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Research Paper

Wavelet analysis of heart rate variability: Impact of wavelet selection

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ABSTRACT

Background: Wavelet transform based analysis of heart rate variability is increasingly being used for a wide variety of clinical applications. There is no gold standard as to which wavelet to use and the correlation between results obtained by using different wavelets is unknown.
Methods: Heart rate variability in electrocardiograms from healthy volunteers was analyzed using the following wavelets (maximum overlap discrete wavelet packet transform): Haar, Daubechies 2, 4, and 8, least asymmetric Daubechies 4 and 8, and best localized Daubechies 7 using the RHRV package in R. Correlation of power in the different frequency bands (ultra low frequency (ULF), very low frequency (VLF), low frequency (LF), high frequency (HF)) as well as total power and LF:HF ratio were calculated. Bland-Altman comparisons were also made for selected wavelets to test for agreement.
Findings: Correlations between results obtained by different wavelets were all statistically significant. Most correlation coefficients were moderate ($0.3 \le r \le 0.7$). They were, however, generally lower for the LF:HF ratio, which is commonly used to assess balance of the autonomic nervous system.
Conclusion: It is necessary to report which wavelet is used when performing wavelet transform based heart rate variability analysis and depending on whether one is interested in detecting onset or intensity of changes performance of wavelets will vary.

1. Introduction

Analysis of heart rate variability (HRV) is increasingly being used [1] as a measure for assessing autonomic nervous system balance. Clinical applications include responses to drug administration [2], objective measurement of pain [3], measuring depth of anesthesia[4], assessing hemorrhagic shock compensation [5], depression [6], sleep staging [7], driver drowsiness [8], and many more.

One of the mathematical models used to analyze HRV – the Fourier transform (FT) – has certain limitations that make it a non-ideal candidate: it is limited to stationary (or periodic) signals, which assumes that the mean heart rate is constant over time, and lacks time resolution. The short time Fourier transform (STFT) has been used to overcome some of these problems, but it basically represents a compromise between either high time resolution or high frequency resolution [9]. For many of the above-mentioned clinical applications a high time resolution is critical in order to detect sudden changes without major delays. At the same time, it is imperative to maintain frequency resolution in order to isolate spectral ranges of interest. The wavelet transform (WT) has been suggested, and increasingly used, to overcome this dilemma in HRV analysis where a temporal localized sliding analysis of the electrocardiogram (ECG) signal is performed. In addition, the shape of the WT-analyzing equation can be chosen to better fit the biomedical signal than the sinusoid shapes used by the FT or STFT. Researchers are frequently offered a wide variety of these wavelets or kernels to choose from: Haar [3], Daubechies [2,6,10–12], biorthogonal [13], Morlet [5], etc. For example, Tejman-Yarden et al. used the Haar wavelet to detect responses to cold pain stimuli in volunteers. They found significant changes in the WT coefficients' density during increasing, stable and decreasing pain [3]. Deschamps et al. [14] used the Daubechies 4 kernel to investigate changes in the HRV frequency bands and total power in laboring women receiving epidural analgesia. High frequency power increased and the low frequency to high frequency ratio decreased significantly in their study population. However, there is no gold standard as to which kernel should be used for HRV analysis and it is not clear how wavelet selection impacts results of WT based HRV analysis [15], or how comparable results obtained by different wavelets are.

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This study therefore investigated the correlations between power in the different frequency bands obtained by maximum overlap discrete wavelet packet transform (MODWPT) based HRV analysis using several commonly used kernels in ECGs obtained from healthy volunteers. We hypothesized that wavelet selection does not have a major impact on outcome of MODWPT based HRV analysis secondary to high correlations between results obtained by different wavelets.

2. Methods

2.1. Participants and ECG acquisition

After obtaining IRB (Stanford University IRB3, #28503) approval and written, informed consent, five healthy volunteers (two male, three female, age range: 28–33 years) were connected to a Propaq monitor (Welch Alynn, Skaneateles Falls, NY, USA) and a 3-lead ECG was acquired. Volunteers were seated on a comfortable, reclining chair and instructed to hold still in order to minimize movement artifacts. Data was recorded in ASCII format for offline-analysis using the real-time ECG output connector of the Propaq monitor and a custom-built, Atmel ATmega2560-based device with a sampling rate of 500 Hz. In addition, we analyzed ECG obtained in identical fashion as described above from an anesthetized patient that was exposed to a painful stimulus (clamping the head for a craniotomy). After obtaining written informed consent the patient was connected to the standard anesthesia monitor (Intellivue MP60, Philips Healthcare, Andover, MA, USA). Data was recorded in ASCII format for offline-analysis using the real-time ECG output connector of the monitor and a custom-built, Atmel ATmega2560-based device with a sampling rate of 500 Hz.

2.2. HRV analysis

Raw data was imported to Kubios [16,17](“Kubios HRV premium software 3.0.0”, Finland), artifacts were automatically corrected

Table 1

Spearman rank correlation coefficients for spectral power obtained by wavelet transform in the ultra low frequency (ULF), very low frequency (VLF), low frequency (LF), high frequency (HF) power bands, as well as the total power (TP) and the LF:HF ratio (LFHF). Data presented as average (minimum to maximum range). All correlations were significant ($p < 0.01$).

ULF	haar	d4	d8	d16	la8	la16
d4	0.90 (0.88–0.92)	–	–	–	–	–
d8	0.72 (0.70–0.76)	0.88 (0.87–0.90)	–	–	–	–
d16	0.41 (0.38–0.44)	0.55 (0.52–0.59)	0.76 (0.74–0.79)	–	–	–
la8	0.93 (0.91–0.94)	0.97 (0.97–0.97)	0.82 (0.81–0.85)	0.48 (0.46–0.52)	–	–
la16	0.94 (0.93–0.95)	0.86 (0.84–0.87)	0.65 (0.63–0.68)	0.34 (0.30–0.37)	0.92 (0.92–0.93)	–
bl14	0.95 (0.94–0.96)	0.95 (0.95–0.96)	0.78 (0.77–0.81)	0.44 (0.41–0.48)	0.98 (0.98–0.98)	0.95 (0.95–0.96)

VLF	haar	d4	d8	d16	la8	la16
d4	0.17 (0.11–0.23)	–	–	–	–	–
d8	0.26 (0.13–0.33)	0.66 (0.57–0.88)	–	–	–	–
d16	0.23 (0.05–0.31)	0.47 (0.41–0.52)	0.75 (0.71–0.80)	–	–	–
la8	0.39 (0.19–0.52)	0.42 (0.25–0.97)	0.53 (0.41–0.82)	0.52 (0.46–0.58)	–	–
la16	0.40 (0.21–0.53)	0.27 (0.10–0.85)	0.33 (0.21–0.64)	0.35 (0.28–0.41)	0.81 (0.77–0.92)	–
bl14	0.29 (0.19–0.37)	0.29 (0.07–0.95)	0.19 (0.02–0.41)	0.12 (0.02–0.41)	0.35 (0.16–0.98)	0.53 (0.40–0.95)

LF	haar	d4	d8	d16	la8	la16
d4	0.56 (0.48–0.59)	–	–	–	–	–
d8	0.63 (0.56–0.68)	0.51 (0.43–0.57)	–	–	–	–
d16	0.43 (0.35–0.48)	0.49 (0.42–0.55)	0.78 (0.75–0.81)	–	–	–
la8	0.45 (0.37–0.50)	0.87 (0.85–0.90)	0.53 (0.47–0.58)	0.57 (0.52–0.62)	–	–
la16	0.40 (0.31–0.48)	0.63 (0.32–0.75)	0.58 (0.32–0.68)	0.60 (0.30–0.75)	0.76 (0.32–0.88)	–
bl14	0.48 (0.40–0.54)	0.60 (0.53–0.65)	0.77 (0.70–0.82)	0.76 (0.69–0.82)	0.74 (0.70–0.79)	0.79 (0.32–0.91)

HF	haar	d4	d8	d16	la8	la16
d4	0.59 (0.49–0.67)	–	–	–	–	–
d8	0.58 (0.51–0.68)	0.67 (0.56–0.81)	–	–	–	–
d16	0.48 (0.37–0.59)	0.60 (0.51–0.72)	0.59 (0.51–0.69)	–	–	–
la8	0.52 (0.44–0.62)	0.63 (0.59–0.69)	0.56 (0.50–0.60)	0.62 (0.56–0.70)	–	–
la16	0.47 (0.38–0.59)	0.56 (0.50–0.62)	0.52 (0.45–0.59)	0.63 (0.55–0.68)	0.87 (0.85–0.90)	–
bl14	0.45 (0.34–0.58)	0.48 (0.38–0.61)	0.36 (0.26–0.53)	0.52 (0.45–0.64)	0.50 (0.43–0.58)	0.54 (0.48–0.60)

TP	haar	d4	d8	d16	la8	la16
d4	0.87 (0.86–0.89)	–	–	–	–	–
d8	0.80 (0.78–0.82)	0.85 (0.83–0.87)	–	–	–	–
d16	0.59 (0.53–0.63)	0.66 (0.61–0.69)	0.84 (0.82–0.87)	–	–	–
la8	0.84 (0.82–0.86)	0.94 (0.92–0.96)	0.81 (0.77–0.83)	0.63 (0.56–0.68)	–	–
la16	0.84 (0.81–0.86)	0.85 (0.82–0.87)	0.74 (0.70–0.79)	0.55 (0.48–0.61)	0.94 (0.94–0.95)	–
bl14	0.86 (0.84–0.88)	0.87 (0.81–0.90)	0.82 (0.76–0.87)	0.62 (0.57–0.69)	0.91 (0.86–0.93)	0.94 (0.89–0.96)

LFHF	haar	d4	d8	d16	la8	la16
d4	0.26 (0.17–0.41)	–	–	–	–	–
d8	0.42 (0.32–0.55)	0.44 (0.32–0.57)	–	–	–	–
d16	0.28 (0.22–0.39)	0.43 (0.34–0.52)	0.62 (0.58–0.68)	–	–	–
la8	0.25 (0.17–0.38)	0.70 (0.67–0.74)	0.41 (0.34–0.49)	0.50 (0.45–0.57)	–	–
la16	0.21 (0.12–0.35)	0.55 (0.51–0.61)	0.49 (0.43–0.52)	0.58 (0.51–0.63)	0.83 (0.79–0.87)	–
bl14	0.22 (0.11–0.37)	0.43 (0.38–0.50)	0.48 (0.42–0.52)	0.57 (0.50–0.62)	0.56 (0.49–0.62)	0.69 (0.67–0.72)