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# Real-time Evaluation of Spectral Heart Rate Variability

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*Abstract*—**The most common spectral indices of Heart Rate Variability are the powers in the High Frequency (HF), Low Frequency (LF) and Very Low Frequency (VLF) bands. These indices have typically been computed using Fourier transforms. In this paper we propose a multirate filtering approach that does not require that the initial R-R intervals be interpolated to a regular sampling grid. The main advantage of this technique is that the HF, LF and VLF indices can now be updated at a high rate, allowing the tracking of short term HRV changes. The key to this real-time evaluation of spectral HRV is the first stage filter that converts the irregularly sampled R-R intervals to a regularly sampled signal.**

## I. INTRODUCTION

HEART rate variability [1] (HRV) has been found to be a promising tool to identify the interaction between the two antagonistic components of the autonomic nervous system, namely the sympathetic nervous system and the parasympathetic (or vagal) nervous system.

The HRV measurements can be divided into a set of time measurements, e.g. SDNN, RMSSD, etc…, and a set of spectral indices that includes [1,2]

- HF: high frequency power in the range [0.15-0.4] Hz, a marker for vagal activities.
- LF: low frequency power in the range [0.04 – 0.15] Hz, a combined marker for both sympathetic and vagal activities.
- LF/HF: a composite marker for the sympathovagal balance.
- VLF: very low frequency power in the range [0.003-0.04] Hz
- ULF: ultra low frequency power below 3 mHz.

The typical process for evaluating the power of the main spectral bands, HF, LF, VLF and ULF, has been to interpolate the R-R intervals to a regular grid and then take Fourier transforms. In earlier papers, the author and colleagues have pointed out that the interpolation process can cause significant attenuation of the components in the HF band leading to incorrect conclusions when the HF index is borderline significant [3], and recommended that, instead of using a Fourier transform, a (windowed) Lomb-Welch periodogram be used [4,5].

The Lomb-Welch periodogram, while able to yield the correct frequency powers, suffers from a computational disadvantage. It requires considerably more computation steps than the traditional Fourier transform method.

Like other spectral computations, the Lomb-Welch operates in batch mode. The lowest frequency component in the analysis determines the record length, and indirectly the rate at which these spectra components are calculated. For example, if the evaluation of the VLF band is desired, data from 5, preferably 15 minutes (0.003Hz corresponds to a period of 333 s, 5.5 minutes) are needed, yielding at least a delay of half this duration (the Fourier transform results can be associated with the time corresponding to the center of the window, just as with symmetrical finite impulse response filters). The computational load of evaluating a transform is also not negligible. By overlapping data, a higher update rate can be achieved, but at the expense of much increased computational burden.

Jasson et al. [6] have used Wigner-Ville transforms on 2 Hz interpolated R-R intervals to compute instantaneous spectral measurement. This is really just a variation of the concept mentioned above where transforms are computed at a high rate by increasing the overlap. The very high computational load, a 128 point transform every 0.5 second, makes this technique unsuitable for practical use.

In this paper, we present a multi-rate filter approach to the problem of evaluating the HF, LF, VLF and ULF components of HRV. By focusing on these components themselves, instead of the underlying spectra, real-time computation becomes practical. With this filtering approach, the stationarity assumption of transforms is not required.

## II. METHOD

### A. Low-Pass Filter for non-uniformly sampled data

The R-R sequence used to evaluate the HRV spectral indices is basically a non-uniformly sampled signal. The first step in the spectral HRV evaluation is to low-pass filter this signal to remove any component above 0.4 Hz. For the design of the filter, a sampling rate of 20 Hz was used. A 301 point symmetrical finite impulse response (FIR) digital filter was designed using the fdatool program of MATLAB (The Mathworks, Inc., Natick, MA). The length of the filter was chosen to be odd in order for the center of the window to fall on a filter point. With the filter coefficients centered on this center point, one essentially has a zero phase filter.

With the 20 Hz assumed sampling rate, the filter coefficients are accurate for a time grid of 50 ms. This corresponds to 1/50$^{th}$ of a 0.4 Hz cycle. To filter the non-uniformly sampled R-R series, filter coefficients are linearly

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interpolated from the 301 coefficients to the delays required by the locations of the R complexes. Effectively, from the 301 point filter with delay spacing of 50 ms, by linear interpolation we have derived a high resolution low pass filter. For each set of coefficients a different normalization factor must be computed to avoid the picket-fence effect caused by the variable sets of coefficients.

Since the HRV signal of interest is limited to 0.4 Hz, with most of the power below 0.3 Hz (respiratory sinus arrhythmia), the output can be resampled at a 1 sample/s rate, a factor of 2.5 over the HRV bandwidth. Thus, the output y(n), evaluated at time nT, where T is 1 s, is given by

$$y(n) = \sum_{t \geq nT-7.5}^{t \leq nT+7.5} RR(t)h(nT-t) / \sum_{t \geq nT-7.5}^{t \leq nT+7.5} h(nT-t) \qquad (1)$$

The times t in both summations are the times of the detected QRS complexes, and h(.) is the interpolated digital filter coefficients. The term 7.5 in the limits of the summations in Eq. (1) corresponds to the group delay of 7.5 s of the digital filter. This is an adaptive (due to the varying normalization factor) time-varying (the set of coefficients depends on the timing of the R-R sequence) digital filter. Eq. (1) is non-causal. In practice, the causal filter will have a group delay of 7.5 s.

### B. *Multirate low-pass filters for HRV spectral indices*

The output of the above adaptive time-varying filter is the HRV sequence which is now a regularly sampled signal at a 1 s/s rate. The HF, LF and VLF indices can be generated from the HRV signal by multirate filtering taking into account the bandwidths of the respective signals. By using symmetrical FIR digital filters, bandpass filtering can be achieved by lowpass filtering and then subtracting the resulting signal from the delayed input signal. The process to compute the four HRV indices is illustrated in Fig. 1. The lengths and sampling rates of the filters are shown in Table I.

TABLE I
FILTER LENGTH AND SAMPLING RATE

| Filter | Length (points) | Sampling Rate |
|---|---|---|
| 0.4 Hz LP | 301 | 20 s/s |
| 0.15 Hz LP | 51 | 1 s/s |
| 0.04 Hz LP | 97 | 0.5 s/s |
| 0.003 Hz LP | 199 | 0.1 s/s |

There was no attempt to optimize the filters. Shorter filters can be designed with different frequency characteristics.

If the LF/HF, or LF/(power in LF+HF) measures are desired, they can be computed for every LF sample, or every HF sample by linearly interpolating the LF samples.

## III. RESULTS

A 15 minute segment, from a 24 hour Holter record is illustrated in Fig. 2. This is from the first subject from the MIT-BIH “Long term” data base available on Physionet [7]. Since no averaging of the power was done, the RMS value is the same as the absolute value of the signal.

In Fig. 3, a 3 minute segment from the same Holter record is shown. In this case a 7 s, 30 s, 70 s and 70 s power averaging was performed on the HF, LF, VLF and ULF signals.

## IV. DISCUSSION

For off-line evaluation, the lengths of the filters are not critical. For real-time evaluation, with symmetrical filters, the group delay, which is equal to half the overall filter length, determines how soon a decision can be made based on the data. For our design, the group delays are given in Table II.

TABLE II
FILTER GROUP DELAY

| Filter | Group Delay | Total Delay |
|---|---|---|
| 0.4 Hz LP | 7.5 s | |
| 0.15 Hz LP | 25 s | HF: 32.5 s |
| 0.04 Hz LP | 96 s | LF: 128.5 s |
| 0.003 Hz LP | 990 s | VLF, UHF: 1118.5 s |

In Fig.3, notice the increased HF energy peaks which correspond to short bursts of high frequency activities. These would not be so clearly visible in a transform approach due to the much broader equivalent averaging.

## V. CONCLUSION

With the adaptive time-varying HRV filter, followed by multirate digital filters, it is now practical to evaluate HRV spectral parameters in real-time. While the spectral structure appears to be lost with this approach, the lighter computational burden makes implementation of the proposed method of HRV spectral measurement practical in portable instruments. The spectral structure can still be recovered by performing Fourier transform on the individual ondices.

With a method for practical real-time evaluation of the HF, LF, VLF and ULF signals, the biomedical engineer now has a new tool for analyzing the fine variations of the HRV in response to external or internal stimuli..

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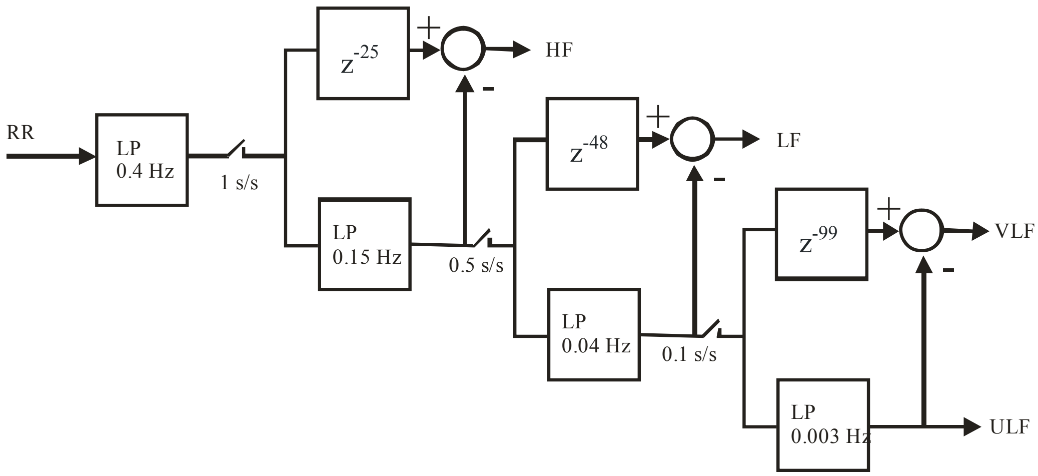


Fig. 1. Multirate filter for HRV spectral component evaluation. The first low-pass filter is the adaptive time-varying filter discussed above. The other low-pass filters are symmetrical digital filters with an odd number of coefficients. The delays are needed to account for the group delays of the corresponding filters. If needed, the ULF signal can be resampled at 0.01 s/s.

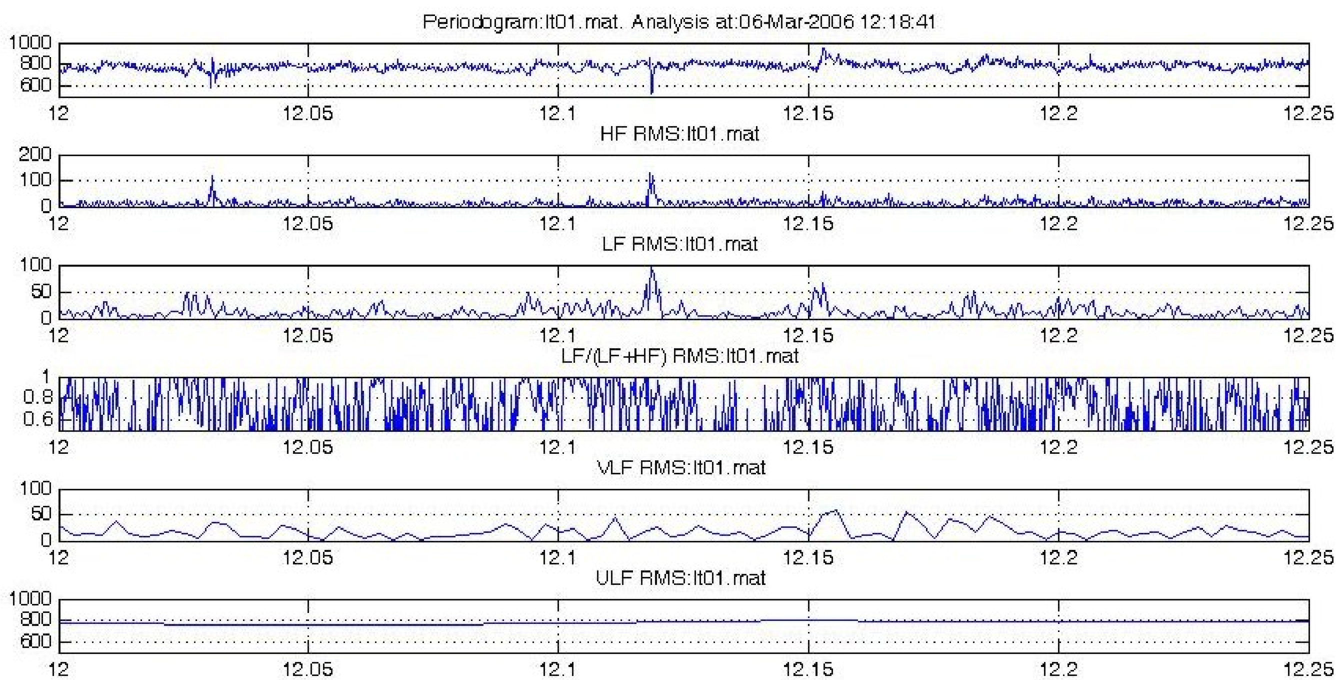


Fig. 2. 15minute R-R record segment, from 24 hour Holter, and the derived HF, LF, LF/(LF+HF), VLF, and ULF indices. In this graph, the absolute values of the filtered signals are displayed since no averaging of the power over time was performed. Thus, except for the unitless LF/(LF+HF) graph, the vertical axis units on the other graphs are ms Instead of displaying the LF/HF, we have chosen to show the ratio of the LF and the square root of the sum of the squares of the LF and HF signal. This ratio is limited to a maximum value of 1, which indicates sympathetic dominance. The sampling rates are: HF: 1 s/s; LF: 0.5 s/s; VLF and ULF: 0.1 s/s. The horizontal axis indicates the time from the beginning of the recording in units of hours.

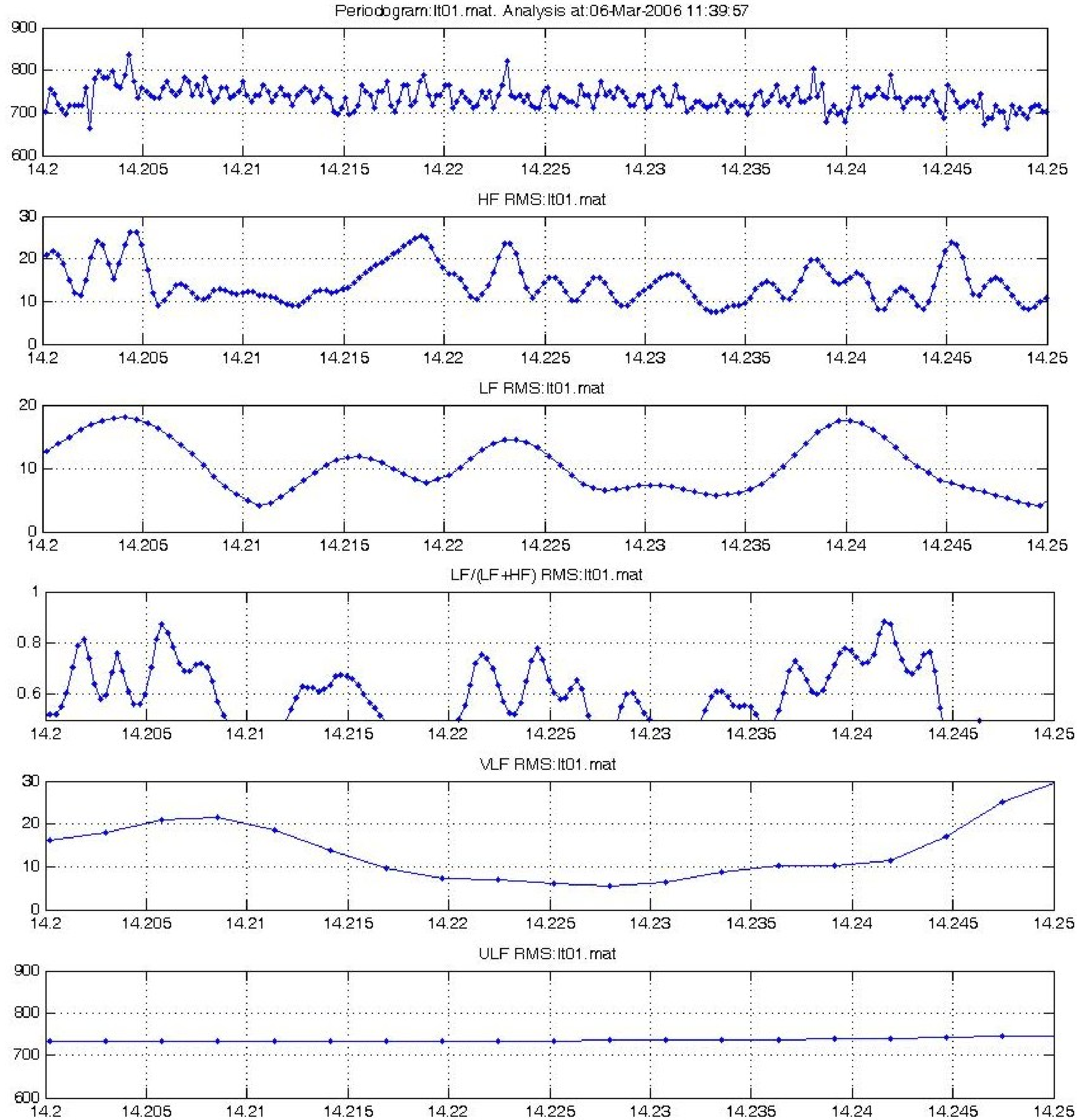


Fig. 3. 3 minute R-R record segment and the derived HF, LF, LF/LF+HF), VLF and ULF indices. Power averaging with windows of 7 s long for HF, 30 s for LF, and 70 s for both VLF and ULF, were used. Horizontal axis is time, in hours, from the beginning of recording. The vertical axis is signal amplitude, in ms, except for the LF/(LF+HF) graph which is unitless. The LF/(LF+HF) graph shows that the LF component is slightly larger, but with interesting HF peaks. With a bandwidth of only 3 mHz, the ULF signal is almost constant in this 3 minute interval.