BIOPAC Systems, Inc.
Registered to ISO 9001:2008
42 Aero Camino, Goleta, CA 93117
Tel (805) 685-0066 | Fax (805) 685-0067
info@biopac.com | **www.biopac.com**

Updated 01.07.2016

Application Note 246 R-R Interval Processing Using BIOPAC's HRV Algorithm Implementation

Acq*Knowledge* calculates heart rate variability using the Welch periodogram and least squares de-trending methods. To properly select the parameter values needed for the calculation of the Power Spectral Density, which is the "work-horse" tool for Heart Rate Variability analysis, a brief tutorial is presented.

- *See also: Preparing Data for HRV Analysis (#233) and HRV Statistical & Geometric Measures (#129)*

The Periodogram

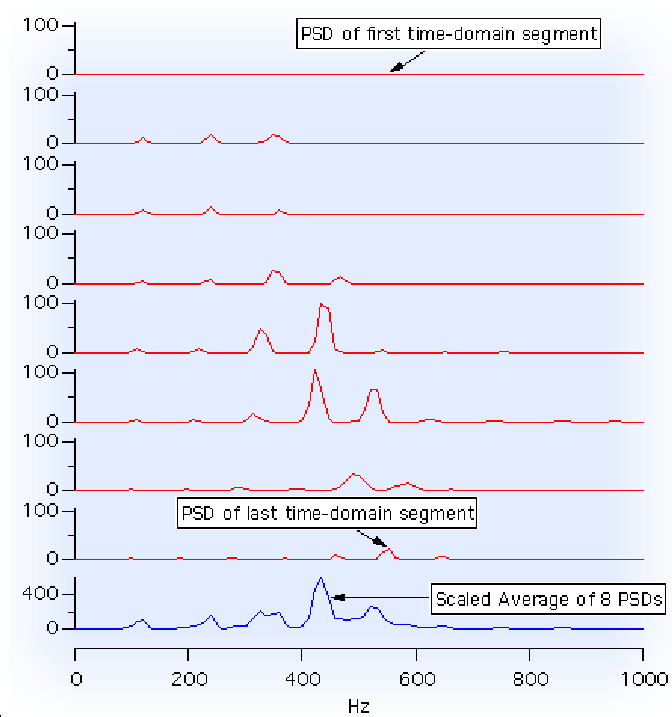
The Welch Periodogram is a method by which a large time-sampled waveform can be frequency-transformed by partitioning the data into shorter segments, transforming each segment, then, averaging the results over all the segments to create a composite frequency-space waveform. Figure 1 shows the basic technique (described in more detail in the first part of this application note: R-R Interval Processing Approach).

The reasons for using the periodogram are as follows:

- the averaging of the individual PSDs allows for the reduction of variance errors
- it is logarithmically more efficient to take many shorter FFTs than one longer one which makes this technique attractive for processing long runs of data [2]

To properly create a PSD profile, values for three parameters must be judiciously selected:

- Window size or data segment
- Overlap size
- Number of frequency points



[1] Fig. 1 Basic Welch periodogram technique for processing time-domain waveforms into the frequency domain for frequency/power analyses.

Window size/Data Segment

The data segment[a] is a subset of the total number of data samples, N, as shown in Figure 2a. The segment, in time samples, determines the resolution within frequency waveform. To grasp this, a Fourier Transform of an aperiodic time-space square wave[3], as represented in Figure 2b, is shown in Figure 2c. The key point centers on the resolution of either waveform in its respective domain. For coarse time spacing via large Δ, one will experience fine discrimination or resolution in frequency via $1/\Delta$ and vice-versa. The same philosophy holds true with the number of data segments in the data sample space versus frequency points in the frequency transform space.

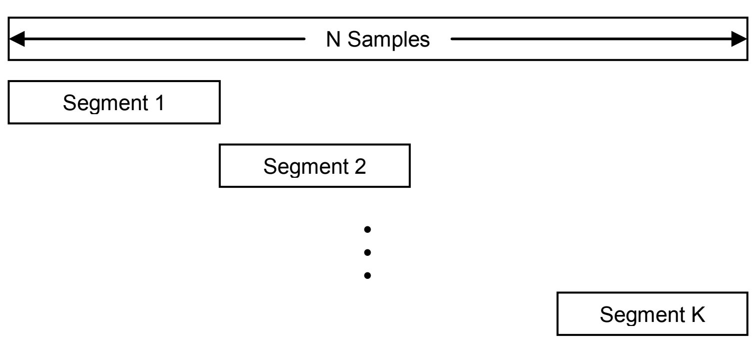


Fig. 2a Segmentation of the N data sample source

[a] See ***Appendix A*** for a way to estimate number of segments from window size and overlap parameters.

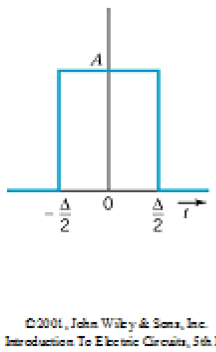


Fig. 2b An aperiodic square wave

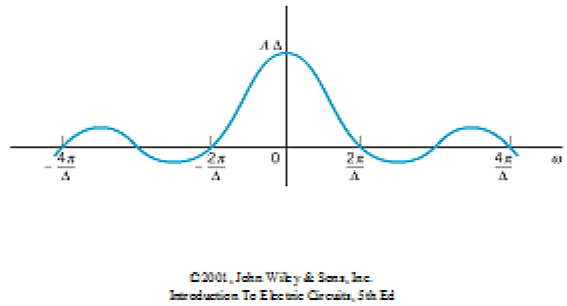


Fig. 2c The transform of the square wave

Another key point with using data segments is that taking FFTs of various data segments can introduce discontinuities at the segment boundaries or edges. These discontinuities manifest themselves as spurious frequency components in the transform space. To reduce these spurious components, a windowing function tapers the data down to zero at each end of the data segments. The window is multiplied with the data segment and is the **same sample length** as the data segment.[4] To this end, several window functions can be used, among them are: Hamming, Hanning, and Blackman.

Overlap size[5]

The value assigned to the overlap parameter determines how many data segments can be obtained from the original sequence. For example, considering a 100 samples data sequence, if each data segment is 50 samples, then with no overlap, averaging can only occur between two PSDs. If overlap is set to 50%, then averaging over three PSDs is possible. More averaging reduces the error variance of the final PSD resolution.

There is a practical reason for not requesting overlap values > 50%.

- For averaging to reduce the error variance, it is assumed that the samples that get averaged are uncorrelated. If two segments are overlapped by a value approaching 90%, then the resulting PSD is nearly the same and averaging can no longer effectively reduce the error variance.

Number of frequency points (Nfft)[6]

Increasing the number of frequency points affects the grid points on which the spectrum is evaluated. This parameter does not enhance physical resolution but provides a finer grid on the frequency axis to observe the spectrum; the higher the number, the finer the axis grid.

In choosing the Nfft parameter the following should be considered:

- For Nfft ≥ data segment, the FFT transform is zero-padded and all the samples of the data segment are applied to the transform
- Nfft ≤ data segment, some data samples are not applied to the FFT transform → loss of frequency resolution

Summary [6]

The rules or guidelines are summarized and hopefully provide the user some useful insights into the periodogram:

- Making *N* larger increases the length of the data segment (bigger time window) thereby reducing time resolution, but increasing frequency resolution (spectrum will have more jagged/random spikes, which may only be the response to noise variations, or can potentially resolve two closely spaced deterministic frequencies).
- Making *N* smaller increases time resolution but reduces frequency resolution (spectrum will look more smooth, but possibly loosing fine detail of actual signal properties).
- Increasing the N_{FFT} parameter (number of DFT points) increases the grid points on which the spectrum is evaluated through interpolation. It does not enhance physical resolution but provides a finer gird on the frequency axis to observe the spectrum.
- The finite window of data can be tapered to reduce the error or the interference from strong frequencies in one part of the spectrum on weaker frequencies in another (spectral leakage). A tapered window enhances the time resolution by emphasizing one part of the time segment over the end points, but it reduces the frequency resolution. Acq*Knowledge*, for example, can generate window functions such as *hamming()*, *hann()*, *blackman()*.

Effects of Varying the Periodogram Parameters

To understand how the parameters of data segment/window size and overlap affect the resulting PSD waveform, the following figures show parametric runs of the Welch algorithm.

Consider the following R-R tachogram shown in Figure 3:

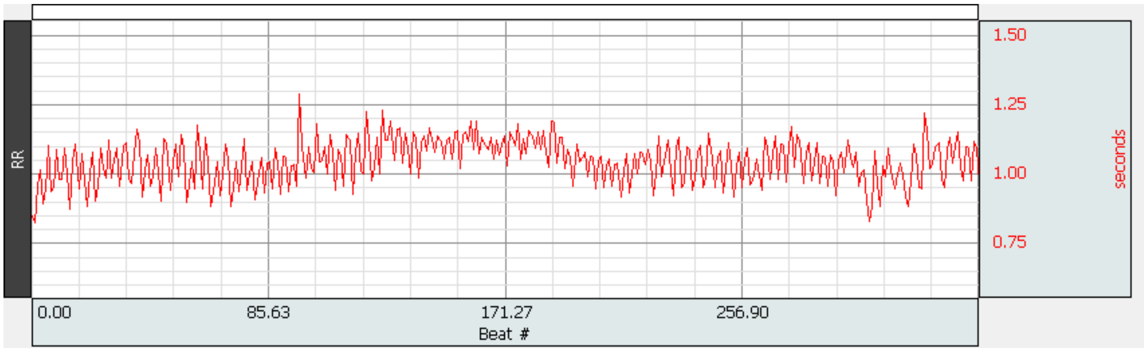


Fig. 3 A raw R-R tachogram

Varying the window size/overlap

Two parameters, window size (same as data segment length) and overlap are varied.

Case 1 less data segments:

- Window size = 1 data segment (full width of available data)
- Overlap = 1% of window size (minimal overlap)
- FFT width = 1024

Case 2 more data segments:

- Window size = ~ 25% of the full data width
- Overlap = 50% of Window size (number of segments ~ 7 for this example)
- FFT width = 1024

The resulting PSDs are shown in Figures 4a, 4b. A lesser number of segments allowed for finer frequency resolution as seen in Figure 4a. The larger overlap and smaller window size allowed for a larger number of segments which resulted in a PSD that has coarser, somewhat smoother frequency profile as shown in Figure 4b.

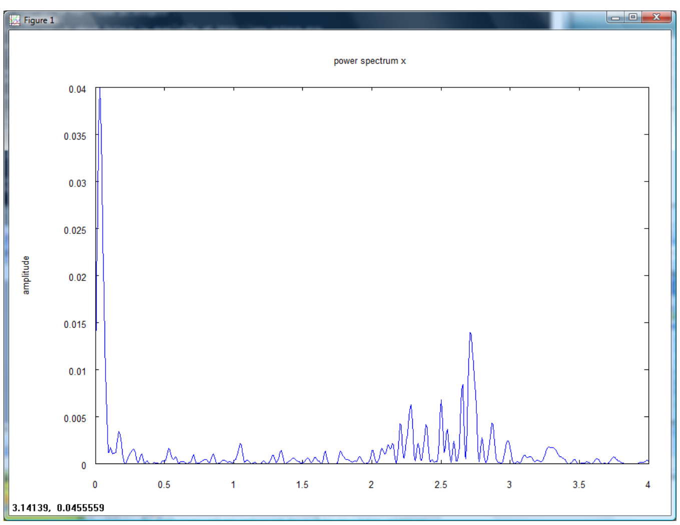


Fig. 4a PSD from Case 1 parameters

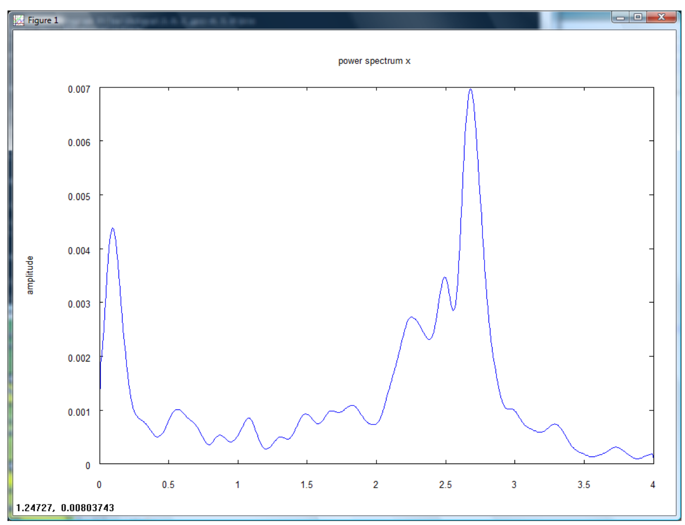


Fig. 4b PSD from Case 2 parameters

HRV Example Analysis

The PSD tool is an integral component for HRV analysis. Rather than analyze whole ECG waveforms, variations to the ECG beat pattern are extracted and examined to determine the influences that outside stimuli (physiological, chemical, enviromental) have on the heart. The PSD displays these variations in a frequency plot.

The R-R interval waveform reflects the deviation of the ECG from a nominal beat cadence of the human heart. This note will step the user through a simple analysis of an ECG waveform for Heart Rate Variability**.**

The first step is to obtain an ECG waveform. Sample data files contained within the Acq*Knowledge* directory are an ideal place to extract a pre-recorded ECG signal. For this note the waveform contained in the file "ECG LeadII.acq" in the Sample Data File directory is used.

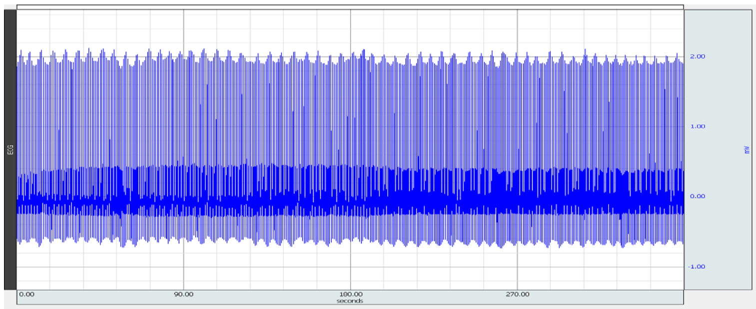


Fig. 5a ECG Lead II waveform

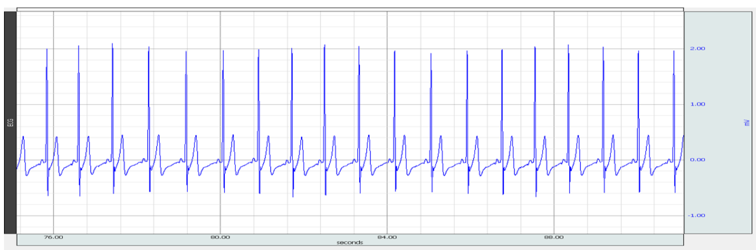


Fig. 5b Expanded view of the ECG Lead II waveform

When obtained, invoke the HRV algorithm through the Analysis menu > HRV and RSA > Single-epoch HRV-Spectral.

The "Single-epoch HRV-Spectral" option will generate the following four-tabbed Heart Rate Variability dialog (Figure 6a).

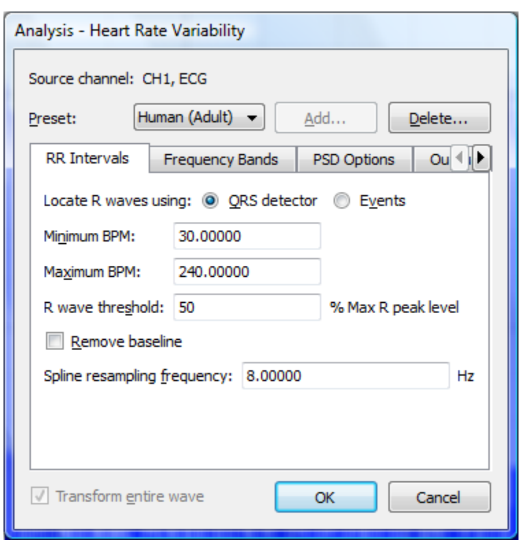


Fig. 6a The four-tabbed HRV dialog

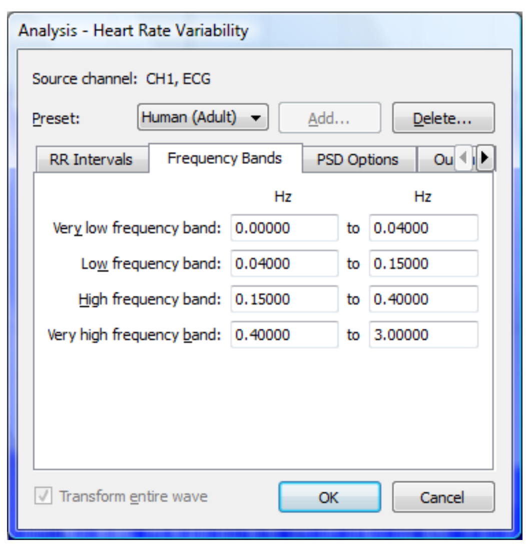


Fig. 6b Frequency band allocation for R wave analysis

On the "RR Intervals" tab, set the R wave extraction parameters using the defaults listed in the dialog.

On the "Frequency Bands" tab (Figure 6b), set the band demarcations; the values listed should suffice for most analyses.

On the "PSD Options" tab (Figure 6c), set the PSD parameters as discussed in the previous section. These parameters provide the user latitude in tailoring the PSD calculations to the available data set. Note the two checkboxes pertaining to linear detrending. Table 1 presents the combination of selections and the expected outcome of each. The HRV tool has both boxes checked as a default selection. <u>It is recommended that users adhere to the default selection.</u>

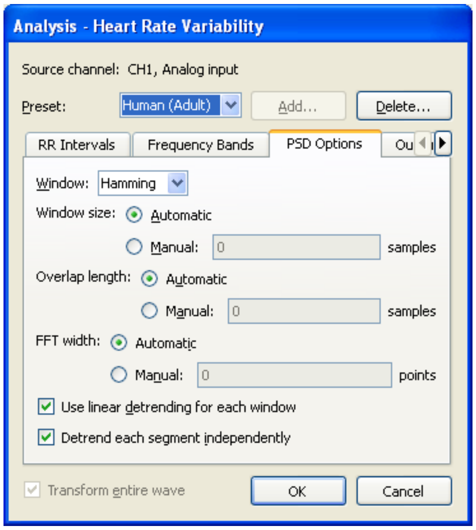


Fig. 6c PSD parameters.

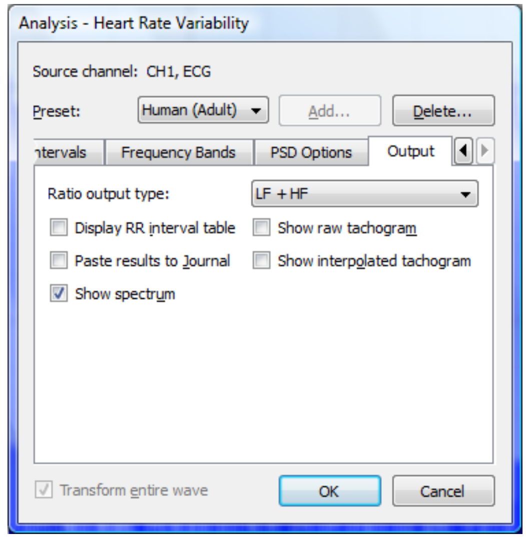


Fig. 6d Output options

Selected Option	Option Effect
☐ Use linear detrending for each window ☐ Detrend each segment independently or ☐ Use linear detrending for each window ☑ Detrend each segment independently	No detrending.
☑ Use linear detrending for each window ☐ Detrend each segment independently	Detrending is invoked but the effects of previous segment detrending is felt by the next segment. **Not the recommended option – for experimental purposes only.**
☑ Use linear detrending for each window ☑ Detrend each segment independently	Detrending is invoked. Each segment is detrended independently. **The recommended option**.

Table 1

The options for window size, overlap, and FFT length can be manually inserted or automatic values can be assigned. Table 2 lists the parameter and the resulting value when the "Automatic" option is selected. The default values are calculated dynamically based on multiple factors:

- Max time interval between consecutive R-wave events (max R-R interval)
- number of cycles collected
- spline re-sampling frequency which is defaulted to 8 Hz

Note: n = sample size of the R-R interpolated waveform based on cycles collected

Parameter	Assigned "Automatic" value
Window size	$\frac{n}{4.5}$
Overlap	$\frac{Window\,size}{2}$
FFT width	$N_{fft} = \left\{ \begin{array}{c} 256, L < 256 \\ 2^{ceil\left(\frac{\log(L)}{\log(2)}\right)}, L \geq 256 \end{array} \right\}$ *L = Window size.* *ceil = returns the smallest integer no less than the number*

Table 2 Values assigned to the PSD parameters when the "*Automatic*" radio button is depressed

The window size determines the overlap and FFT width values.

On the "Output" tab, toggle the checkboxes to enable/disable output choices.

For a first pass through the tool, click the Manual button within the PSD dialog (Figure 6c) and **set the Overlap parameter to 1 sample**. Here the data segments are nearly contiguous. Check the box for "Show spectrum" as shown in Figure 6d, click OK and the PSD spectra should be generated (Figure 7):

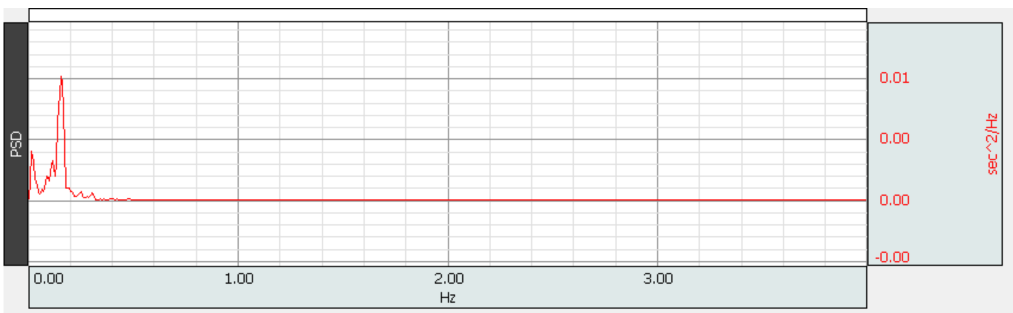


Fig. 7 Graph of the PSD of the ECG waveform shown in Figure 5a.

Postscript

After the first pass is completed, the user can rerun the HRV algorithm any number of times as desired, requesting more output or adjusting the HRV parameters. See ***Appendices B and C*** for a detailed procedure.

Other HRV packages have been exercised with this same ECG file. Comparison plots are listed in ***Appendix D***.

If the user is solely interested in the frequency spectrum and not in the sympathetic/vagal ratios, a couple of alternative methods can be followed as shown in ***Appendix E***.

A discussion of an additional calculation option for the sympathetic and vagal ratios is listed in ***Appendix F***.

A listing of technical references on the mathematical foundation of the PSD and independent implementations of the same are contained in ***Appendix G***.

References

[1] http://www.wavemetrics.com/Products/IGORPro/dataanalysis/signalprocessing/powerspectra.htm
[2] http://www.gyte.edu.tr/dosya/102/dersler/elm222/ch15.ppt#269,20,Figure 15.9-1 An aperiodic pulse.
[3] http://www.engr.uky.edu/~donohue/ee422/Lab2_EE422.doc
[4] http://www.dsprelated.com/showmessage/81197/1.php
[5] http://www.engr.uky.edu/~donohue/ee422/Lab2_EE422.doc

Appendix A—Estimating Number of Segments from Window and Overlap Parameters

One can estimate the number of segments needed to partition the data samples using the data segment size and overlap value as follows.

From Figure A-1, the length of the source data is labeled as N.

- The all data segments are some fraction of N and denoted as $\alpha \cdot N$.
- The overlap is some fraction of the window size, labeled as $\beta \cdot \alpha \cdot N$.

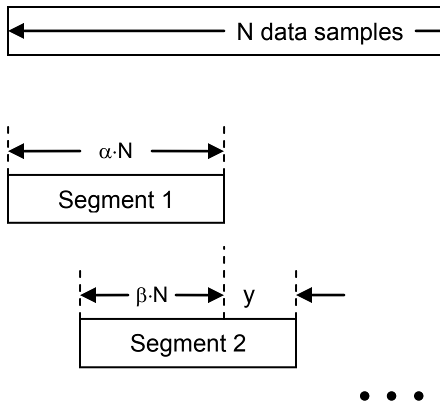


Figure A-1 Schematic for derivation of the number of segments

Segment 1 and y pieces of subsequent segments should sum to equal the length of the data set, N. Examining the figure:

$$\alpha \cdot N + x \cdot y = N$$

where

$$y = (\alpha \cdot N) - (\beta \cdot \alpha \cdot N)$$

$x =$ *number of y pieces needed to help span the data set with* $(\alpha \cdot N)$ *and indicates the number of other segments in addition to the first*

Solving for x, one obtains:

$$x = \frac{N - (\alpha \cdot N)}{(\alpha \cdot N) - (\beta \cdot \alpha \cdot N)}$$

or

$$x = \frac{1}{\alpha} \bullet \frac{(1-\alpha)}{(1-\beta)}$$

The total number of segments calculates to

$$d = 1 + x$$

As an example, using a window segment that is 50% (=α) of the data sample size, and an overlap that is 50% (=β), the number of segments calculates to 3.

Appendix B—Deriving the PSD parameters from the R-R tachograms

The R-R interpolated waveform appears as follows as derived from the ECG waveform using the HRV routine.

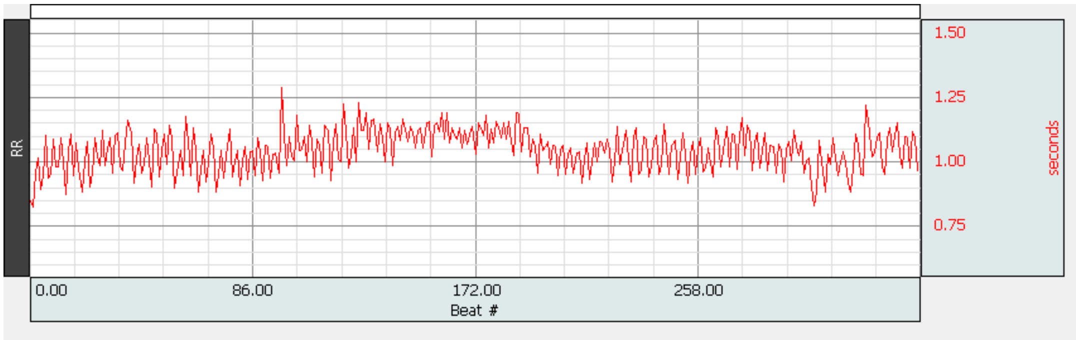


Fig. B-1 Raw tachogram of the ECG waveform of Fig. 3. Note the spacing between waveform peaks is **not** even in time.

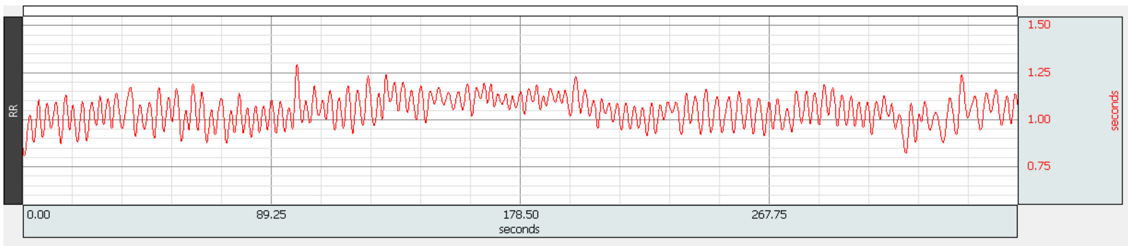


Fig. B-2 The R-R interpolated waveform from the ECG graph of Figure 3.

The resulting tachograms show ECG beat variations:

- Raw tachogram is the uneven sampling of the R waveform
- Interpolated tachogram is re-sampled and re-plotted graph of the raw tachogram where the sampling is evenly divided across the waveform. This is why a spline f'requency is specified. It is used in a cubic spline interpolation routine and applied to the raw tachogram to create a smooth curve to allow for even sampling which is required when using the FFT.

The Interpolated R-R interval waveform is the waveform from which the PSD will be calculated. Highlighting the whole waveform, and performing a ΔS measurement should reveal the total number of samples = N. To insert reasonable values for the PSD parameters in the HRV routine, do the following:

- Window size = N/2 (guarantee at least two segments, yet maintain good frequency resolution)
- Overlap = 1 sample (can go higher if more segments are needed yet maintain Window size and frequency resolution, up to 50% of the Window size)
- Nfft to a power of 2 ≥ Window size (to include all the windowed data samples into the FFT transform)

Re-running the HRV routine with custom PSD parameters renders the following spectral plot.

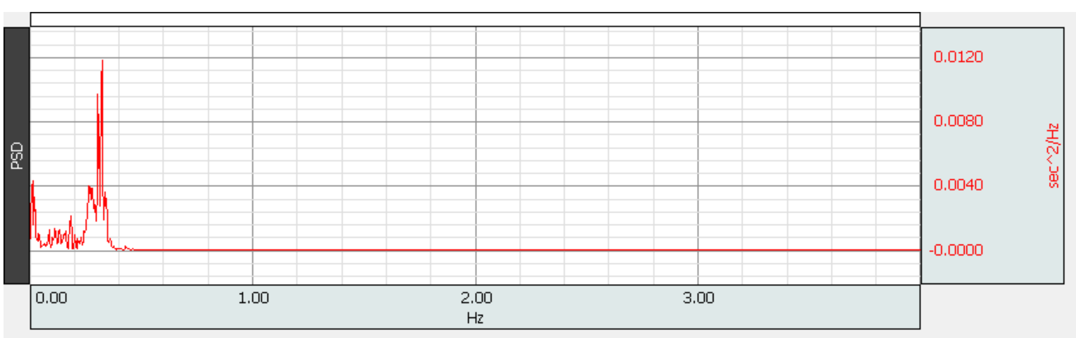


Fig. B-3 PSD of the R-R interpolated waveform.

The user can adjust the parameters for better frequency granularity or increased/decreased PSD averaging.

Appendix C—Analysis Procedure - Fine Tuning the PSD parameters

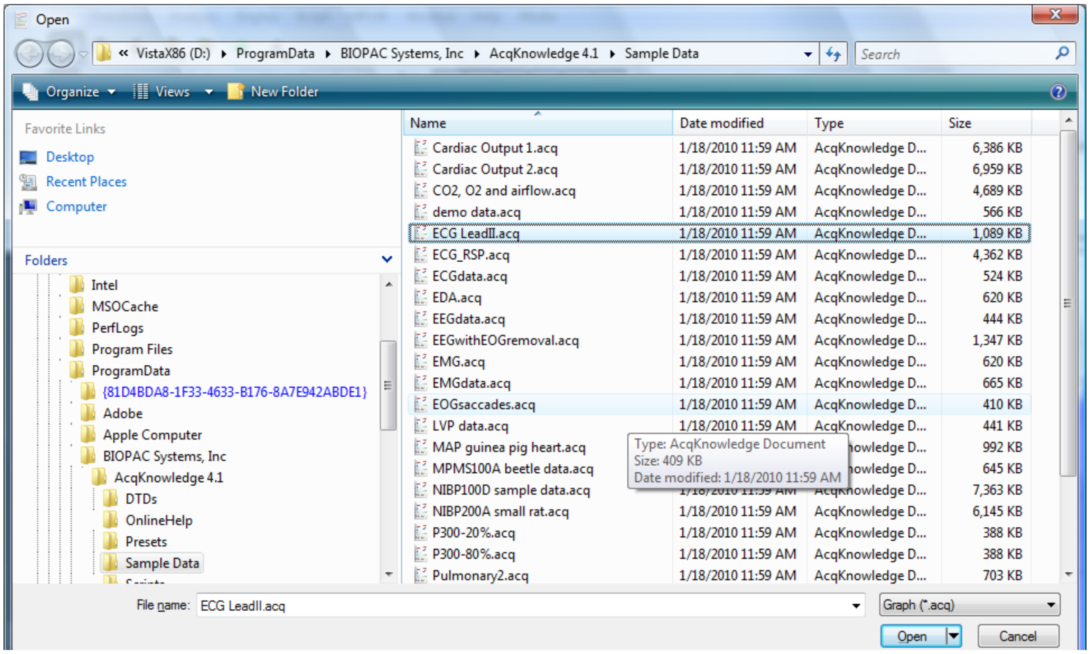
To fine-tune the HRV analysis parameters to the available data, a first pass through the tool is **necessary to extract** the R-R interpolated waveform. Table C-1 lists a simple procedure followed by a pictorial exhibit of the same. Here, the example file "ECG LeadII.acq" will be used. **This procedure is not necessary if the user wishes to use the default values/selections of the PSD tab.**

Step	Task	Motivation
1	Open and display "ECG LeadII.acq"	Open the example data file
2	Choose "Analysis menu > HRV and RSA > Single-epoch HRV-Spectral."	Invoke the HRV analysis tool
3	View the HRV dialog, click the Ouput tab. Enable the "Show Interpolated Tachogram" checkbox. Click OK on the HRV dialog.	For a first pass, the interpolated tachogram will be used to establish the PSD parameters of window size, overlap and FFT width. Remember that the frequency spectra, sympathetic and vagal ratios are derived from the FFT of the interpolated tachogram.
4	A tachogram should be displayed on the computer screen. Highlight all of the tachogram graph window using Edit > Select All… Next, using the measurement bars, select "Delta S"	Provide the total number of samples used in the data set.
5	Use the value of Delta S to set the PSD parameters on the second pass of the HRV tool. Specifically: • Window size = (Delta S)/2 • Overlap = 1 sample • FFT width = value > Window size and a power of 2	Fine tune the HRV tool to the data set (*see **Appendix B** for more detailed discussion*): • Window size will break the data set into 2 segments. • Minimal overlap is requested for this example. (**User can input a values up to ½ of the window size**). • FFT width should be larger than the Window segment yet is a power of 2 so that all sample data within the Window segment is applied to the FFT.
6	Choose "Analysis menu > HRV and RSA > Single-epoch HRV-Spectral."	Generate the HRV dialog again.
7	Click the PSD Options tab. Click the Manual radio button for the Window size, Overlap length, and FFT size. Enter the values derived in Step 5 into the appropriate text boxes.	Apply the appropriate parameter values to the PSD equations.
8	Go to the Output tab. Apply check marks to "Show spectrum". Can remove the check mark previously applied to "Show Interpolated Tachogram"	Select the option to show the spectra.
9	Click OK on HRV dialog	Re-calculate the HRV values: ratios & PSD
10	View the spectrum plot	Identify the frequency components contained within the R-R wave.

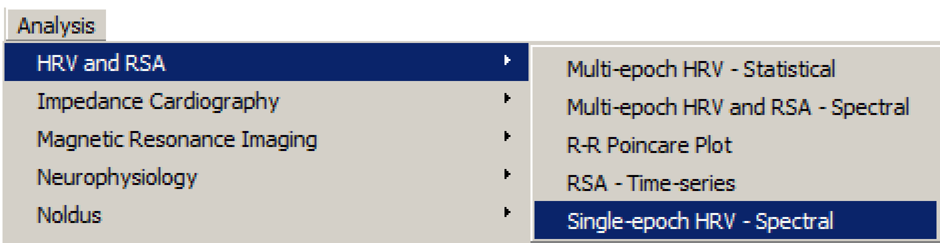
Table C-1 First pass procedures through the HRV analysis tool

Pictorially, the sequence of steps should appear as follows:

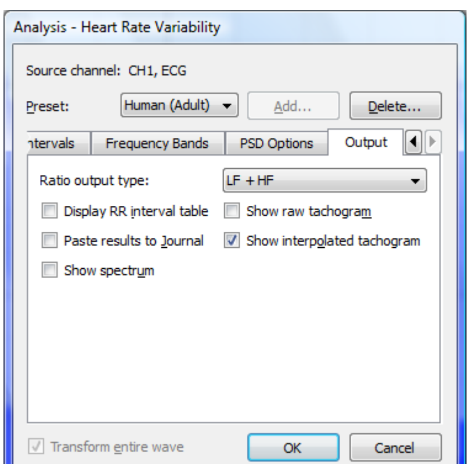
Step 1:



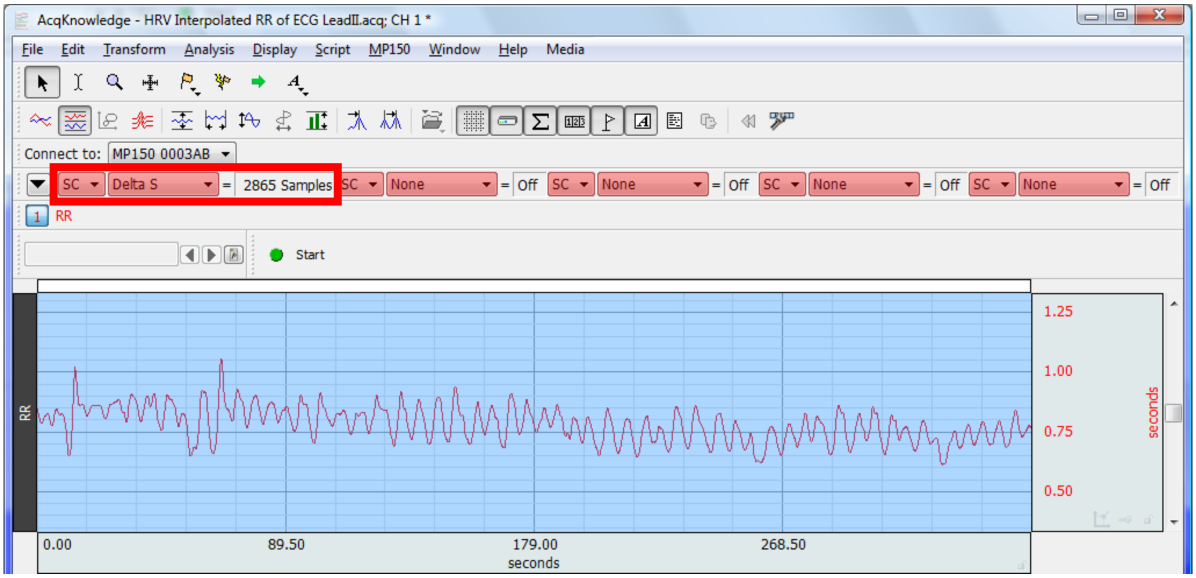
Step 2:



Step 3:



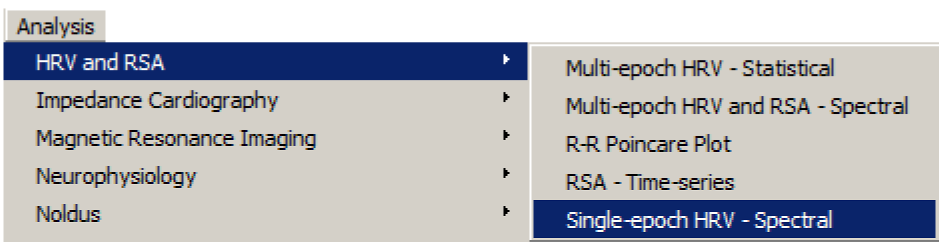
Step 4:



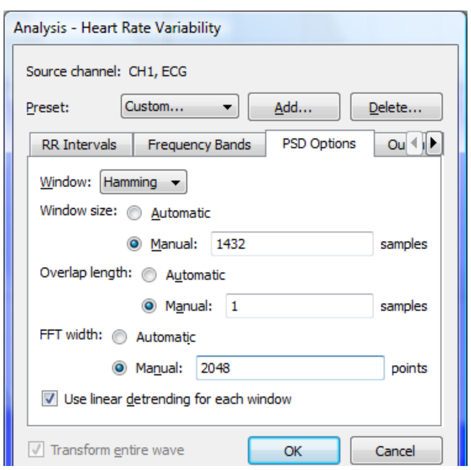
Step 5:

Window size	Overlap	FFT width
= 2865/2 = 1432	= 1	= 2048

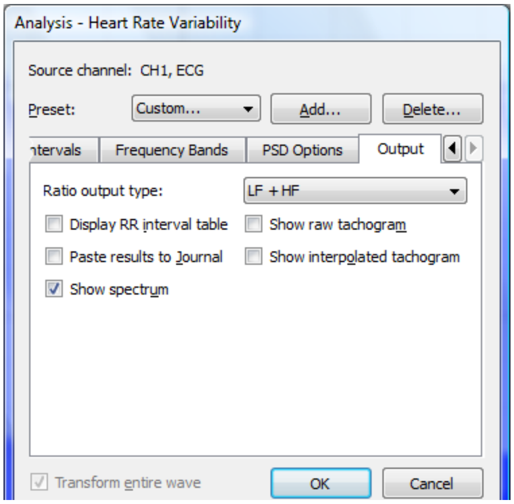
Step 6:



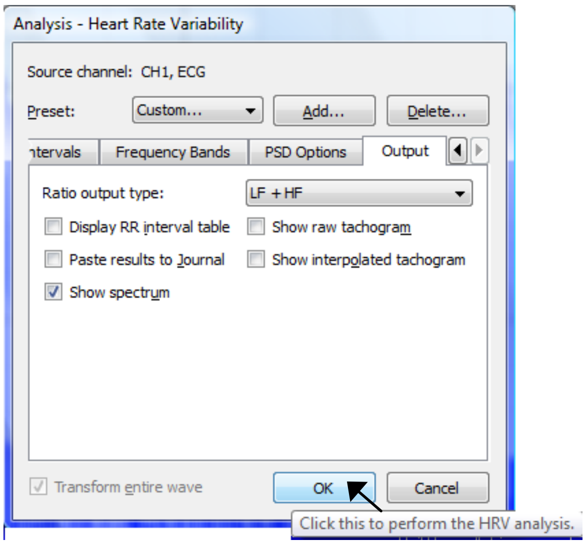
Step 7:



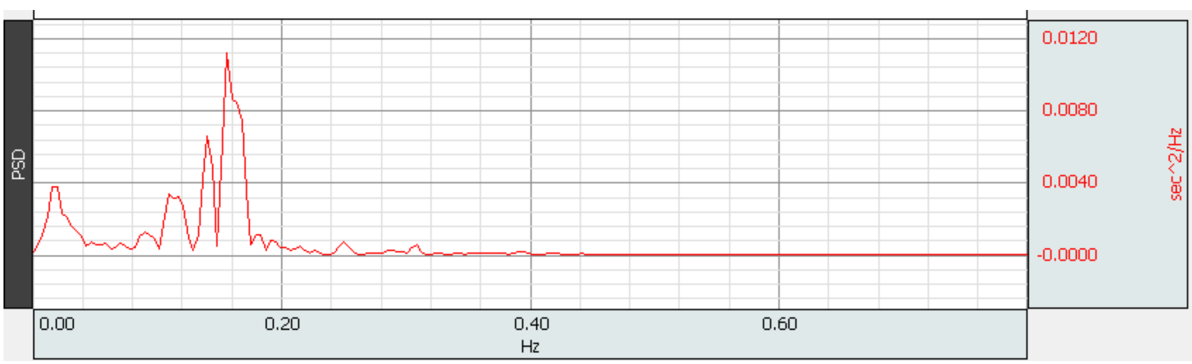
Step 8:



Step 9:



Step 10:



Appendix D—Frequency Ratios and Spectral Plot Comparisons to Other HRV Implementations

The ECG waveform as stored in the sample data file "ECG LeadII.acq" is shown in Figure D-1, the raw tachogram of said waveform is shown in Figure D-2.

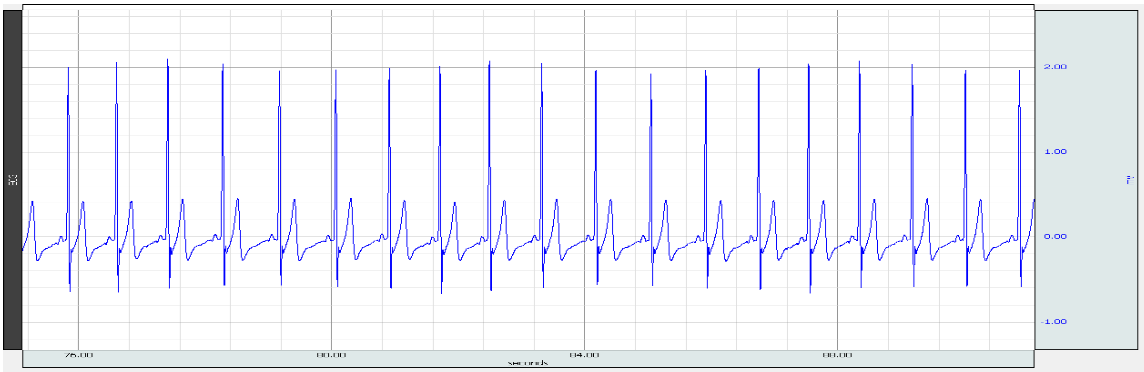


Fig. D-1 ECG waveform

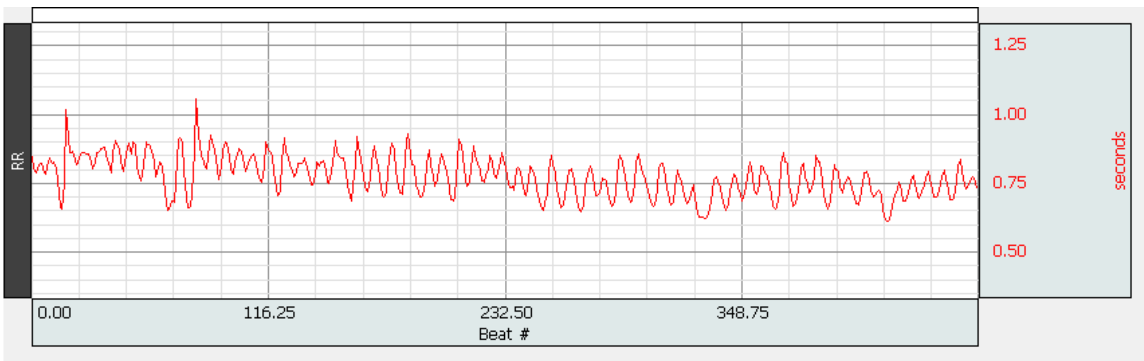


Fig. D-2 Raw R-R tachogram of the ECG waveform

Table 1 compares the sympathetic/vagal ratios across three HRV implementations: Acq*Knowledge*, Kupio, and Nevrokard:

- Acq*Knowledge* from BIOPAC Systems, Inc.
- Kupio from the University of Kupio, Finland: Dept of Applied Physics: Biomedical Signal Analysis Group
- Nevrokard from Nevrokard Kiauta, Slovenia

The spectral plots are shown in Figures D-1, D-2, D-3

Upon examining the table and figures, one can conclude that all three of the HRV implementations show consistent correlation in the spectral profiles and frequency ratios using the same source data set.

Implementation	**Sympathetic/Vagal Ratio (LF/ HF)**
Acq*Knowledge*	1.107
Kupio	1.104
Nevrokard	1.09

Table D-1 Comparison of frequency ratio across two HRV implementation packages

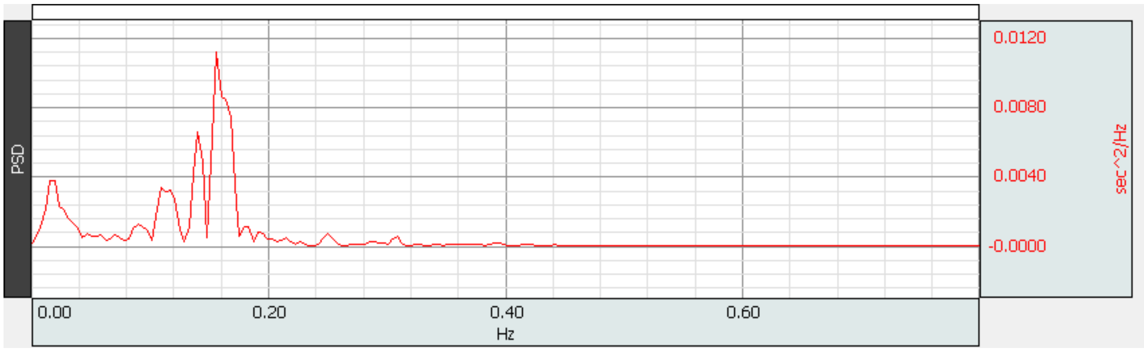
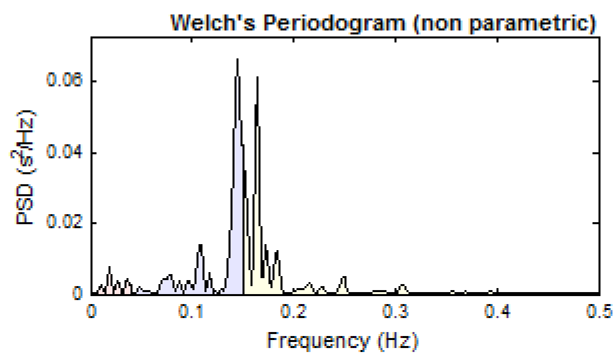


Fig. D-1 HRV spectrum using Acq*Knowledge*



Frequency Band	Peak (Hz)	Power (ms^2)	Power (%)	Power (n.u.)
VLF	0.0195	80	4.6	
LF	0.1445	868	50.0	52.5
HF	0.1641	786	45.3	47.5
LF/HF			1.104	

Fig. D-2 HRV spectrum using Kupio

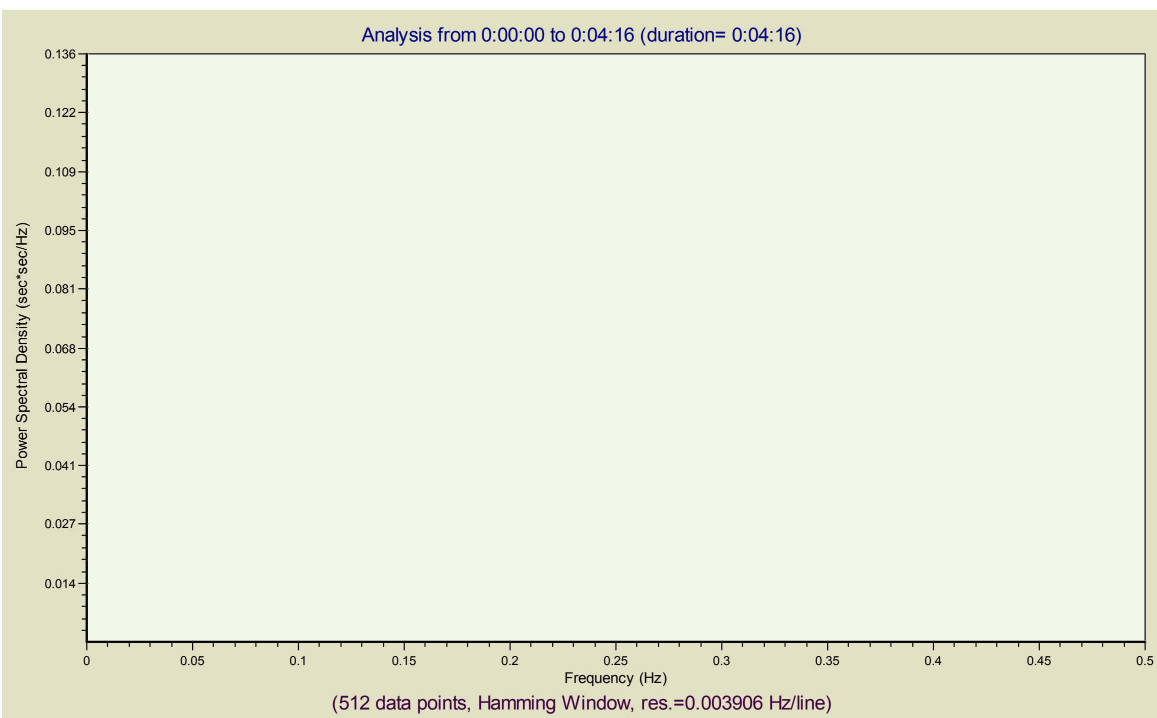


Fig. D-3 HRV spectrum using Nevrokard

Appendix E—Alternative Methods of Obtaining a Spectral Profile

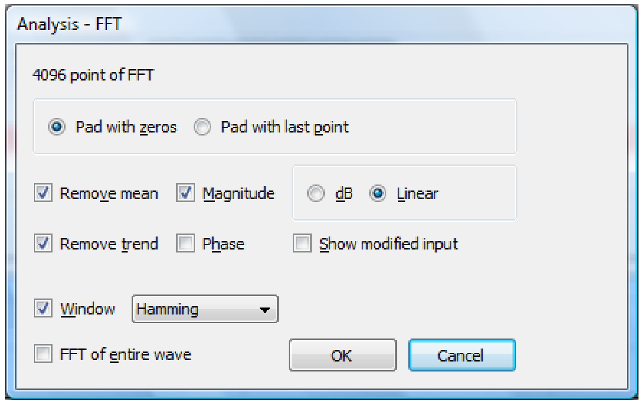
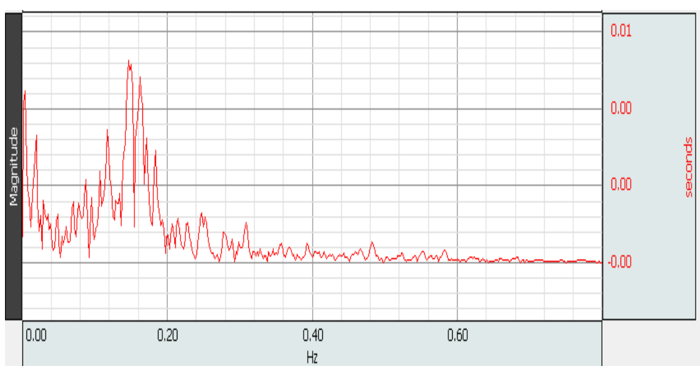
Path	Acq*Knowledge* Menu	Features/Options
1	Analysis > Power Spectral Density	The user needs to obtain the R-R interpolated waveform. The PSD UI is the same as the PSD UI within the HRV tool.
2	Analysis > FFT…	The user needs the R-R interpolated waveform. Apply the following options:  A side feature of this tool is that in the upper left corner of the window the number FFT points is displayed Note that this not the PSD profile since PSD ~ $\lvert FFT \rvert^2$. The resulting waveform is the magnitude of the frequency components only, but the frequency distribution should be the same whether PSD or FFT is plotted. 

Table E-1 Alternative ways to obtain the spectral profile of the R-R interpolated waveform

Appendix F—Revised sympathetic and vagal ratios

Options have been added for the calculation of the HRV ratios: sympathetic and vagal and are derived as follows.

Reporting a sum for a frequency range when computing the power in an individual band has been implemented as follows:

Given a frequency range f_{low}, f_{high} define the set *S* of all samples of the PSD

where $S = \{PSD(f_{low}), \ldots, PSD(f_{high})\}$.

Define the sum of the power within the frequency range as:

$$s(f_{low}, f_{high}) = \left(\frac{S_1}{2} + \sum_{i=2}^{i=|S|-1} S_i + \frac{S_{|S|}}{2} \right) \times \frac{(f_{high} - f_{low})}{|S|-1}.$$

where

|*S*| = is the set magnitude, that is, the number of elements in the set

This applies the scaling factor to a sum of the frequencies in the frequency range, with the magnitudes at the endpoints divided by 2. Previous implementations would perform a direct sum of all amplitudes within the frequency band.

Result reporting has been changed for the overall ratios. The VLF section is now included in the ratios. A new VLF ratio has been introduced.

Define:

$$s_{vlf} = s(vlf_{low}, vlf_{high})$$

$$s_{lf} = s(lf_{low}, lf_{high})$$

$$s_{hf} = s(hf_{low}, hf_{high}) \ .$$

The new VLF ratio is:

$$ratio_{vlf} = \frac{s_{vlf}}{s_{vlf} + s_{lf} + s_{hf}}.$$

The **new sympathetic ratio** is defined as:

$$ratio_{lf} = \frac{s_{lf}}{s_{vlf} + s_{lf} + s_{hf}}.$$

The **new vagal ratio** is defined as:

$$ratio_{hf} = \frac{s_{hf}}{s_{vlf} + s_{lf} + s_{hf}}.$$

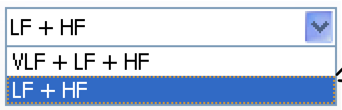
The previous algorithm defines the sympathetic ratio as:

$$ratio_{lf_{old}} = \frac{s_{lf}}{s_{lf} + s_{hf}}.$$

The previous algorithm defines the vagal ratio as:

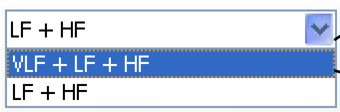
$$ratio_{hf_{old}} = \frac{s_{hf}}{s_{lf} + s_{hf}}.$$

Within the Acq*Knowledge* HRV tool on the Output Tab, the following ratio equations are invoked from the drop-down menu options:



previous *sympathetic* $ratio_{lf_{old}} = \frac{s_{lf}}{s_{lf} + s_{hf}}$

previous *vagal* $ratio_{hf_{old}} = \frac{s_{hf}}{s_{lf} + s_{hf}}$



new *sympathetic* $ratio_{lf} = \frac{s_{lf}}{s_{vlf} + s_{lf} + s_{hf}}$

new *vagal* $ratio_{hf} = \frac{s_{hf}}{s_{vlf} + s_{lf} + s_{hf}}$

Appendix G—Technical References on the PSD

F-1. Welch, PD; The Use of Fast Fourier Transform for the Estimation of Power Spectra: A Method Based on Time Averaging Over Short, Modified Periodograms", IEEE Transactions on Audio Electroacoustics, Volume AU-15 (June 1967), pages 70–73.

F-2. Numerical Recipes in C - The Art of Scientific Computing, Cambridge University Press, Chapter 12

F-3. Oppenheim, Alan V.; Schafer, Ronald W. (1975). *Digital signal processing*. Englewood Cliffs, N.J.: Prentice-Hall. pp. 548–554.

F-4. Proakis, J.G. and Manolakis, D.G.; Digital Signal Processing, Upper Saddle River, NJ: Prentice-Hall, 1996, pp 910–913.

F-5. http://www.gnu.org/software/octave/ GNU Octave is a high-level language, primarily intended for numerical computations. It provides a convenient command line interface for solving linear and nonlinear problems numerically, and for performing other numerical experiments using a language that is mostly compatible with Matlab. It may also be used as a batch-oriented language. Octave contains an implementation of the Welch periodogram