SEB4233
Biomedical Signal Processing

ECG Analysis 3: Heart Rate Variability

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Heart rate Variability

- "Inter-beat-interval" (IBI, in ms units).
  - The length of the cardiac cycle
  - Also termed as"heart period", i.e., the period of the cardiac cycle.
  - Can be determined by measuring each occurrence of a specific component of the ECG waveform.
- R-wave
  - The most common point of the cardiac cycle used when measuring heart period is the peak of the R-wave.
  - This is due to the fact that the R wave is manifested as a sharp positive peak followed by a negative deflection in the ECG waveform.
  - The peak of the R-wave is normally greater in amplitude than all other peaks in the ECG making it easily distinguishable.
- Thus, IBI (also known as R-R interval) is often defined as the duration between successive R-waves

1 Band-pass Filtering

- The purpose of the filtering is to enhance the QRS complexes of the digitised ECG, while suppressing noise and artefacts.
- The frequency content of a QRS for newborn is essentially in the interval of 5-15 Hz.
- The lower cut-off frequency should be chosen to minimise the influence of large amplitude of P and T waves while still accentuating ectopic beats.
- The upper cut-off frequency is needed to suppress motion artefacts but not narrow QRS complexes.

2 QRS waves detection algorithms (R wave localization)

- Most QRS detectors involve two stages:
  - the signal transformation
    - to obtain a single positive peak for each QRS, which thus allows the use of a threshold-based peak detector in the second stage.
  - the decision rule
    - applied to the output of the first stage to determine the locality of a QRS complex.
- Nygards and Sornmo found that the envelope of the ECG to be useful for obtaining a positive-valued peak for each QRS waveform from the ECG. The envelope is defined by

$$z(n) = \sqrt{(x^2(n) + \hat{x}^2(n))}$$

  where $x(n)$ is discrete time signal (i.e. the discrete ECG) and $\hat{x}(n)$ is the discrete Hilbert Transform of $x(n)$.
- The envelope is further smoothed out by using a smoothing filter with a triangular impulse response (or also known as Barlett window) to remove any ripples present in the function.
- The resultant signal is known as the 'delineation function', $d(n)$, in which the QRS waveform is represented by a single positive pulse centred around the position of the R peak.
- The onset and the end of the QRS complex is then determined from threshold crossings in the delineation function.

3 Outliers removal

- A cardiac beat originating elsewhere than at the SA is known as the ectopic beat. Ectopic beats are usually manifested as a premature beat followed by a longer than normal RR interval before the next normal beat.
- Ectopic beats affect RR interval/HRV analysis by introducing artefact into the computations of time, frequency and time-frequency domain features.
- The ectopic beats and any artefacts due to QRS missed detections are denoted as outliers. These outliers affect the quality of the RR interval series.
- The time-domain signal associated with HRV exhibits a sharp transient at the ectopic beat making it unusable, particularly when estimating the spectral estimate of HRV.
- An isolated ectopic beat corrupts the spectral estimate because of the broad-band nature of the impulse-like artefact. In particular, frequency-domain features are erroneously overestimated.

3 Outliers removal (Cont.)

- Therefore, corrections of outliers must be done prior to analysis or index estimations of the HRV.
- A widely used technique to reduce effects of outliers is to discard the outliers from the time series and interpolate the RR interval signal using either linear or cubic splines.
- Cubic spline interpolation is well suited for replacing isolated ectopic beats.
- It is, however, not suitable for replacing runs of ectopic beats, since it results in a large and apparently artifactual increase in low-frequency power.
- Linear interpolation is a better choice when faced with runs of outliers.

4 Resampling

- Resampling methods is used to transform the time series into equidistantly sampled signals
- Two main resampling approaches are widely used;
  - ➢ The interpolation-resampling
  - ➢ The window-averaging-resampling
- Proper resampling methods ensures:
  - ➢ RR interval time series do not suffer from the distortion
  - ➢ Provide an equal time scale for further frequency and TF analysis
- The above mentioned resampling methods can be applied to :
  - ➢ RR interval time series - the instantaneous heart period (IHP)
  - ➢ Reciprocal of the RR interval time series - the instantaneous heart rate (IHR)

5 Detrending

- Trends have been found to result from alterations in posture or activity during ECG recording.
- They tend to mask spectral components (i.e. spectral peaks) of HRV
- The steeper the trend, the less detail is evident in the spectra.
- Detrending often yields more informative spectra with all major spectral peaks visible.
- Hence, average heart rate and trends are often removed from the data segment before further analysis is performed.
- These trends are usually very low frequency and can be removed by a high pass filter.
- Alternatively, a linear trend is assumed, estimated using linear regression, and subtracted from the time series

Analysis of Heart Rate Variability (HRV)

- Analysis of Heart rate variability (HRV) provides a non-invasive method to assess the neuronal influences on the cardiaoregulatory function.
- Since as defined before HRV is the fluctuation of RR intervals, these physiological fluctuations reflect the nonlinear feedback control systems created by the interaction between sympathetic and parasympathetic activities.
- The separate rhythmic contributions from sympathetic and parasympathetic activities modulate the heart rate, and thus the RR intervals in the ECG.
- The HRV analysis can be performed on short-term ECG recordings (lasting from 1 to 5 minutes) or on long-term recordings lasting for 24 hours depending on application at hand.
- Two conventional approaches to the analysis of HRV: the time-domain and the frequency-domain (spectral).
- Due to the nonstationary nature of the HRV, these approaches fail to reveal valuable information embedded in signal.
- To remedy this situation, time-frequency based methods have been recently introduced.

Time-domain analysis

- Time-domain features are derived from simple statistical calculations or
- The most commonly used indices for short term analysis are the mean and variance of RR intervals.

Time-domain analysis

Table 2.1: Statistical and geometrical parameters recommended by the Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology

Statistical Measures	Units	Description
SDNN	ms	Standard deviation of all RR intervals.
SDANN	ms	Standard deviation of the averages of RR intervals in all 5 min segments of the entire recording.
RMSSD	ms	The square root of the mean of the sum of the squares of differences between adjacent RR intervals.
SDNN index	ms	Mean of the standard deviations of all RR intervals for all 5 min segments of the entire recording.
SDSD		Standard deviation of differences between adjacent RR intervals
NN50 count		Number of pairs of adjacent RR intervals differing by more than 50 ms in the entire recording. Three variants are possible counting all such RR intervals pairs or only pairs in which the first or the second interval is longer.
pNN50	%	NN50 count divided by the total number of all RR intervals.
Geometric measures	**Units**	**Description**
HRV triangular index		Total number of all RR intervals divided by the height of the histogram of all RR intervals measured on a discrete scale with bins of 7·8125 ms (1/128 s).
TINN	ms	Baseline width of the minimum square difference triangular interpolation of the highest peak of the histogram of all RR intervals.
Differential index	ms	Difference between the widths of the histogram of differences between adjacent RR intervals measured at selected heights (e.g. at the levels of 1000 and 10 000 samples).
Logarithmic index		Coefficient of the negative exponential curve which is the best approximation of the histogram of absolute differences between adjacent RR intervals.

Frequency domain analysis

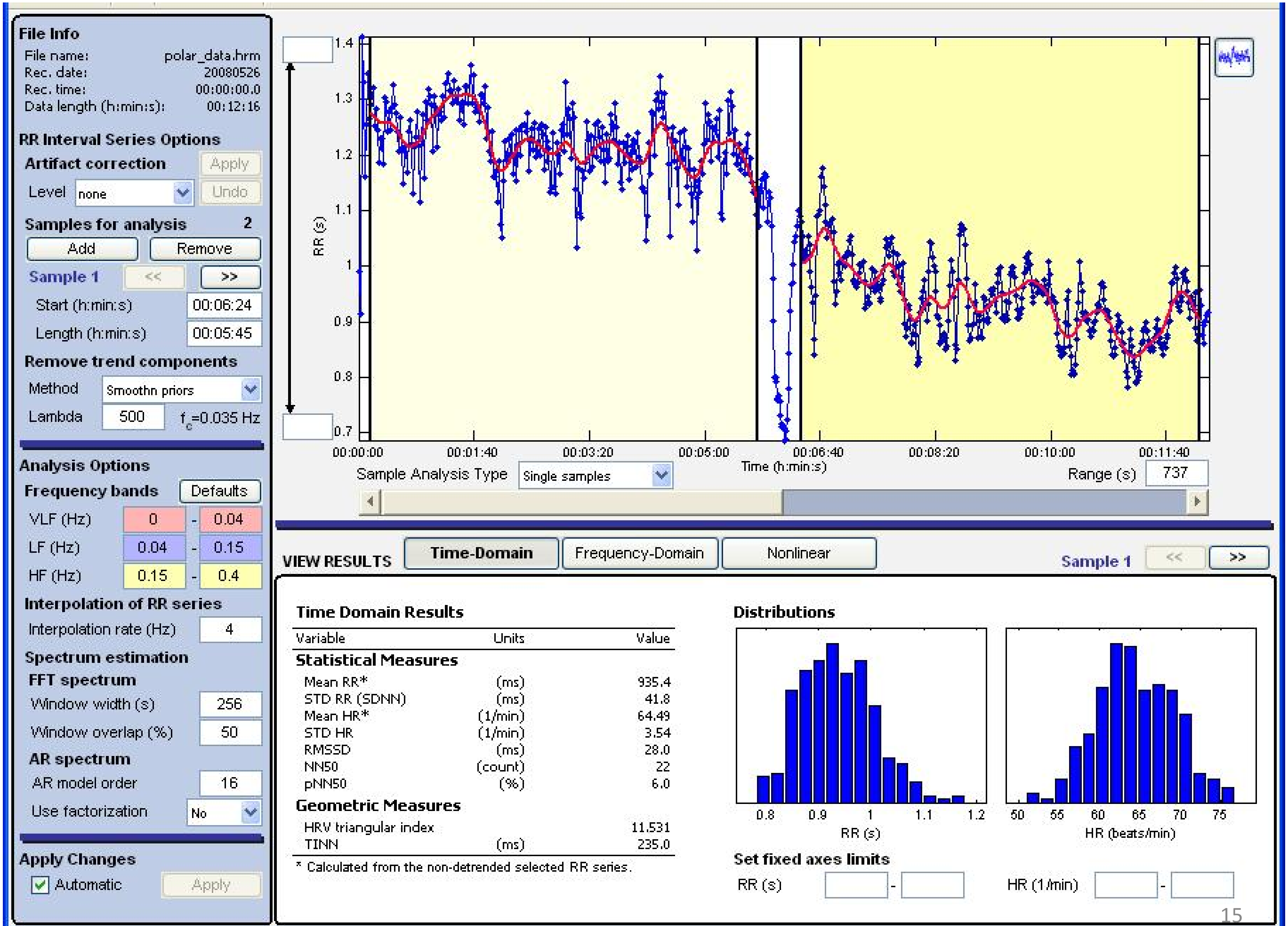
- Spectral analysis involves decomposition of the series of sequential RR intervals into its various frequency components and quantifies them in terms of their relative intensity, termed ‘power’.
- The power spectrum is usually divided into different spectral bands and the powers are calculated in these bands.
- There are three major spectral peaks in the adult short-term HRV power spectrum
  - A high-frequency (HF) spectral peak appears generally between 0.15 and 0.5 Hz.
  - A low-frequency (LF) peak occurs around 0.1 Hz (generally between 0.04 and 0.15 Hz).
  - Very low-frequency (VLF) heart rate oscillations are below 0.04 Hz.
- As the neonatal heart rate oscillations differ from that of the adult, 0.2 Hz is utilized as the cut-off point between LF and HF bands.
- Studies that exclude VLF band, start LF at 0.02 Hz [33, 36-38] and those that include the VLF band use 0.04 Hz as the cut-off point dividing the two [34, 35].
- Currently, the most commonly recommended frequency bands for short-term newborn HRV are [0.01 – 0.05] Hz for LF, [0.05 – 0.2] Hz for MF, and [0.2 – 1] Hz for HF [29].
- The frequency bands are patient-dependent, and can be strongly affected by physiologic conditions such as body position and breathing frequency

Frequency domain analysis

- The spectral peaks in HRV power spectrum reflect the amplitude of the heart rate fluctuations present at different oscillation frequencies.
- Thus, relationships between HRV and physiological variables that relate to oscillatory control systems in homeostasis are established using spectral estimation techniques.
- sympathetic activities manifest themselves in the low frequency band (LF) ascribed to baroreceptor reflex and vasomotor activity.
- The mid frequency (MF) component is known to be both parasympathetically and sympathetically mediated.
- The High frequency (HF) correlates with respiratory fluctuations mediated by parasympathetic activities .

Frequency domain analysis

- Methods for the calculation of PSD are generally classified into 2 approaches: *non-parametric* and *parametric*.
- The advantages of the non-parametric methods are:
  - The simplicity of the algorithm employed (Fast Fourier Transform, FFT)
  - The high processing speed
- The advantages of parametric methods are:
  - Better spectral resolution in the case of short data lengths on which the signal is supposed to maintain stationarity
  - Easy identification of the central frequency of each spectral component in preselected frequency bands.
- The disadvantage of parametric methods, however, is the need to verify the suitability of the chosen model and its complexity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Add
Remove
Sample 1
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Length (h:min:s) 00:05:45
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Frequency bands
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VLF (Hz) 0 - 0.04
LF (Hz) 0.04 - 0.15
HF (Hz) 0.15 - 0.4
Interpolation of RR series
Interpolation rate (Hz) 4
Spectrum estimation
FFT spectrum
Window width (s) 256
Window overlap (%) 50
AR spectrum
AR model order 16
Use factorization No
Apply Changes
Automatic
Apply
RR (s)
Time (h:min:s)
00:00:00 00:01:40 00:03:20 00:05:00 00:06:40 00:08:20 00:10:00 00:11:40
Sample Analysis Type Single samples
Range (s) 737
VIEW RESULTS
Time-Domain
Frequency-Domain
Nonlinear
Sample 1
Time Domain Results
Variable Units Value
Statistical Measures
Mean RR* (ms) 935.4
STD RR (SDNN) (ms) 41.8
Mean HR* (1/min) 64.49
STD HR (1/min) 3.54
RMSSD (ms) 28.0
NN50 (count) 22
pNN50 (%) 6.0
Geometric Measures
HRV triangular index 11.531
TINN (ms) 235.0
* Calculated from the non-detrended selected RR series.
Distributions
RR (s)
HR (beats/min)
Set fixed axes limits
RR (s) -
HR (1/min) -

HRV Analysis Results

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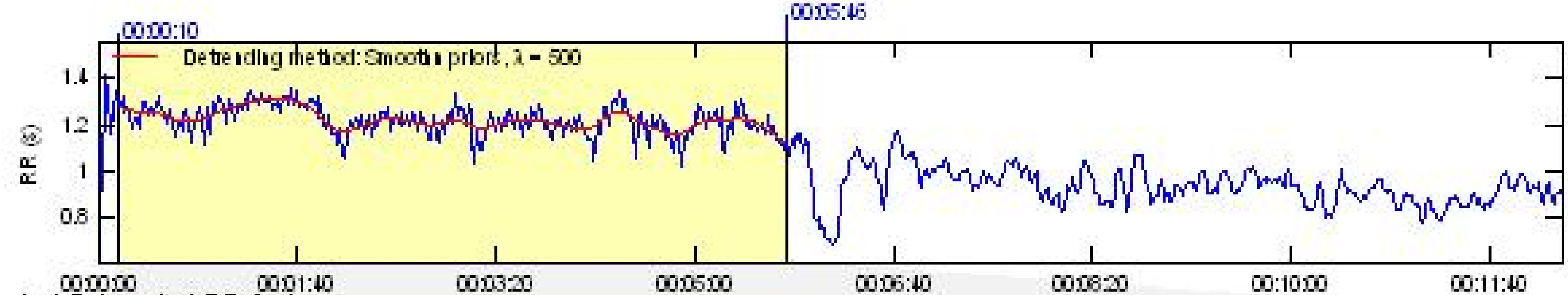
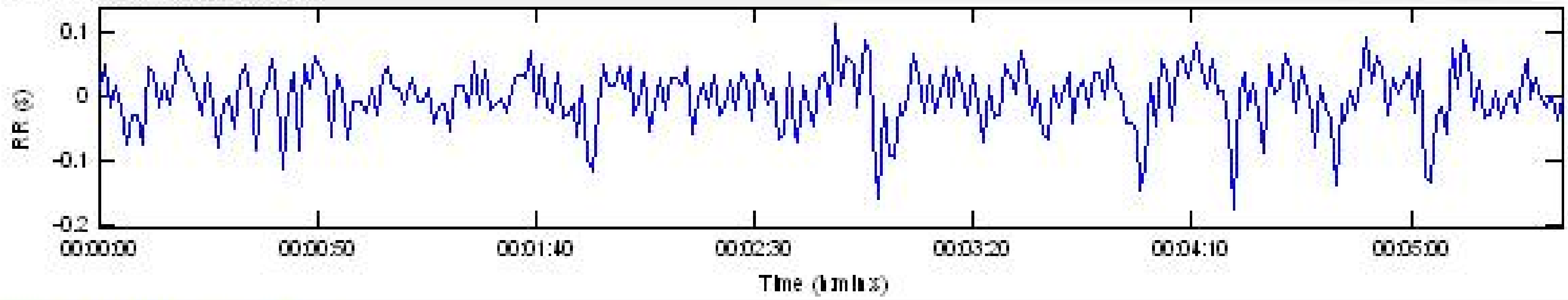
RR Interval Time Series

Results for single samples: sample 2/2



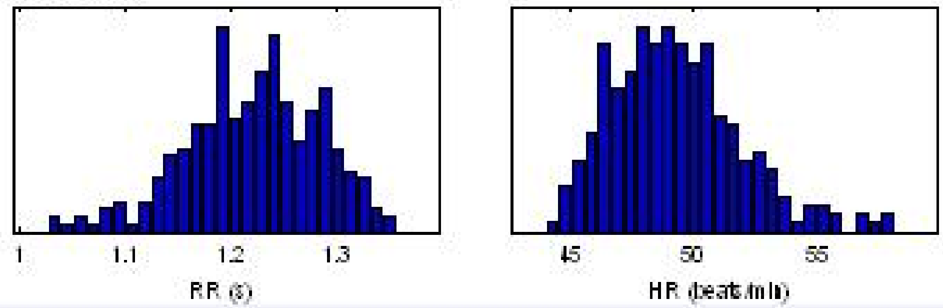
Selected Detrended RR Series



Time-Domain Results

Variable	Units	Value
Mean RR*	(ms)	1220.8
STD RR (SDNN)	(ms)	46.1
Mean HR*	(1/min)	49.28
STD HR	(1/min)	2.40
RMSSD	(ms)	59.0
NN50	(count)	115
pNN50	(%)	42.0
RR triangular index		9.821
TINN	(ms)	225.0

Distributions*



HRV Analysis Results

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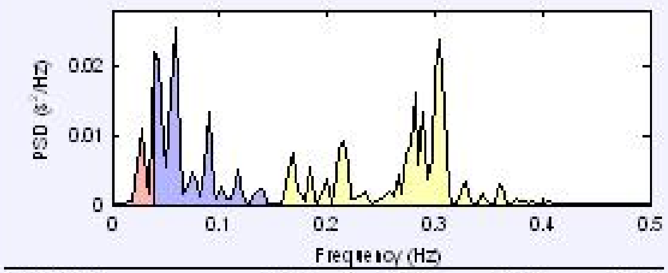
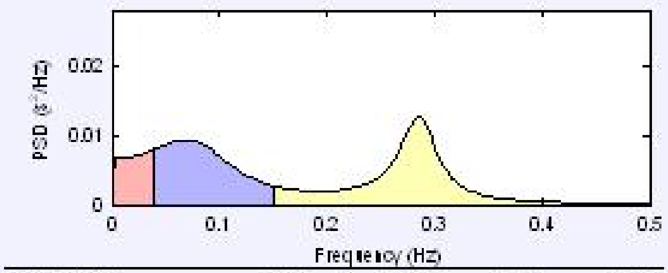
Frequency-Domain Results

FFT spectrum (Welch's periodogram: 256 s window with 50% overlap)



Frequency Band	Peak (Hz)	Power (ms²)	Power (%)	Power (n.u.)
VLF (0-0.04 Hz)	0.0391	156	10.1	
LF (0.04-0.15 Hz)	0.0586	563	36.5	40.5
HF (0.15-0.4 Hz)	0.3047	826	53.5	59.5
Total		1544		
LF/HF		0.682		

AR Spectrum (AR model order = 16, not factorized)

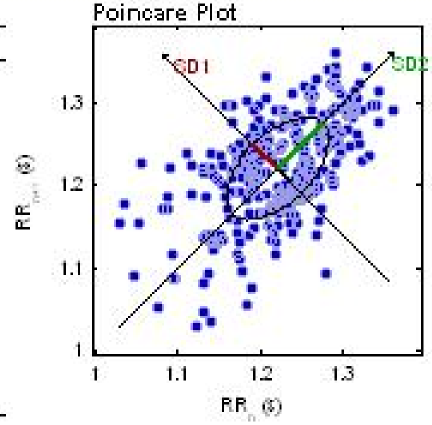


Frequency Band	Peak (Hz)	Power (ms²)	Power (%)	Power (n.u.)
VLF (0-0.04 Hz)	0.0391	277	14.5	
LF (0.04-0.15 Hz)	0.0703	739	38.7	45.2
HF (0.15-0.4 Hz)	0.2852	895	46.8	54.8
Total		1912		
LF/HF		0.825		

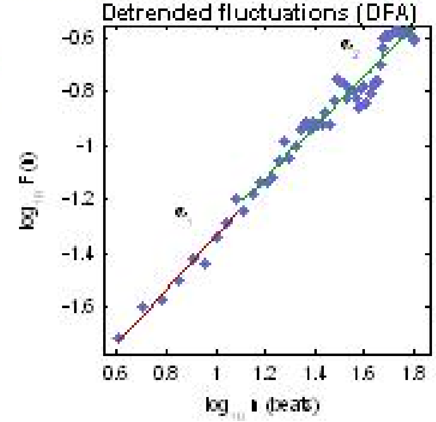
Nonlinear Results*

Variable	Units	Value
Poincare plot		
SD1	(ms)	42.1
SD2	(ms)	79.1
Recurrence plot		
Mean line length (Lmean)	(beats)	8.05
Max line length (Lmax)	(beats)	43
Recurrence rate (REC)	(%)	24.21
Determinism (DET)	(%)	96.49
Shannon Entropy (ShanEn)		2.853
Other		
Approximate entropy (ApEn)		1.015
Sample entropy (SampEn)		1.733
Detrended fluctuations (DFA): α1		0.986
Detrended fluctuations (DFA): α2		0.935
Correlation dimension (D2)		4.004

Poincare Plot



Detrended fluctuations (DFA)



*Results are calculated from the non-detrended selected RR series.

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Kubios HRV, version 2.0
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