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Original Article

Times Varying Spectral Coherence Investigation of Cardiovascular Signals Based on Energy Concentration in Healthy Young and Elderly Subjects by the Adaptive Continuous Morlet Wavelet Transform

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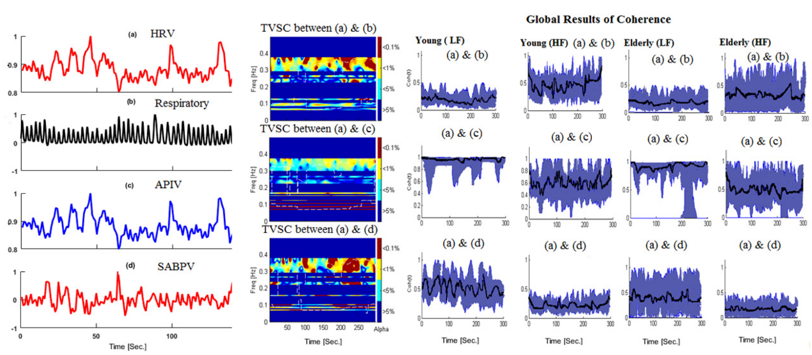
Highlights

- Adaptive continuous Morlet wavelet transform.
- Algorithm to calculate maximum energy concentration.
- Synthetic signal demonstrated as characteristics of cardiovascular signals.
- Effect of maximum energy concentration on time-varying spectrum coherence.
- To investigate the time-varying spectrum coherence among cardiovascular signals.

Graphical abstract



Abstract

Objective: The aims of this study, to investigate the interaction among heart rate variability (HRV), respiratory, systolic arterial blood pressure variability (SABPV) and systolic arterial pressure interval variability (APIV) signals for understanding of cardiovascular control.
Methods: In this study, three methods referred as adaptive continuous Morlet wavelet transform (ADCMWT), adaptive Stockwell transform (ADST) and adaptive modified Stockwell transform (ADMST) was used to assess the accuracy (AC) of time-varying spectral coherence (TVSC). The adaptation of these estimators was based on maximum energy concentration measurement. The capability to correct temporal localization of time–frequency regions was validated on synthetic time series data modeled as dynamic characteristics of cardiovascular signals.
Results: The results on synthetic simulated data show that the ADCMWT method allows for the temporal localization of the time–frequency regions with higher accuracy (AC $>$ 96.074% for SNR $\geq$ 0 dB), compared to ADST (AC $>$ 90.71% for SNR $\geq$ 0 dB) and ADMST (AC $>$ 84.45% for SNR $\geq$ 5 dB). Further, the ADCMWT was applied to real cardiovascular data obtained from Fantasia standard data base and grouped as, 8 young subjects (4M + 4F, age range 23–32) and 8 elderly subjects (4M + 4F, age range 70–82) for estimating the TVSC in low frequency (LF) band (0.04 Hz–0.15 Hz) and high frequency (HF) band (0.15 Hz–0.4 Hz) of HRV spectrum. The global result depict that the median value of interquartile range of coherency between HRV-SABPV and HRV-APIV signals in LF and HF band were significantly ($p = 0.00001$) lower

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in elderly group subjects compared to young group subjects. The coupling between HRV-Respiratory signals in LF band was not significantly affected with the aging of healthy subjects. However, this coupling in HF band significantly reduced in elderly compare to young group subjects ($p = 0.0125$).
Conclusion: The comparative study shows that the time-varying spectra and accurate localization of coupling between two physiological signals can be affected by energy concentration. The ADCMWT at $w_0 = 6$, could be an alternative, possibly more suitable and highly accurate method for assessment and detection of time varying spectral and coherence components of cardiovascular time series.

Keywords: Adaptive continuous Morlet wavelet transforms; Energy concentration measurement; Instantaneous frequency; Smoothing operator

1. Introduction

Heart rate variability (HRV) analysis is a noninvasive method in monitoring the activity of autonomic nervous system (ANS) [1]. The ANS consists of sympathetic and parasympathetic components. The distinct rhythmic activities from sympathetic and parasympathetic components modulate the heart rate, and thus the RR intervals (HRV) in the electrocardiogram (ECG) at different frequencies. Sympathetic activity is associated with the low-frequency (LF) range (0.04 Hz–0.15 Hz) while parasympathetic activity is associated with the higher-frequency (HF) range (0.15–0.4 Hz) of the heart rate [2]. The mid-frequency (MF), centered near 0.1 Hz, is associated with both sympathetic and parasympathetic. The HF corresponds to the respiratory and the LF is mediated by a variety of different influences [3].

Coherence provides the degree of similarity between the spectral components of two signals, locates the common frequency present in both signals at the same time and the average signals power is higher at this common frequency [4,5]. Estimation of the coherence spectrum of sampled time series of two signals is usually based on procedures employing the fast Fourier transform (FFT). This analysis approach is computationally efficient and provides an excellent frequency resolution [6]. However, it does not tell anything about localization of time of common frequency components of two signals. This method is insufficient when studied about real life signals like cardiovascular signals. The cardiovascular signals synchronized in LF and HF band and to vary over time, hence usually assessed using time varying spectral coherence (TVSC). The TVSC has been used in many field of science, including neuroscience, detection of uterine electrical activity synchronization in labor [7], sleep apnea, time-varying estimation of correlation between cardiovascular signals and baroreflex sensitivity [8–12]. Further, application of TVSC has been mentioned detailed in discussion section. Typically, Parametric and nonparametric estimators has been introduced to estimate the TVSC of the signals. The most of parametric methods are frameworked on the base of Yule–Walker autoregressive modeling [13,14]. But these methods are subjected to error due to model misspecification. For highly non-stationary signals these methods have performed less accurately compared to nonparametric methods [15]. The estimation of nonparametric methods are based on power spectrum through some average or smoothing operations performed directly on the periodogram of signals, and not require assumption on the order of model. Including of these methods, in analysis of cardiovascular signals, the short time Fourier transform (STFT), Smoothed Pseudo-Wigner–Ville distribution (SPWVD), Multitaper Spectrogram (MTSP) and standard Stockwell transform (SST) have been recently proposed to detect the transient phenomenon of cardiovascular signals [16–19]. Out of these, two methods of time–frequency coherence (TFC) as SPWVD and MTSP have been proposed in 2012 to estimate the coupling between cardiovascular signals and also included the automatically localization of time–frequency regions in which TVSC is statistically significant [20]. It has been observed that, the Wavelet transform is specifically efficient in the analysis of transient and time variant signals by enabling simultaneously shifting and scaling of mother wavelet function [21]. The use of both discrete and continuous wavelet transform in cardio vascular signals and to detect the dynamic behavior of respiratory sinus arrhythmia (RSA) in cardiovascular variability by using Wavelet transform coherence (WTC) method has been reported [22,23].

The SST is a linear time–frequency analysis, which can be viewed as impermanent of STFT and continuous wavelet transform. Because of this hybrid strategy, it enables the use of frequency variables and multiresolution strategy of continuous wavelets analysis [24,6]. Since the Gaussian window function of SST depends on frequency, therefore the SST produces excellent frequency resolution at lower frequencies and sharper time localization at higher frequencies [25]. The characteristic of window function changes with frequency and not with time, thus the SST method is inappropriate in determining signals, whose spectral components have fast and slow dependency on time [26–28].

In ideal case, the time–frequency mapping provides information about the frequency occurring at a given instant of time without cross-information about the adjacent instant [29,16]. The most important aim of a time–frequency analysis method is to be close to ideal case and having excellent resolution [30]. The energy concentration measurement related with resolution in the time–frequency analysis is one of its most essential and severely studied parts in time–frequency analysis of non-stationary signals [31].

This paper introduces the use of three adaptive methods as ADCMWT, ADST and ADMST to study the time varying spectra (TVS) of cardiovascular control system and detect the interaction between short term cardiovascular signals. Adaptation of these methods is based on energy concentration measurement.