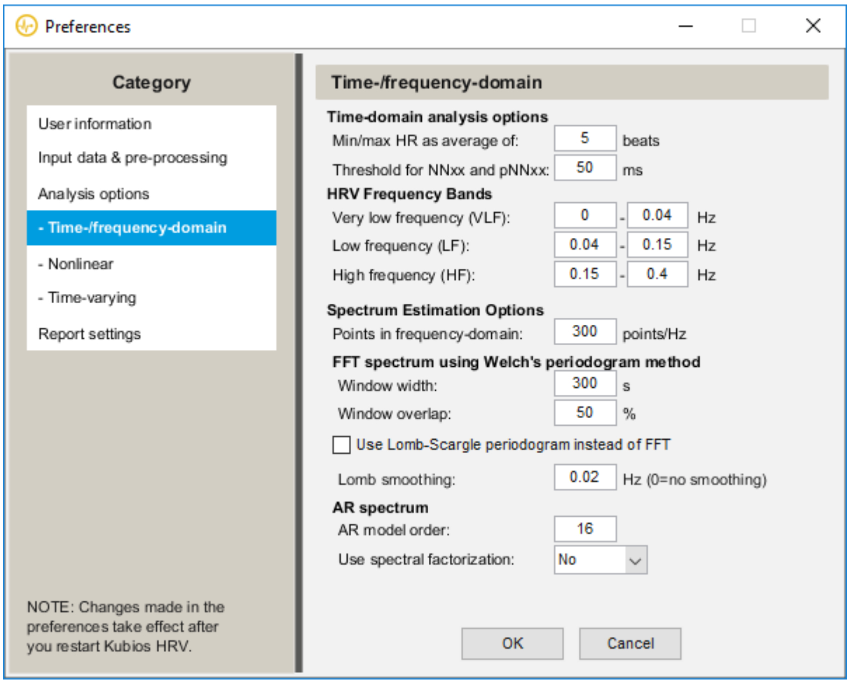


Figure 12: Set up preferences window of the software – Analysis options: time-/frequency-domain methods.

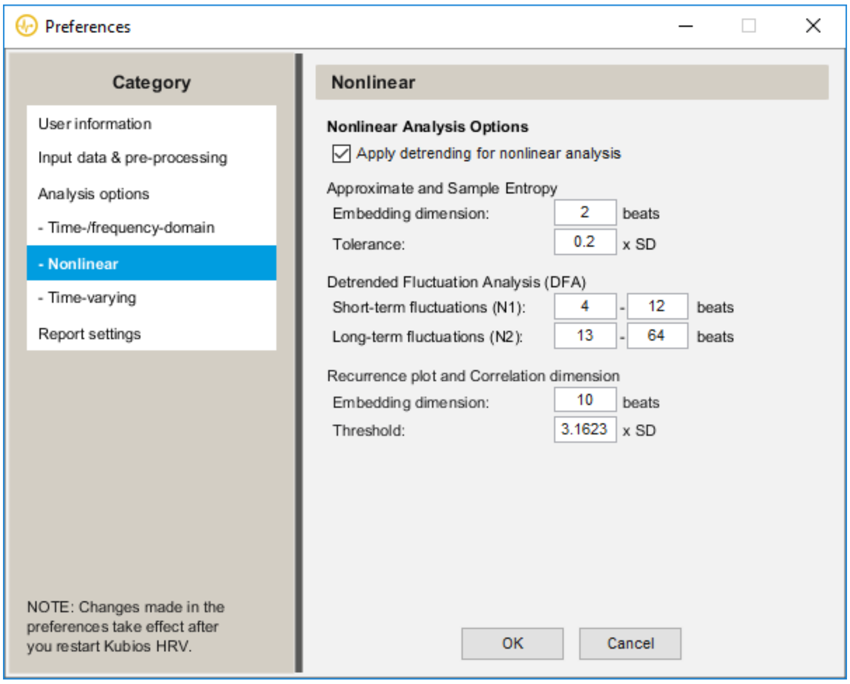


Figure 13: Set up preferences window of the software – Analysis options: nonlinear methods.

are available at these intervals. For example, you you want to performe time-varying analysis at 10-min non-overlapping segments for the whole duration of recording, you need to select the whole recording as an analysis sample and then define the window width and grid interval both to 600 seconds. For the time-varying spectrum estimation there are two options: 1) the well known spectrogrm (default) and 2) a Kalman smoother spectrum estimate proposed in [22].

The **Report settings** shown in Fig. 15 include the following options. The contents of the results to be exported can be selected by checking the Standard and/or Time-varying results options. If either one

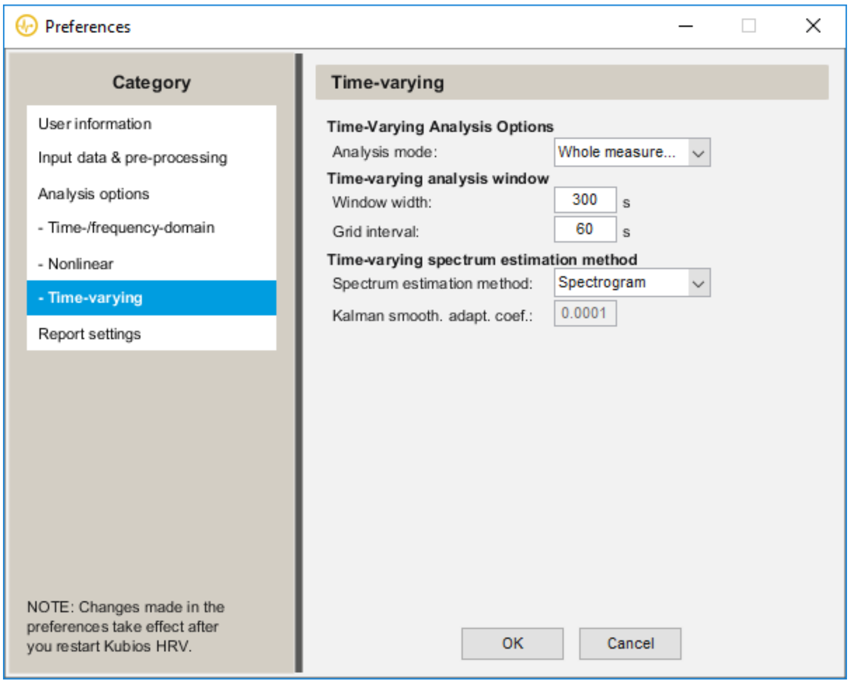


Figure 14: Set up preferences window of the software – Analysis options: time-varying methods.

of these is unchecked, only the selected results will be exported (in PDF reports or the other export file formats). Concerning the ASCII text file as well as the "SPSS friendly" CSV batch file, the field delimiter and decimal point used when saving the results can be selected (the default values being comma "," for field delimiter and dot "." for decimal separator). The paper size of the report page(s) can be changed between A4 (210×297 mm) and Letter (8.5×11 inch) size. Only one spectrum figure is shown in the report page, but you can here choose if you want to show the FFT/Lomb or the AR spectrum estimate. For the time-varying report page you can choose which parameters are displayed by selecting: 1) two time-domain parameters (STD RR, STD HR, RMSSD, NNxx, pNNxx, HRV triangular index, TINN), 2) two frequency-domain parameters (VLF, LF and HF peaks frequencies, band powers in different units and LF/HF ratio can be selected), and 3) two nonlinear parameters (SD1, SD2, SD2/SD1, ApEn, SampEn, DFA α_1, DFA α_2).

All modifications for the preferences are saved by pressing the OK button. Please note that the changes made into preferences take effect only after restarting Kubios HRV (either closing the analysis session or closing the program). In addition to above described analysis options, there are various other editable options which have mainly influence on the usability of the software. Such options are e.g. the Range and Y-limit values of the data axis and various visualization options. The values of these options are preserved in memory and any changes made to them will be applied in the future sessions.

All the preferences and preserved options used by Kubios HRV are saved in user specific folders[2].

Windows 7,8 or 10:

HRV Standard: `C:\Users\<username>\AppData\Roaming\Kubios\KubiosHRVStandard`

HRV Premium: `C:\Users\<username>\AppData\Roaming\Kubios\KubiosHRVPremium`

Mac OSX:

HRV Standard: `~/Library/Preferences/Kubios/KubiosHRVStandard`

[2]Note that the AppData folder in Windows is hidden by default and are not visible in the File Explorer if the "Show hidden files and folders" is not selected from the "Folder Options" section of the File Explorer.

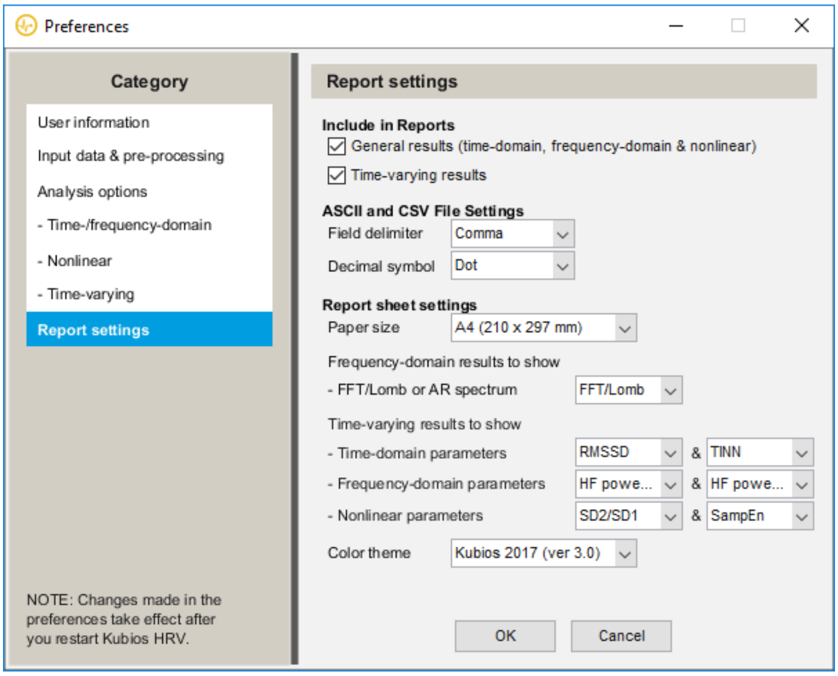


Figure 15: Set up preferences window of the software: Report settings category.

HRV Premium: `~/Library/Preferences/Kubios/KubiosHRVPremium`

Linux:

HRV Standard: `~/.kubios/KubiosHRVStandard`

HRV Premium: `~/.kubios/KubiosHRVPremium`

where `<username>` is the name of your user profile. The folder will include a file named `KubiosHRVprefs.mat`, which includes all the preferences for the analysis options, user information and user interface usability. The file is created when Kubios HRV is started for the first time and it will be updated whenever the preference values are edited/updated. The original settings of the preferences can be restored by deleting this preference file. Also, if the preference file gets somehow corrupted, the preference file will be rewritten using the default values.

7 Kubios HRV analysis parameters

Kubios HRV is provides a detailed analyses of HRV with over 40 analysis parameters. Summary of all HRV parameters calculated by Kubios HRV is given in 3.

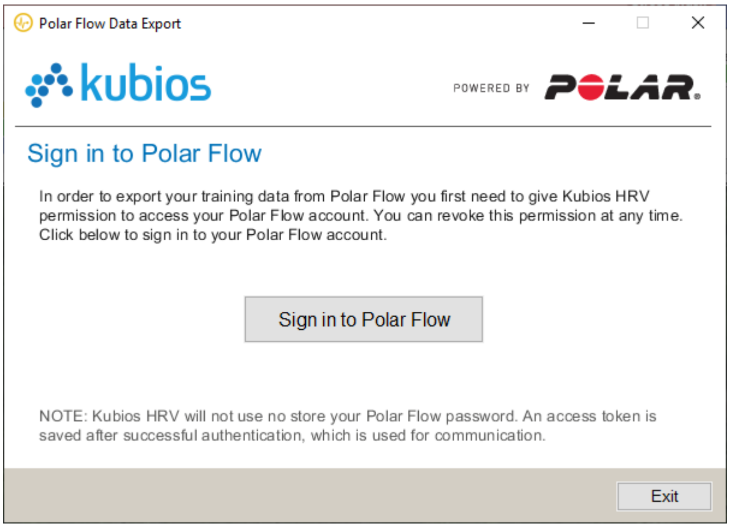
Table 3: HRV parameters calculated by Kubios HRV software (* only preview is available in Standard version ** parameters are available only in Premium version).

Parameter	Units	Description	References
Overview			
Stress index	-	Square root of Baevsky's stress index	[2]
PNS index	-	Parasympathetic nervous system activity compared to normal resting values	
SNS index	-	Sympathetic nervous system activity compared to normal resting values	
HR zones*	[%]	Time spent in Maximum, Hard, Moderate, Light, Very light, and Inactive HR zones	
Stress zones*	[%]	Time spent in Very high, High, Elevated, Normal, and Low stress levels	
RMSSD zones**	[%]	Time spent in Very low, Low, Lowered, Normal, and High RMSSD levels	
Energy exp.*	[kcal]	Basal metabolic rate (BMR) using the Mifflin-St Jeor formula and energy expenditure (EE) estimated using Keytel's model	[12]
Time-Domain			
$\overline{\text{RR}}$	[ms]	The mean of RR intervals	
STD RR (SDNN)	[ms]	Standard deviation of RR intervals	
$\overline{\text{HR}}$	[1/min]	The mean heart rate	
STD HR	[1/min]	Standard deviation of instantaneous heart rate values	
Min & Max HR	[1/min]	Minimum and maximum HR computed using N beat moving average (default value: $N = 5$)	
RMSSD	[ms]	Square root of the mean squared differences between successive RR intervals	
NNxx	[beats]	Number of successive RR interval pairs that differ more than xx ms (default value: xx$= 50$)	
pNNxx	[%]	NNxx 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	[25]
TINN	[ms]	Baseline width of the RR interval histogram	[25]
SDANN	[ms]	Standard deviation of the averages of RR intervals in 5-min segments	[25]
SDNNI	[ms]	Mean of the standard deviations of RR intervals in 5-min segments	[25]
Frequency-Domain			
Spectrum		Welch's (or Lomb-Scargle*) periodogram and AR spectrum estimates	
Peak frequency	[Hz]	VLF, LF, and HF band peak frequencies	
Absolute power	[ms^2]	Absolute powers of VLF, LF, and HF bands	
Absolute power	[log]	Natural logarithm transformed values of absolute powers of VLF, LF, and HF bands	
Relative power	[%]	Relative powers of VLF, LF, and HF bands $\text{VLF}\,[\%] = \text{VLF}\,[\text{ms}^2]/\text{total power}\,[\text{ms}^2] \times 100\%$ $\text{LF}\,[\%] = \text{LF}\,[\text{ms}^2]/\text{total power}\,[\text{ms}^2] \times 100\%$ $\text{HF}\,[\%] = \text{HF}\,[\text{ms}^2]/\text{total power}\,[\text{ms}^2] \times 100\%$	
Normalized power	[n.u.]	Powers of LF and HF bands in normalised units $\text{LF}\,[\text{n.u.}] = \text{LF}\,[\text{ms}^2]/(\text{total power}\,[\text{ms}^2] - \text{VLF}\,[\text{ms}^2])$ $\text{HF}\,[\text{n.u.}] = \text{HF}\,[\text{ms}^2]/(\text{total power}\,[\text{ms}^2] - \text{VLF}\,[\text{ms}^2])$	
LF/HF	-	Ratio between LF and HF band powers	
EDR**	[Hz]	ECG derived respiration (available only if ECG data used for HRV analysis)	
Nonlinear			
SD1	[ms]	In Poincaré plot, the standard deviation perpendicular to the line-of-identity	[4, 5]
SD2	[ms]	In Poincaré plot, the standard deviation along the line-of-identity	
SD2/SD1	-	Ratio between SD2 and SD1	
ApEn	-	Approximate entropy	[21, 8]
SampEn	-	Sample entropy	[21]
DFA, α_1	-	In detrended fluctuation analysis, short term fluctuation slope	[18, 19]
DFA, α_2	-	In detrended fluctuation analysis, long term fluctuation slope	
D_2**	-	Correlation dimension	[10, 11]
RPA**:		Recurrence plot analysis:	[26, 7, 28]
Lmean	[beats]	Mean line length	
Lmax	[beats]	Maximum line length	
REC	[%]	Recurrence rate	
DET	[%]	Determinism	
ShanEn	-	Shannon entropy	
MSE**	-	Multiscale entropy for scale factor values $\tau = 1, 2, \ldots, 20$	[6]
Time-Varying**			
Overview parameters: Stress index, PNS index, SNS index			
Time-domain parameters: $\overline{\text{RR}}$, SDNN, $\overline{\text{HR}}$, STD HR, Min HR, Max HR, RMSSD, NNxx, pNNxx, HRV tri ind., TINN			
Frequency-domain parameters: Time-varying spectrum (Spectrogram) VLF, LF and HF peak frequencies VLF, LF and HF powers in ms^2, log and % LF and HF powers in n.u. LF/HF ratio EDR			
Nonlinear parameters: SD1, SD2, SD2/SD1, ApEn, SampEn, DFA α_1 and α_2			

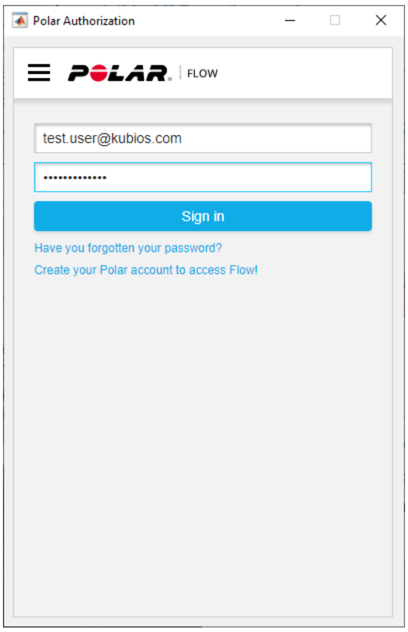
A Appendix: Polar Flow export (available in Premium)

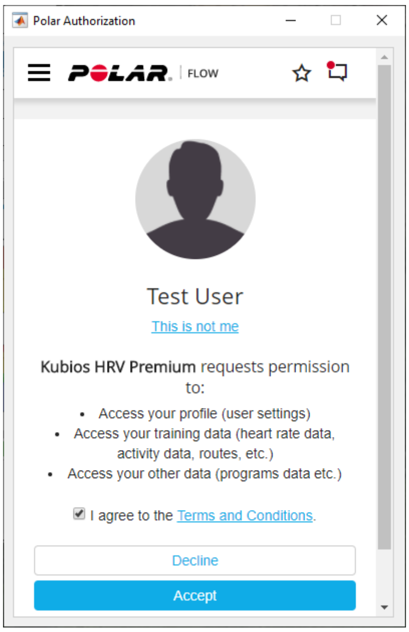
The Polar Flow export option provides an easy way to export your Polar Flow measurements into your computer hard drive in FIT file format, which can then be analyzed in Kubios HRV software. Previously, Polar users were able to export RR data from Polar Flow only when using the RR recording test available in Polar V800. However, by using the new Polar Flow export functionality, you will have access to the RR data required for HRV analysis from all Polar Flow compatible Polar devices when using them with H6, H7 or H10 heart rate sensor. Furthermore, you can access the RR data also from your exercise mode measurements (which has not been possible before even with the V800 monitor). In order to start exporting your Polar Flow measurements, click Polar Flow Export in Tools menu and follow given instructions. The steps needed to link your Polar Flow account with Kubios HRV are shortly described below. Please note that only those training sessions that are added to Polar Flow after linking with Kubios HRV are accessible through Polar Flow API.

When you click the Polar Flow Export option for the first time, a window instructing you to sign in to your Polar Flow account pops up



Click "Sign in to Polar Flow" to continue.

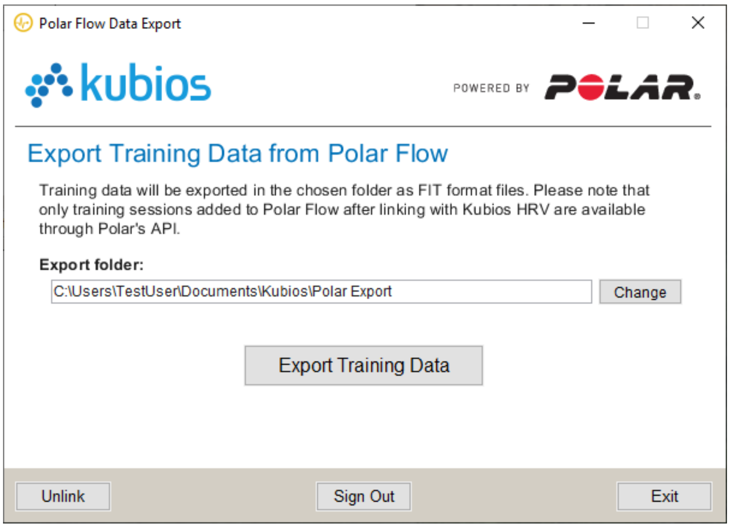




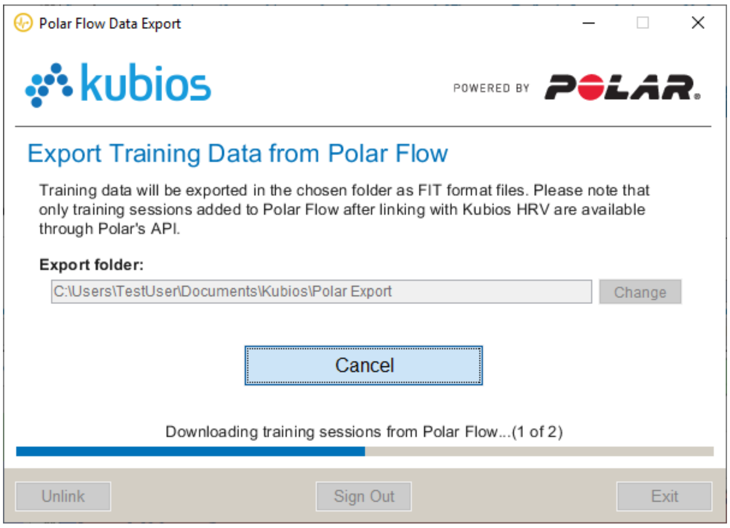
Next, you need to Sign In to your Polar Flow account and give Kubios HRV permission to access your

Polar Flow account data. The Terms and Conditions link is not unfortunately working on the popup figure, but you can find these from https://www.kubios.com/polar-flow-authorization. To continue, confirm that you agree to the Terms and Conditions and click Accept. You should then receive a notice that your Polar Flow account is successfully linked with Kubios HRV.

Once you have linked your Polar Flow account with Kubios HRV, you can export your training data by clicking the Polar Flow Export from Tools menu.



You can define the export folder, where your training data from Polar Flow will be exported. Every training measurement that you have uploaded into Polar Flow after linking your account with Kubios HRV or after the previous successful export, will be exported into the selected folder in FIT file format when clicking Export Training Data button.



If you do not have new measurements uploaded to Polar Flow, you will receive a notification "No new training data available in Polar Flow". Please note, that not all the FIT files exported from Polar Flow necessarily include RR data and can not thus be opened in Kubios HRV. RR data is available only when you have used a chest strap (Polar H6, H7 or H10) to record heart rate. RR data is not available when you have measured heart rate from your wrist (wrist-based HR) or by using the optical Polar OH1 armband.

You can Unlink Kubios HRV from your Polar Flow account whenever you want. However, you should do this only if you do not anymore need to access your training data in Kubios HRV. If you want to temporarily disable the access to your Polar Flow account from Kubios HRV, you can Sign Out from your account instead. In this case, you are required to sign in again the next time you want to export data from Polar Flow, but all your latest training data are still accessible through the Polar Flow link.

B Appendix: Kubios HRV figures

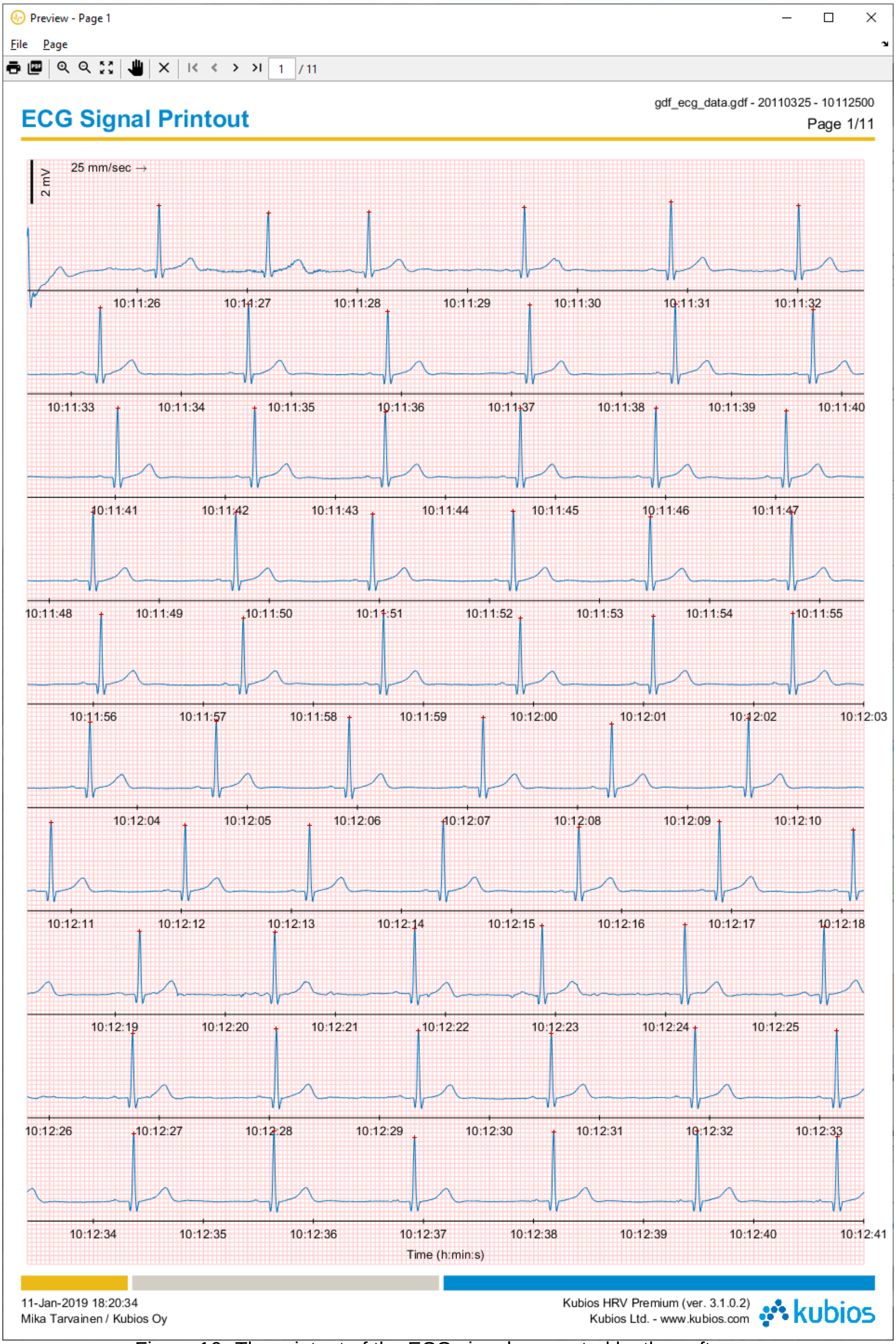


Figure 16: The printout of the ECG signal generated by the software.

gdf_ecg_data_hrv.txt - Notepad

File Edit Format View Help

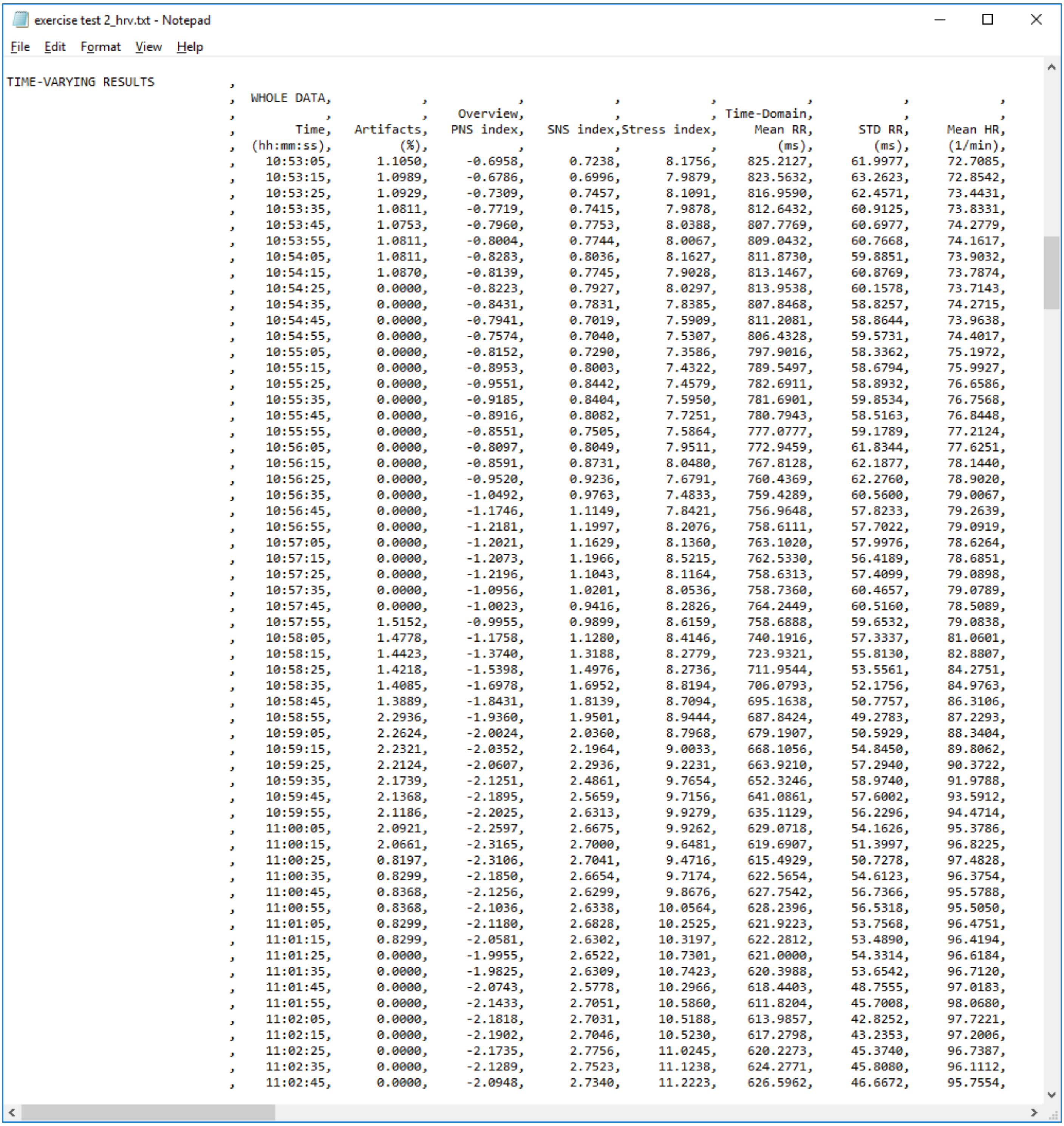
```
RESULTS FOR SINGLE SAMPLES
GENERAL RESULTS
                              ,   SAMPLE 1,          ,   SAMPLE 2,          ,
Results Overview              ,
  PNS index:                  ,     2.0976,          ,    -0.9035,          ,
  SNS index:                  ,    -1.4239,          ,     0.7153,          ,
  Stress index:               ,     7.7092,          ,    10.2157,          ,

Time-Domain Results           ,
 Statistical parameters       ,
  Mean RR  (ms):              ,  1221.8653,          ,   926.2762,          ,
  STD RR (ms):                ,    46.9558,          ,    38.8521,          ,
  Mean HR (beats/min):        ,    49.1052,          ,    64.7755,          ,
  STD HR (beats/min):         ,     1.9664,          ,     2.7292,          ,
  Min HR (beats/min):         ,    45.3378,          ,    56.2588,          ,
  Max HR (beats/min):         ,    54.1956,          ,    75.2068,          ,
  RMSSD (ms):                 ,    60.2735,          ,    25.7212,          ,
  NNxx (beats):               ,        107,          ,         13,          ,
  pNNxx (%):                  ,    43.8525,          ,     4.0248,          ,
  SDANN (ms):                 ,           ,          ,           ,          ,
  SDNN index (ms):            ,           ,          ,           ,          ,
 Geometric parameters         ,
  RR tri index:               ,   9.800000,          ,   9.818182,          ,
  TINN (ms):                  ,   222.0000,          ,   195.0000,          ,

Frequency-Domain Results      ,FFT spectrum, AR spectrum,FFT spectrum, AR spectrum,
 Peak frequencies             ,
  VLF (Hz):                   ,   0.040000,   0.040000,   0.036667,   0.040000,
  LF (Hz):                    ,   0.050000,   0.066667,   0.090000,   0.076667,
  HF (Hz):                    ,   0.280000,   0.283333,   0.153333,   0.150000,
 Absolute powers              ,
  VLF (ms^2):                 ,   180.8218,   297.7777,   255.9336,   179.3181,
  LF (ms^2):                  ,   763.6735,   734.0305,  1303.7187,  1094.9688,
  HF (ms^2):                  ,   924.7122,   879.5288,   257.0478,   221.6942,
  VLF (log):                  ,     5.1975,     5.6963,     5.5449,     5.1892,
  LF (log):                   ,     6.6381,     6.5986,     7.1730,     6.9985,
  HF (log):                   ,     6.8295,     6.7794,     5.5493,     5.4013,
 Relative powers              ,
  VLF (%):                    ,     9.6734,    15.5717,    14.0870,    11.9850,
  LF (%):                     ,    40.8543,    38.3847,    71.7590,    73.1842,
  HF (%):                     ,    49.4694,    45.9932,    14.1484,    14.8173,
 Normalized powers            ,
  LF (n.u.):                  ,    45.2295,    45.4642,    83.5252,    83.1497,
  HF (n.u.):                  ,    54.7672,    54.4761,    16.4683,    16.8350,
 Total power (ms^2):          ,  1869.2625,  1912.3014,  1816.8025,  1496.1827,
 LF/HF ratio:                 ,     0.8258,     0.8346,     5.0719,     4.9391,
 EDR (Hz):                    ,   0.281484,          ,   0.211432,          ,

Nonlinear Results             ,
 Poincare plot                ,
  SD1 (ms):                   ,  42.707471,          ,  18.216088,          ,
  SD2 (ms):                   ,  50.974043,          ,  51.899223,          ,
  SD2/SD1 ratio:              ,   1.193563,          ,   2.849087,          ,
 Approximate entropy (ApEn):  ,     0.9847,          ,     1.1039,          ,
 Sample entropy (SampEn):     ,     1.8090,          ,     1.4747,          ,
 Detrended fluctuation analysis (DFA),
  alpha 1:                    ,     0.7933,          ,     1.4561,          ,
  alpha 2:                    ,     0.2283,          ,     0.3835,          ,
 Correlation dimension (D2):  ,     3.7293,          ,     3.1393,          ,
 Recurrence plot analysis (RPA),
  Mean line length (beats):   ,     7.0860,          ,    10.3558,          ,
  Max line length (beats):    ,         38,          ,        206,          ,
  Recurrence rate (REC) (%):  ,    18.9421,          ,    30.2746,          ,
  Determinism (DET) (%):      ,    95.2417,          ,    98.2490,          ,
  Shannon entropy:            ,     2.6716,          ,     3.1229,          ,
```

Figure 17: Kubios HRV Premium results for supine rest (Sample 1) and standing (Sample 2) saved as a CSV formatted text file.



exercise test 2_hrv.txt - Notepad

File Edit Format View Help

TIME-VARYING RESULTS

WHOLE DATA		Overview			Time-Domain		
Time	Artifacts	PNS index	SNS index	Stress index	Mean RR	STD RR	Mean HR
(hh:mm:ss)	(%)				(ms)	(ms)	(1/min)
10:53:05	1.1050	-0.6958	0.7238	8.1756	825.2127	61.9977	72.7085
10:53:15	1.0989	-0.6786	0.6996	7.9879	823.5632	63.2623	72.8542
10:53:25	1.0929	-0.7309	0.7457	8.1091	816.9590	62.4571	73.4431
10:53:35	1.0811	-0.7719	0.7415	7.9878	812.6432	60.9125	73.8331
10:53:45	1.0753	-0.7960	0.7753	8.0388	807.7769	60.6977	74.2779
10:53:55	1.0811	-0.8004	0.7744	8.0067	809.0432	60.7668	74.1617
10:54:05	1.0811	-0.8283	0.8036	8.1627	811.8730	59.8851	73.9032
10:54:15	1.0870	-0.8139	0.7745	7.9028	813.1467	60.8769	73.7874
10:54:25	0.0000	-0.8223	0.7927	8.0297	813.9538	60.1578	73.7143
10:54:35	0.0000	-0.8431	0.7831	7.8385	807.8468	58.8257	74.2715
10:54:45	0.0000	-0.7941	0.7019	7.5909	811.2081	58.8644	73.9638
10:54:55	0.0000	-0.7574	0.7040	7.5307	806.4328	59.5731	74.4017
10:55:05	0.0000	-0.8152	0.7290	7.3586	797.9016	58.3362	75.1972
10:55:15	0.0000	-0.8953	0.8003	7.4322	789.5497	58.6794	75.9927
10:55:25	0.0000	-0.9551	0.8442	7.4579	782.6911	58.8932	76.6586
10:55:35	0.0000	-0.9185	0.8404	7.5950	781.6901	59.8534	76.7568
10:55:45	0.0000	-0.8916	0.8082	7.7251	780.7943	58.5163	76.8448
10:55:55	0.0000	-0.8551	0.7505	7.5864	777.0777	59.1789	77.2124
10:56:05	0.0000	-0.8097	0.8049	7.9511	772.9459	61.8344	77.6251
10:56:15	0.0000	-0.8591	0.8731	8.0480	767.8128	62.1877	78.1440
10:56:25	0.0000	-0.9520	0.9236	7.6791	760.4369	62.2760	78.9020
10:56:35	0.0000	-1.0492	0.9763	7.4833	759.4289	60.5600	79.0067
10:56:45	0.0000	-1.1746	1.1149	7.8421	756.9648	57.8233	79.2639
10:56:55	0.0000	-1.2181	1.1997	8.2076	758.6111	57.7022	79.0919
10:57:05	0.0000	-1.2021	1.1629	8.1360	763.1020	57.9976	78.6264
10:57:15	0.0000	-1.2073	1.1966	8.5215	762.5330	56.4189	78.6851
10:57:25	0.0000	-1.2196	1.1043	8.1164	758.6313	57.4099	79.0898
10:57:35	0.0000	-1.0956	1.0201	8.0536	758.7360	60.4657	79.0789
10:57:45	0.0000	-1.0023	0.9416	8.2826	764.2449	60.5160	78.5089
10:57:55	1.5152	-0.9955	0.9899	8.6159	758.6888	59.6532	79.0838
10:58:05	1.4778	-1.1758	1.1280	8.4146	740.1916	57.3337	81.0601
10:58:15	1.4423	-1.3740	1.3188	8.2779	723.9321	55.8130	82.8807
10:58:25	1.4218	-1.5398	1.4976	8.2736	711.9544	53.5561	84.2751
10:58:35	1.4085	-1.6978	1.6952	8.8194	706.0793	52.1756	84.9763
10:58:45	1.3889	-1.8431	1.8139	8.7094	695.1638	50.7757	86.3106
10:58:55	2.2936	-1.9360	1.9501	8.9444	687.8424	49.2783	87.2293
10:59:05	2.2624	-2.0024	2.0360	8.7968	679.1907	50.5929	88.3404
10:59:15	2.2321	-2.0352	2.1964	9.0033	668.1056	54.8450	89.8062
10:59:25	2.2124	-2.0607	2.2936	9.2231	663.9210	57.2940	90.3722
10:59:35	2.1739	-2.1251	2.4861	9.7654	652.3246	58.9740	91.9788
10:59:45	2.1368	-2.1895	2.5659	9.7156	641.0861	57.6002	93.5912
10:59:55	2.1186	-2.2025	2.6313	9.9279	635.1129	56.2296	94.4714
11:00:05	2.0921	-2.2597	2.6675	9.9262	629.0718	54.1626	95.3786
11:00:15	2.0661	-2.3165	2.7000	9.6481	619.6907	51.3997	96.8225
11:00:25	0.8197	-2.3106	2.7041	9.4716	615.4929	50.7278	97.4828
11:00:35	0.8299	-2.1850	2.6654	9.7174	622.5654	54.6123	96.3754
11:00:45	0.8368	-2.1256	2.6299	9.8676	627.7542	56.7366	95.5788
11:00:55	0.8368	-2.1036	2.6338	10.0564	628.2396	56.5318	95.5050
11:01:05	0.8299	-2.1180	2.6828	10.2525	621.9223	53.7568	96.4751
11:01:15	0.8299	-2.0581	2.6302	10.3197	622.2812	53.4890	96.4194
11:01:25	0.0000	-1.9955	2.6522	10.7301	621.0000	54.3314	96.6184
11:01:35	0.0000	-1.9825	2.6309	10.7423	620.3988	53.6542	96.7120
11:01:45	0.0000	-2.0743	2.5778	10.2966	618.4403	48.7555	97.0183
11:01:55	0.0000	-2.1433	2.7051	10.5860	611.8204	45.7008	98.0680
11:02:05	0.0000	-2.1818	2.7031	10.5188	613.9857	42.8252	97.7221
11:02:15	0.0000	-2.1902	2.7046	10.5230	617.2798	43.2353	97.2006
11:02:25	0.0000	-2.1735	2.7756	11.0245	620.2273	45.3740	96.7387
11:02:35	0.0000	-2.1289	2.7523	11.1238	624.2771	45.8080	96.1112
11:02:45	0.0000	-2.0948	2.7340	11.2223	626.5962	46.6672	95.7554

Figure 18: Kubios HRV Premium time-varying analysis results saved as a CSV formatted text file.

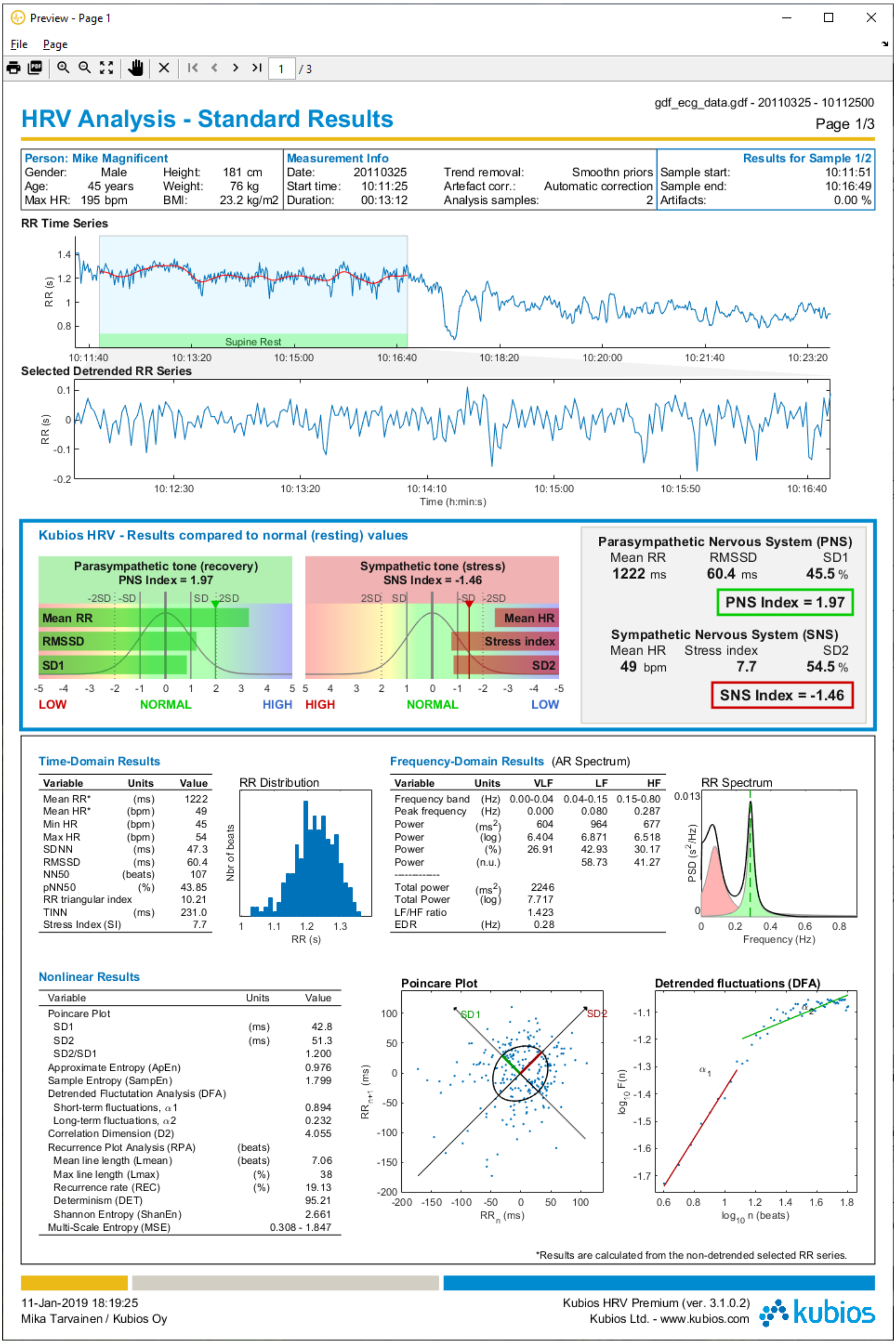


Figure 19: Kubios HRV Premium report page showing standard HRV results for healthy young male during supine rest.

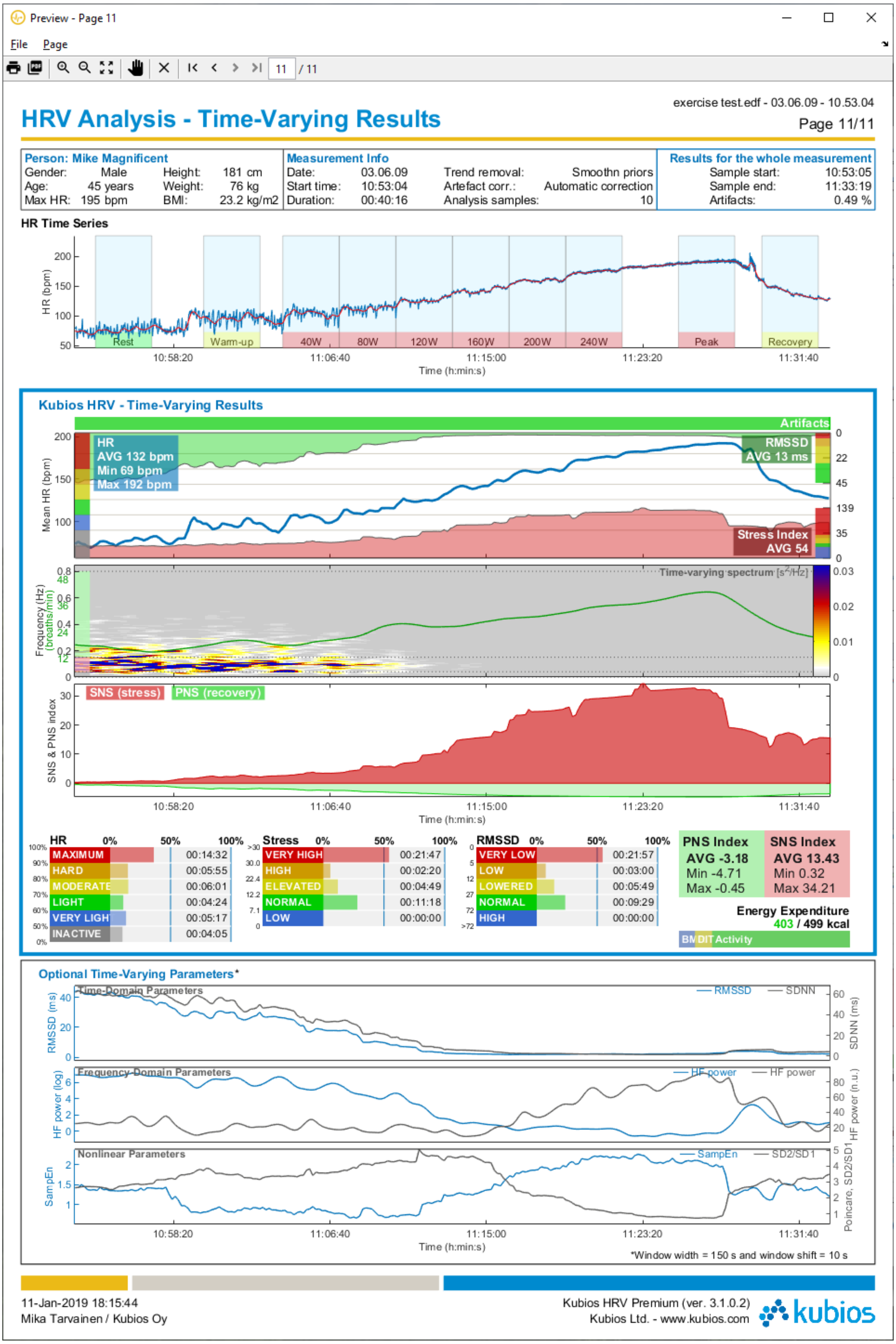


Figure 20: Kubios HRV Premium report page showing time-varying analysis results for maximal cardiopulmonary exercise test performed by healthy young male.

A)

		Sample 1 (S_1)			Sample N (S_N)	
Files analysed	Parameters	Info	HRV results		Info	HRV results
`FileName`	`PRM#[PARAMETERS]`	`S1_[INFO]`	`S1_[VARIABLES]`	...	`S1_[INFO]`	`S1_[VARIABLES]`
`subject_1.txt`	`[1x18] array`	`[1x2]`	`[1x82]`		`[1x2]`	`[1x79]`
`subject_2.txt`	`[1x18] array`	`[1x2]`	`[1x82]`		`[1x2]`	`[1x79]`
⋮	⋮	⋮	⋮		⋮	⋮
`subject_M.txt`	`[1x18] array`	`[1x2]`	`[1x82]`		`[1x2]`	`[1x79]`

B)

Parameters

`#Detrending`: Detrending method used
`#InterpRate`: Interpolation rate of RR data
`#MinMaxHR`: Nbr of beats averaged for Min/Max HR
`#NNxxThreshold`: Threshold for NNxx and pNNxx in msec
`#VLFband`: VLF frequency band limits in Hz
`#LFband`: LF frequency band limits in Hz
`#HFband`: HF frequency band limits in Hz
`#FreqPoints`: Nbr of points in spectra (points/Hz)
`#FFTorLomb`: FFT (Welch) or Lomb periodogram used
`#WelchWindow`: Window width (overlap) in Welch
`#LombWindow`: Smoothing window width in Lomb periodogram
`#ARspectrum`: Order of AR spectrum (factorisation)
`#Entropy`: Embedding dimension (tolerance)
`#DFAshortterm`: DFA, short-term fluctuations range
`#DFAlongterm`: DFA, long-term fluctuations range
`#RecurrencePlot`: RPA, embedding dimension (threshold)
`#NbrSamples`: Number of analysed samples
`#ArtifactCorrection`: RR artifact correction method

Sample Info

`Onset-Offset`: Sample onset-offset times (hh:mm:ss)
`Artifacts (%)`: Corrected artifacts within the sample

HRV variables

`PNS index`: Parasympathetic nervous system tone index
`SNS index`: Sympathetic nervous system tone index
`Stress index`: Square root of Baevsky's stress index
`Mean RR (ms)`: Mean of RR intervals
`SDNN (ms)`: Standard deviation of RR intervals
`Mean HR (bpm)`: Mean heart rate
`SD HR (bpm)`: Standard deviation of heart rate
`Min HR (bpm)`: Minimum HR using N beat MA
`Max HR (bpm)`: Maximum HR using N beat MA
`RMSSD (ms)`: RMS of successive RR interval differences
`NNxx (beats)`: Nbr or successive RRs > xx ms
`pNNxx (%)`: Percentage of successive RRs > xx ms
`HRV triangular index`: RR histogram area/height
`TINN (ms)`: RR histogram baseline width
`SDANN (ms)`: SD of 5-min RR interval segment means
`SDNNI (ms)`: Mean of 5-min RR interval segment SDs
`VLFpeak_FFT`* `(Hz)`: VLF band peak frequency (FFT)
`LFpeak_FFT (Hz)`: LF band peak frequency (FFT)
`HFpeak_FFT (Hz)`: HF band peak frequency (FFT)
`VLFpow_FFT (ms2)`: Absolute VLF power (FFT)
`LFpow_FFT (ms2)`: Absolute LF power (FFT)
`HFpow_FFT (ms2)`: Absolute HF power (FFT)
`VLFpow_FFT (log)`: Log VLF power (FFT)
`LFpow_FFT (log)`: Log LF power (FFT)
`HFpow_FFT (log)`: Log HF power (FFT)
`VLFpow_FFT (%)`: Relative VLF power (FFT)
`LFpow_FFT (%)`: Relative LF power (FFT)
`HFpow_FFT (%)`: Relative HF power (FFT)
`LFpow_FFT (n.u.)`: Normalised LF power (FFT)
`HFpow_FFT (n.u.)`: Normalised HF power (FFT)
`TOTpow_FFT (ms2)`: Total spectral power (FFT)
`LF_HF_ratio_FFT`: LF/HF power ratio (FFT)
`VLFpeak_AR (Hz)`: VLF band peak frequency (AR spectrum)
`LFpeak_AR (Hz)`: LF band peak frequency (AR spectrum)
`HFpeak_AR (Hz)`: HF band peak frequency (AR spectrum)
`VLFpow_AR (ms2)`: Absolute VLF power (AR spectrum)
`LFpow_AR (ms2)`: Absolute LF power (AR spectrum)
`HFpow_AR (ms2)`: Absolute HF power (AR spectrum)
`VLFpow_AR (log)`: Log VLF power (AR spectrum)
`LFpow_AR (log)`: Log LF power (AR spectrum)
`HFpow_AR (log)`: Log HF power (AR spectrum)
`VLFpow_AR (%)`: Relative VLF power (AR spectrum)
`LFpow_AR (%)`: Relative LF power (AR spectrum)
`HFpow_AR (%)`: Relative VLF power (AR spectrum)
`LFpow_AR (n.u.)`: Normalised LF power (AR spectrum)
`HFpow_AR (n.u.)`: Normalised HF power (AR spectrum)
`TOTpow_AR (ms2)`: Total spectral power (AR spectrum)
`LF_HF_ratio_AR`: LF/HF power ratio (AR spectrum)
`EDR (Hz)`: ECG derived respiration
`SD1 (ms)`: Poincaré plot short term variability
`SD2 (ms)`: Poincaré plot long term variability
`SD2_SD1_ratio`: SD2/SD1 ratio
`ApEn`: Approximate entropy
`SampEn`: Sample entropy
`D2`: Correlation dimension
`DFA1`: DFA, short term fluctuations slope
`DFA2`: DFA, long term fluctuations slope
`RP_Lmean (beats)`: RPA, mean line length
`RP_Lmax (beats)`: RPA, maximum line length
`RP_REC (%)`: RPA, recurrence rate
`RP_DET (%)`: RPA, determinism
`RP_ShanEn`: RPA, Shannon entropy
`MSE_1` …`MSE_20`: Multiscale entropy for scales $\tau = 1, \ldots, 20$

* If Lomb-Scargle periodogram is used instead of Welch's periodogram, `FFT` → `Lomb`

Figure 21: Structure of the "SPSS friendly" batch file: A) overview of the file structure and B) short description of the fields.

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