Implicit Comparison of Accuracy of Heart Rate Variability Spectral Measures Estimated via Heart Rate and Heart Period Signals

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Abstract

In this article an overview of existing signals for evaluation of HRV spectral domain measures is made. Functional dependency between heart rate and heart period signals has been analyzed. Artificial data series have been used to extract features of spectra estimated via heart rate and heart period signals. Criteria for choosing between mentioned signals has been introduced and discussed. Implicit comparison of distortions of spectral measures estimation has been tested on "Fantasia" database (Physionet.org). Statistical analysis of differences between calculated spectral HRV measures obtained using heart rate and heart period signals has been presented.

1. Introduction

Heart rate variability (HRV) is widely used as a non-invasive informative marker of activity of the autonomic nervous system [1-3]. Its spectrum analysis is suitable for short-term analysis and spectrum indexes most commonly used in diagnostics. Different discrete signals are applicable for HRV analysis:

Heart period (HP) signal is a graphical representation of sequence of R-R interval magnitudes at time moments of preceding R-wave occurrence;

Heart rate (HR) signal is similar to HP, but instead of R-R intervals, inverse R-R intervals are used, resulting in sequence of instant heart rate values;

Heart timing (HT) signal was used in [4-5] to estimate spectrum of the modulating input of IPFM model;

Sequence of counts [6] is a sequence of delta-functions placed at time of R-wave occurrence, which can be used to estimate spectrum of counts.

Intensive comparisons of spectra, estimated via listed above signals were reported by different authors [4-8]. It was shown that sequence of counts gave significantly biased estimation of spectrum [5]. HT signal advantages strictly based on the fact that integral pulse frequency modulation (IPFM) model [9] is completely accepted. It limits its applications and it is rarely used in practice. In summary, mentioned studies showed practical usefulness of both HR and HP signals on artificial data, but unfortunately no criteria for choosing between HR and HP signals on real data were presented. This uncertainty could cause impression that there is no significant difference between HR and HP spectra measurements even when the studies [6,8] show the opposite. Aim of this study was to provide theoretical and experimental analysis of HRV spectrum measures estimated via HR and HP series and to invent criteria for choosing between HR and HP signals.

2. Interrelation between HR and HP signals

HR and HP signals have nonlinear interrelation:

$$HP(t) = k/HR(t), \tag{1}$$

where *HP(t)* is heart period function of time *t*, *HR(t)* is heart rate function of time *t*, *k* depends on *HP(t)* and *HR(t)* units. Analytic frequency domain transformation involves Fourier integrals calculation for inverse harmonic functions. It becomes non-trivial task even for simple HP and HR signals as it was shown in [8]. Therefore we used numerical simulation of HR and corresponding HP signals to estimate dependency between their spectra.

2.1. Spectral analysis of HR and HP signals

Some properties of dependencies between HR and HP signals could be derived from simple HP signal model:

$$HP(t) = HP_0 + A_0 \sin(2\pi f_0 t), \tag{2}$$

where f_0 - frequency of HRV, A_0 - magnitude of HP variability, HP_0 - mean value of heart period. After selection HP_0=1000*ms*, (HR=1*Hz*), f_0=0.4*Hz*, A_0= 200*ms* we could discretize (2) and find spectra of HP and corresponding HR signal (fig.1) using (1). Spectrum was estimated using Welch FFT method [10] (Hamming window, 8 segments, 50% overlap, FFT vector length 3000 samples) for 300*s* signal, discretized at 10 *Hz*. It could be seen (fig.1) that frequency content of HR signal (dashed line) is almost identical to frequency content of HP signal (solid line), and only high frequency components appear to compensate nonlinearity between HR and HP signals. Fig.2 demonstrates numerical simulation of ratio of first high frequency multiple $A(2f_0)$ harmonic magnitude to main harmonic magnitude $A(f_0)$ as a function of ratio HP_0 / A_0. Even for situations, rarely possible for real data, when $HP_0 / A_0 = 2$, harmonics ratio $A(2f_0)/A(f_0) \approx 6.3\%$.

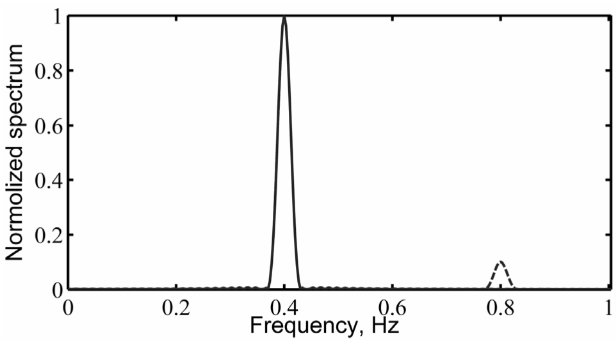

Figure 1. Normalized spectrum of HR signal calculated after nonlinear transformation from initial HP signal.

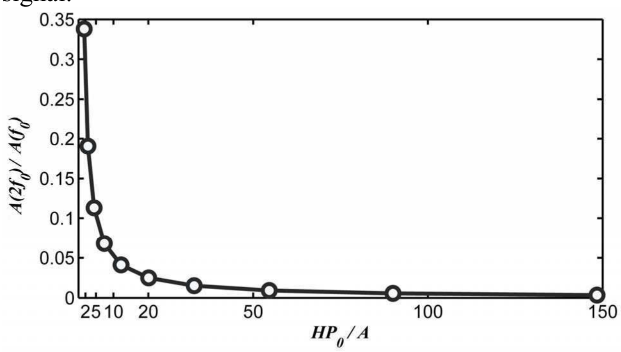

Figure 2. Numerical simulation of multiple harmonics amplitudes as a function of overall HRV.

2.2. Power spectral density analysis

In real applications HRV measures are estimated via power spectral density (PSD) function since HR or HP is assumed to be stochastic signal. PSD includes quadratic function of amplitude spectrum. So, for PSD function influence of isolated nonlinear multiple harmonics would be even smaller then for magnitude spectrum. However, HRV spectrum components are not presented by isolated frequency components in practice, but cover whole modulation domain from 0 to 0.4 *Hz* what results in more significant summary impact of multiple harmonics on the PSD.

We used a modification of the algorithm for generating artificial heart rate signals presented in [11], to generate artificial HP series with equal magnitude of samples in frequency domain of artificial signal and to assess influence of choosing between HR and HP signal on corresponding PSD functions. The fragment of test HP series is presented on fig.3. Usage of phase randomization before inverse FFT allowed us to get new time realization of artificial signal at each simulation run. We completed 1000 Monte-Carlo method runs over artificial HP signal generation procedure. From equation (1) we calculated HR signal and its PSD function as well as PSD function of HP signal for each realization. HP and HR PSD functions were normalized by Euclidean norm of PSD samples vector, then their ratio function were calculated:

$$RF(f) = \frac{nP_{HR}(f)}{nP_{HP}(f)}, \quad (3)$$

where $nP_{HR}(f)$ and $nP_{HP}(f)$ represent normalized PSD functions of HR and HP signals correspondingly.

Fig.4 demonstrates results on statistical analysis of the ratio function. We could see that a linear trend appeared in the ratio function because of multiple harmonics. Kolmogorov-Smirnov (K-S) test was applied to verify significance of differences in probability distributions of PSD values at 0.1 *Hz* and 0.4 *Hz* (fig.4) and was successfully rejected for significance level 0.001.

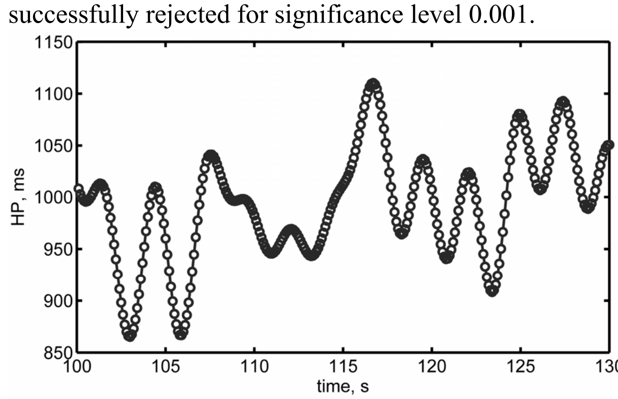

Figure 3. Fragment of model HP signal.

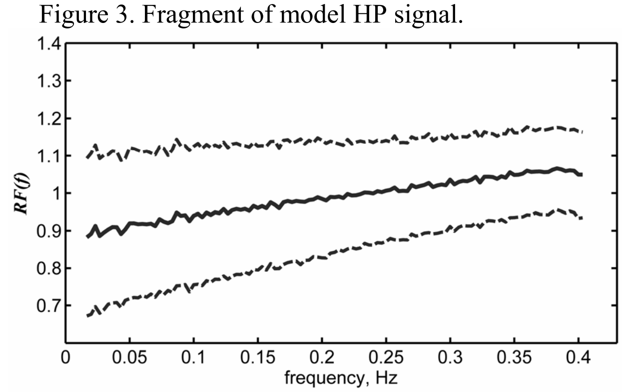

Figure 4. Mean value of $RF(f)$ represented with the solid line, dashed lines bound double SD interval.

Real heart events data has evident harmonic content on the one hand, and it has plenty of nonlinear components which can not be processed correctly by means of harmonic analysis on the other hand. It is known [1,2] that PSD function of signals with nonlinear components (including signals after nonlinear transformations, as it was shown above) can be severely affected. Thus, the less PSD function is distorted, the less nonlinear components are in the signal. Now, if we choose closeness of the signal to pure harmonic signal (the signal without nonlinearities and PSD distortions) as criteria for choosing between HR and HP signals, then we, in fact, should compare PSDs of HR and HP signals distortion. Obviously, these distortions can not be estimated completely since the underlying heart dynamics is unknown. But HR-HP transformation is completely known, hence association between distorted and non-distorted (means for HR-HP transformation only) PSD functions is always known. Therefore the distortions can be compared through pure harmonic signals with known PSD extracted from real data, resulting in implicit comparison of PSD distortions.

Obviously the algorithm for implicit comparison of HR and HP spectrum distortion can not be implemented without real HP and corresponding HR signals. After extraction of HR P_{HR} and HP P_{HP} spectra, we were generating corresponding pure harmonic artificial (model) HR (mHR) and HP (mHP) signals with exactly the same PSD functions by applying inverse Fourier transforms to the spectra and using randomized phase contents. Then the inverses of mHR and mHP signals were calculated and PSD P_{mHP} and P_{mHR} for these model inverse signals were estimated. Relative distortions with respect to initial P_{HR} and P_{HP} functions can then be compared using simple equation:

$$rP_{HP}[f] = \frac{P_{HP}[f] - P_{mHP}[f]}{P_{HP}[f]}, \qquad (4)$$

The function (4) represents implicit PSD distortions of HP (and similarly HR) signal with respect to the PSD of pure harmonic function. Corresponding schematic representation of the algorithm is shown on fig.5.

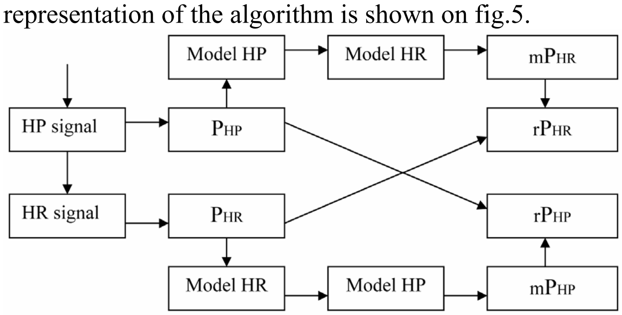

Figure 5. Schematic representation of the algorithm for implicit PSD distortion comparison.

Numerical simulations show that if we generate the HP signal from given PSD P_{HP} as described below with random phase shifts for harmonics, then PSD P_{mHR} of corresponding inverse signal statistically converges to its actual value. Hence, if we assume that HR signal is closer to pure harmonic signal, then model HP signal will be affected by the same inverse transformation when generating model HR signal, and statistically, PSD of model HR signal will converge to PSD of real HR signal. Thus, closeness of the HP signal to harmonic signal could be measured by quality of restored HR PSD, what corresponds to minimum of $rP_{HR}[f]$ function. Then the minimum among $rP_{HR}[f]$ and $rP_{HP}[f]$ functions defines the closeness of HR or HP signal to harmonic signal.

3. HP and HR comparison on real data

We used "Fantasia" database [12] to test our hypothesis on real data. For all records firstly we excluded ectopic beats, and then PSD was estimated using Lomb method (on 5-minutes window with 30 seconds shift between windows) as described in [13] to avoid and exclude possible influence of interpolation errors. The described procedure for implicit spectra comparison was applied to the set of (N=4837) young and (N=4164) old volunteers' 5-minutes record fragments. Results for groups of young and old volunteers are presented on fig.6. Significant difference between $rP_{HR}[f]$ and $rP_{HP}[f]$ functions could be clearly seen.

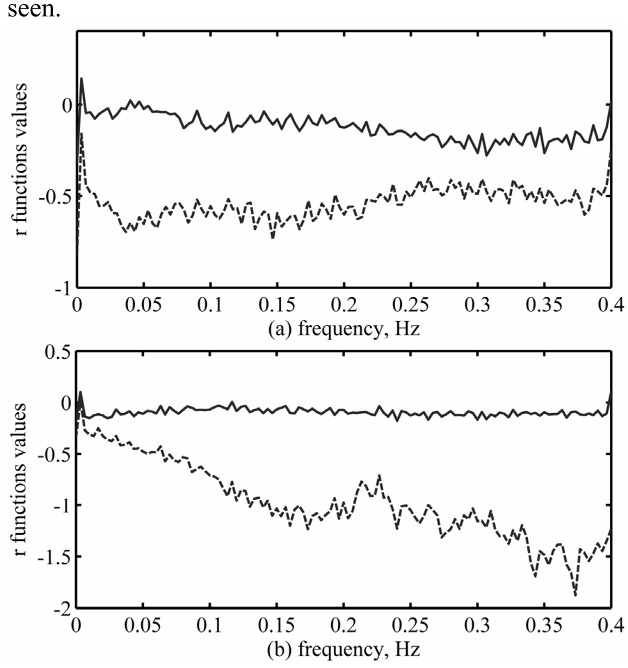

Figure 6. Plots of the $rP_{HR}[f]$ (solid) and $rP_{HP}[f]$ (dashed) for groups of young (a) and old (b) volunteers.

Additionally we analyzed influence of choosing between HR and HP signal on different PSD statistics. We calculated integrate difference of PSD functions for groups of young and old volunteers using formula:

$$K_1 = \frac{\sum_{f=f_0}^{f_k} \left| nP_{HP}(f) - nP_{HR}(f) \right|}{\sum_{f=f_0}^{f_k} nP_{HR}(f)} 100\%, \qquad (5)$$

where $f_0 = 0.04Hz$, $f_k = 0.4Hz$. K_1 was calculated for young $K_1 = (6.68 \pm 4.23)\%$ and old $K_1 = (2.27 \pm 3.53)\%$ volunteers.

Also we analyzed influence of choosing HR or HP signal on separate spectral HRV measures: *nLF*, *nHF* and *LF/HF* (definitions are consistent with definitions in [1]) Measures were estimated via HR and HP signals and then their relative displacements were calculated. Results are presented in table 1. Significant importance for clinical studies has absolute values of *LF/HF* ratio. Fig.7 represents distribution of the ratio displacements with respect to its absolute values.

Table 1. Results of displacements estimation

	Young volunteers		Old volunteers	
Measure	mean, %	SD, %	mean, %	SD, %
K_{nLF}	1.85	5.62	0.93	3.10
K_{nHF}	-8.61	11.44	-1.46	8.50
$K_{\frac{LF}{HF}}$	7.75	30.85	1.51	11.42

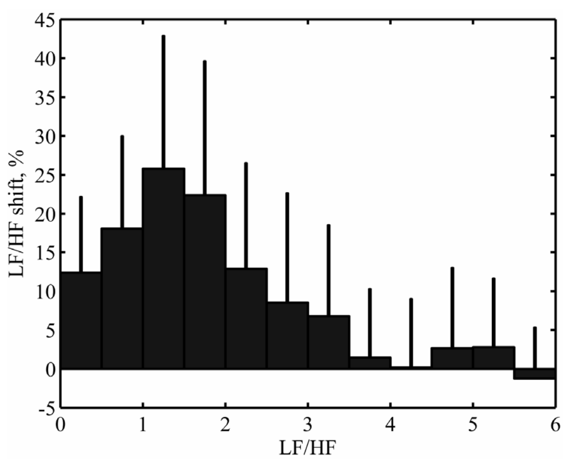

Figure 7. Distribution of shifts (boxes) between *LF/HF* ratio, estimated from HP and HR signals, whiskers show standard deviation.

4. Discussion and conclusions

Resulting $rP_{HR}[f]$ and $rP_{HP}[f]$ functions clearly show significant dominance of distortion for HP PSD function comparing to HR PSD function. Thus, we can conclude that HP signal is closer to pure harmonic signal. HP signal could be chosen for HRV spectral measures estimation according to the criteria of signal closeness to pure harmonic signal.

When estimating PSD of HR signal, it should be taken into account that its PSD could be more affected by nonlinear components of the HR signal.

Displacements of *LF/HF* index represented in table 1 and fig.7 show that it impossible to make correct interchange of HRV spectrum measures (even in normalized units) acquired using HR and HP signals.

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