HIGH FREQUENCY FILTERING OF 24-HOUR HEART RATE DATA

Albinas Stankus, Assistant Prof.
Mechatronics Science Institute, Klaipeda University, Klaipeda, Lithuania
Institute of Behavioral Medicine, Lithuanian University of Health Sciences, Palanga, Lithuania
Vytautas Stankus, Assistant Prof.
Department of Physics, Kaunas University of Technology, Kaunas,Lithuania
Rimantas Didziokas, Prof.
Mechatronics Science Institute, Klaipėda University, Klaipėda, Lithuania
Giedrius Varoneckas, Prof.
Mechatronics Science Institute, Klaipeda University, Klaipeda, Lithuania
Institute of Behavioral Medicine, Lithuanian University of Health Sciences, Palanga, Lithuania

Abstract

Heart rate (HR) and its variability (HRV) analysis based on spectral methods have been widely applied for assessment of autonomic nervous system activities. However, an observation of existing frequency dynamic in particular spectral bands of HRV, especially when analysis is done in short time RR interval series, is problematic using these methods. We used self-developed digital filters to solve this problem. The high-frequency (HF; 0.15-0.4 Hz) band of RR intervals is filtered with 3 finite (FIR) and 4 infinite impulse response (IIR) filters from original 24-hour HR record. We showed that the use of various filters for identification of respiration influence on HR. An analysis using FIR filters gives more accurate results, but requires more calculation resources. No differences between results obtained using filtering and spectral analysis were observed. The use of FIR and IIR filters are simple and effective for processing of both, 24-hour data and short-time series of RR intervals.

Keywords: Heart rate, heart rate variability, spectral analysis, filtering

Introduction

Heart rate (HR) and its variability (HRV) are defined by spectrum expression in the known main frequency bands of HR record. Low frequency component (LF), which corresponds to blood pressure dynamics, and high frequency component (HF), which is caused by influence of respiration on HR, are especially important for assessment of autonomic control. Spectral analysis method is using successfully for determination of LF and HF components in short-time RR interval series (Malik M. et al, 1996). A lot of non-stationary elements are seen in 24-hour HR records due to big and slow oscillations in RR intervals. Therefore, the use of spectral analysis for long time RR interval sequences can give distortion in the assessment of HF component. On the other hand, spectral analysis method gives integral values of RR interval sequence. Because of that the analysis of shorter RR interval sequence gives more information on dynamics in particular frequency bands. But it reduces the reliability of the results. This problem was solved by using of wavelet analysis method (Addison P.S., 2005). RR interval data filtering in particular frequency methods in main reviews about many HRV analysis methods are almost not mentioned, except some exceptions (Kamath M. V., 1993). The filters were used for respiratory sinus arrhythmia assessment in foremost HRV analysis works (Womack, B.F., 1971; Chick DR, Womack B.F., 1975). Baxter F. Womack utilized both; recursive and fast Fourier transform digital filtering. Nowadays HRV is calculated from spectrum of RR intervals and is expressed as the sum of power within a frequency range. Integral values after spectral analysis and after filtering by FIR and IIR filters were compared in another work (Tsung-Chieh Lee; Hung-Wen Chiu, 2010). The errors from FIR method were 37.5% in LF and 80% in HF power that are better than from IIR method. The orders of IIR filters chosen in this test were only 2-10 and the LF band and HF band signals of HRV were filtered from 256 beats signal. FIR filters were with 10-40 orders. The filtering method allows to observe the dynamics of variance in time in chosen frequency band.

The goal of this work was to compare assessments of high frequency of 24-hour heart rate using different filters and spectral analysis.

Methodology

Twenty four hour Holter monitoring was done in 213 persons undergoing the rehabilitation programme at the Cardiovascular rehabilitation clinic of the Institute of Behavioral Medicine of Lithuanian University of Health Sciences. The age of persons was 58±9 years. RR intervals were determined from the Holter's electrocardiogram. Artifacts in RR interval sequence were excluded by special software. The developed software allowed to apply filtering and spectral analysis methods for whole or chosen length RR interval sequences.

Spectral analysis of RR interval is accepted method for assessment of autonomic HR control. The rhythmic components of HRV were separated and quantitatively assessed by means of power spectral analysis. Three main spectral components were calculated from short term recordings by integrating the power spectral density in standards defined frequency bands: the powers of high frequency (HF; 0.15–0.4Hz), low frequency (LF; 0.04–0.15Hz) and very low frequency (VLF; 0.003–0,04Hz) components of HR. RR interval average (xRR, ms), standard deviation (sRR, ms), HF (ms), LF (ms) and VLF (ms) components pick to pick amplitude values in milliseconds were analyzed. Obtained results were stored in database for further analysis. Statistical analysis was performed using Student's t-test for mean values. The main digital filters specification characteristics as the magnitude response, phase response, and the allowable deviation for each were chosen for assessment of RR intervals filtering methods. Figure 1 illustrates the magnitude frequency responses of a bandpass filter, which passes a certain band of frequencies and attenuates lower 0.15Hz and higher 0.40Hz frequencies. In the previous figure, stopband edge frequency 0.10Hz indicates the maximum frequency of the lower frequency range that you want to attenuate, and stopband edge frequency 0.45Hz indicates the minimum frequency of the higher frequency range that you want to attenuate. The frequency range between passband edge frequency 0.15Hz and 0.40Hz indicates the range of frequencies that can pass through the filter.

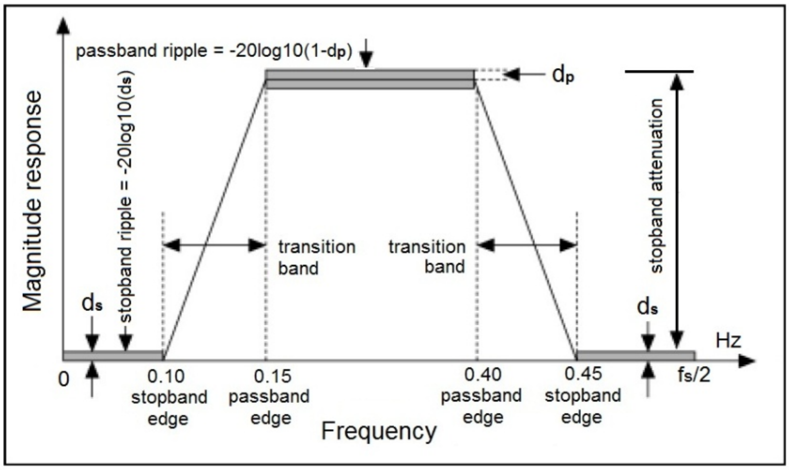

Figure 1. The design of the chosen filter

The frequency range from the passband edge to the stopband edge frequency is the transition band, which has a frequency response that is unspecified. The filter passband and stopband can contain oscillations (ripples). The magnitude of the passband ripple indicates dp, which equals the maximum deviation from the unity, the magnitude response of the stopband ripple indicates ds, which equals the maximum deviation from zero.

In this paper the whole sequence of chosen filters provide the following FIR filter designed on these methods: Kaiser Window, Dolph-Chebyshev Window, Equi-Ripple FIR filters; and the following IIR filter design methods: Butterworth, Chebyshev, Inverse Chebyshev and Elliptic filter.

Edge steepness of chosen filter was from 0.1 to 0.15Hz at low frequency side and from 0.4 to 0.45Hz at high frequency side. Defined limits of filtered frequency band oblige to interpolate RR interval sequence by higher frequency doubled 0.45Hz or more. The sequence was interpolated using 0.1s period. Beyond the edge of 0.45Hz frequency stopband attenuation value was chosen 60dB. It was done because the values over 60dB rouse the number of calculation sections from 40 to 60 (100dB) for FIR filters and from 200 to 380 for IIR filters. The ripple level in the passband was equal 0.1. Although, only FIR filters can have exactly linear phase, IIR filters that you design using Butterworth, Chebyshev, Inverse Chebyshev or Elliptic methods usually have a nonconstant group delay, which means that they have nonlinear phase or phase distortion. Choosing of phase characteristics and group delay do not influence the investigation results, because in the analysis of HRV of particular frequency bands integral methods dominate. Phase shifts do not influence these methods results. Dispersion and standard deviation was calculated in chosen intervals of time sequence after filtering. The data as in spectral analysis were stored as amplitude values in milliseconds. To compare the filters this procedure was performed with all 7 filters. Moreover obtained results of processing of the same time sequence intervals were compared with spectral analysis results.

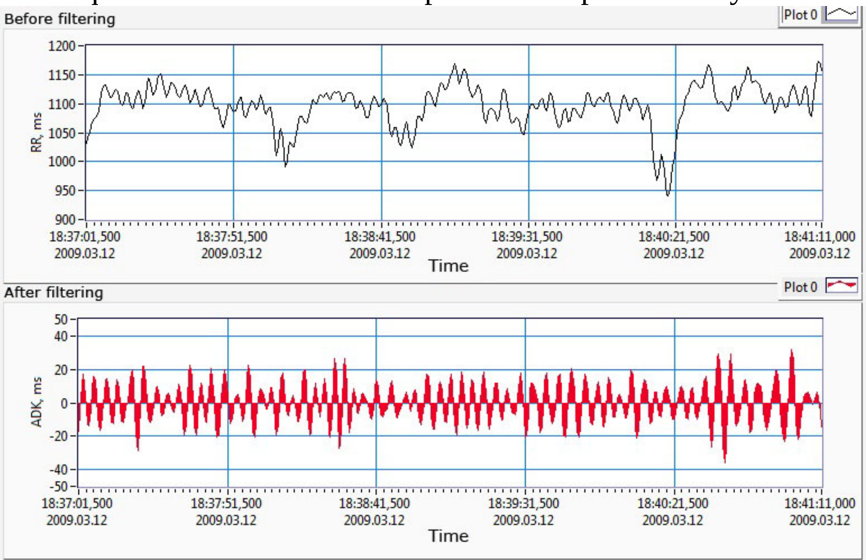

Figure 2. Sequence of RR intervals before and after filtering

RR intervals sequence of 4 minutes and 10 seconds before and after filtering is showed in Fig. 2. Choosing of observation window size depends on tasks of investigation. One hour duration observation window was chosen for further analysis. Obtained results were processed by statistical methods, but the priority was given to variation coefficient method.

Results and discussion

Twenty four hour RR interval sequence filtering was made using all seven filters. Figure 3 demonstrates that despite the large changes of HRV at exceptional time intervals, no essential differences between filtering results were found. Coefficient of variation during the day, when it was calculated every other hour, varied from 1.14 to 5.3 % (3.58±0.94%). The HF component expresses non-uniformly, but practically no differences between amplitudes were observed in every hour interval.

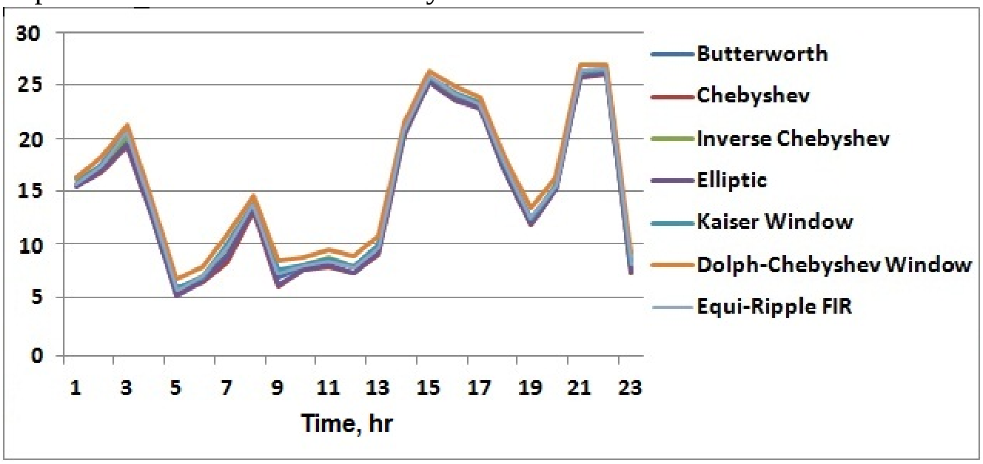

Figure 3. Dynamics of HF component during 24-hour record using different filters.

Coefficient of variation showed the stability of obtained data and very small difference between used filters. The more precision analysis showed, that there is difference between using of FIR and IIR filters. HF amplitude is reliably higher after using FIR filter, than after using IIR filters ($p<0.001$), but the difference is very small and did not exceed 4 ms.

The results of HR analysis using FIR and IIR filters were compared with the results of spectral HR analysis. Choosing of IIR was determined of other authors' references data (Womack, B.F, 1971; Proakis J., 1995). The maximally flat FIR filter is described by Herrmann (Herrmann O., 1971). It is known that IIR filter can provide a significantly faster and more efficient filtering operation than FIR filter. The main features of the four IIR-based design methods are summarize in Table 1 (Kehtarnavaz N., 2008).

Table 1. Comparison of IIR filters

IIR Filter	Ripple in passband	Ripple in stopband	Order for given filter specifications
Butterworth	No	No	Highest
Chebyshev	Yes	No	Lower
Inverse Chebyshev	No	Yes	Lower
Elliptic	Yes	Yes	Lowest

The table shows, that classical Butterworth filter don't cause ripples, but is slowest. Conversely elliptical filter is 4-5 times faster, than Butterworth, but cause a ripples in passband and stopband. We choose Butterworth filter which effectiveness depends on value of stopband attenuation. We found that changing stopband attenuation value from 60dB to 10dB number of order for this specifications filter decreases from 74 to 26. Moreover, when 60dB value was used, the filter destroys about 20s of sequence duration. This value decreases to 5s, when just 10dB was used. Reducing the edge of steepness from 60dB to 10 dB gives increasing of average HF value just to 3ms and it was non-reliably ($p>0.5$).

When test signal with amplitude of HF component equal to 40ms was used, the amplitude value changed up till 43ms. These data shows, that when integral indicators are applying for HRV assessment, the choosing of the edge of steepness for IIR filter influence the final results very small. RR intervals filtering was made using Butterworth filter and assessment was made for obtained sequence standard deviation hourly. Obtained values were compared with results of spectral analysis using the same intervals of time. The dynamics of HF component, which was estimated by spectral analysis and of results of difference HF amplitude due to filtering of the 24-hour HR data are presented in Figure 4.

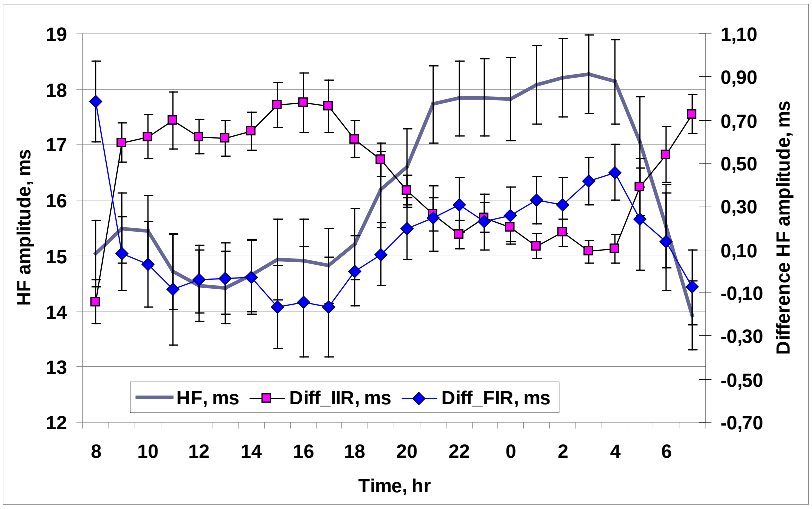

Figure 4. The dynamics of RR intervals HF component during the 24-hour HR data.

Figure 4 shows, that during night-time HF component reliably increases. It confirms that parasympathetic nervous system dominates in regulation of HR during the night. The results showed that the difference between data, obtained by different methods is very small. It is important to notice that in first hour more difference is due to losses of first values of sequence by filter. Equi-Ripple FIR method, which yields optimal filters and often produces the best results for most FIR filter design problems were chosen from FIR filter group.

The same calculations were made as for IIR filter. The comparing of these results with results obtained by spectral analysis showed that differences were very small and minimal at day time, when many non-stationary time segments exists in heart rate dynamic. It was observed that more errors were made by IIR filter, than FIR filter in these time intervals. Obtained results confirm that it is possible rather precisely estimate HRV using various FIR and IIR filters. The differences decrease when optimal characteristics are chosen. It is important do not forget, that for obtaining very precise results, the analysis of first values of RR interval sequence, which magnitude depends on number of using sections, should be eliminated. Non-reliable results of HR data filtering presented in literature (Chick D.R., 1975) could be influenced by two reasons: short time sequence (256 RR intervals) and contribution of initial values.

Conclusion

The results of investigations showed that reliable and stable results of HR data filtering were obtained for identification of HF component using various filters. This method allows to observe the HF dynamics of RR intervals, using desirable observation window in time. FIR filters are more precise, but it requires more calculation resources. Obtained results showed no difference between using of spectral analysis method and filtering in HF component. The application of FIR and IIR filters in HR analysis is simple and useful as for whole time sequence, as for particular time series. A filter-based method is superior to spectral HR analysis, because enables to observe a dynamics of HF component.

Acknowledgements

This investigation was partly financed by Council of Lithuanian Science (contract Nr. TAP-LU-11-005). Investigation was realized by cooperation with Mechatronics Science Institute of Klaipeda University and Institute of Behavioral Medicine of LUHS.

References:

Malik M. et all. Heart rate variability. Standards of measurement, physiological interpretation, and clinical use. Eur Heart J, 1996, 17, 354–381.

Addison P.S. Wavelet transforms and the ECG: a review. Physiol Meas,. 2005, 26(5), R155-199.

Kamath M. V. and Fallen E. L. Power spectral analysis of HRV: A noninvasive signature of cardiac autonomic functions. Crit. Rev. Biomed. Eng., 1993, 21, 245–311.

Womack, B.F. The Analysis of Respiratory Sinus Arrhythmia Using Spectral Analysis and Digital Filtering . IEEE Trans Biomed Eng., 1971, 18(6), 399-499.

Chick D.R., Womack B.F. Approximate identification and digital simulation of the respiration--heart-rate system. Med Instrum. 1975, 9(1), 15-20.

Tsung-Chieh Lee; Hung-Wen Chiu. Frequency-domain heart rate variability analysis performed by digital filters. Computing in Cardiology, 2010, 37, 589–592.

Proakis J. and Manolakis D. Digital Signal Processing: Principles, Algorithms, and Applications, Prentice-Hall, 1995.

Herrmann O. On the approximation problem in nonrecursive Digital filter design. IEEE Trans. Circuit Theory, 1971, 18, 411–413.

Kehtarnavaz N. Digital Signal Processing System Design: LabVIEW-Based Hybrid Programming. 2008, Elsevier Inc., 342p.