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**Wavelet-based correlations of impedance cardiography signals and heart rate variability**

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**Abstract.** The wavelet-based correlation analysis is employed to study impedance cardiography signals (variation in the impedance of the thorax \(z(t)\) and time derivative of the thoracic impedance \(-dz/dt\)) and heart rate variability (HRV). A method of computer thoracic tetrapolar polyrheocardiography is used for hemodynamic registrations. The modulus of wavelet-correlation function shows the level of correlation, and the phase indicates the mean phase shift of oscillations at the given scale (frequency). Significant correlations essentially exceeding the values obtained for noise signals are defined within two spectral ranges, which correspond to respiratory activity (0.14-0.5 Hz), endothelial related metabolic activity and neuroendocrine rhythms (0.0095-0.02 Hz). Probably, the phase shift of oscillations in all frequency ranges is related to the peculiarities of parasympathetic and neuro-humoral regulation of a cardiovascular system.

**1. Introduction**

It is well known that the spectral analysis of heart rate variability (HRV) is a simple method for non-invasive quantitative estimation of the autonomic input in the heart. It can also be used as a valuable prognostic characteristic [1]. Just like HRV, impedance cardiography signals (variation in the impedance of the thorax \(z(t)\) and time derivative of the thoracic impedance \(-dz/dt\)) have a complex spectral structure, including nonstationary components. Only two of these, viz. cardiac and respiratory, are studied properly. The low frequency (<0.15 Hz) components of impedance cardiography (ICG) signals have not been adequately explored, even though they may contain important physiological information.

The frequency-domain analysis enables decomposition of the HRV signal into high – (HF, 0.15 – 0.4 Hz), low – (LF, 0.04 – 0.15 Hz) and very low – (VLF, < 0.04 Hz) frequency oscillations. The HF oscillations are linked with the respiratory activity and are generally considered as a marker of vagal modulation. The LF range refers to the intrinsic myogenic activity and is modulated by both the sympathetic and parasympathetic nervous systems. The neurogenic (sympathetic) regulation mechanisms manifest themselves within the range 0.02 – 0.06 Hz. The analysis of long-term recordings can yield additional information concerning the ultra low-frequency (ULF < 0.003 Hz) components related to endothelial metabolic activity and neuroendocrine rhythms [2].

Recently, a wavelet-transform-based correlation analysis has been developed. This technique is a method to study not only the spectral composition of unsteady signals, but the degree of correlation of two signals, separately at each timescale, as well [3,4]. The purpose of the present paper is to explore the low frequency components of impedance cardiography oscillations and to perform the wavelet-transform-based correlation analysis of ICG and the HRV signals within a wide frequency range 0.5 – 0.0095 Hz. The correlation function of the measured signals was compared with the correlation of two noisy signals simulated using a Gaussian distribution.
2. Measuring technique and data analysis algorithm

2.1. Measurements
Twenty healthy men at the age of 19 to 22 participated in the study. A method of computer thoracic tetrapolar polyrheocardiography was used for hemodynamic registration [5]. A 20-min ICG and HRV time series were recorded simultaneously and then were analyzed by wavelet transformation. The values of the HRV and impedance cardiography parameters were compared for the supine body positions.

2.2. Wavelet analysis
The continuous wavelet transform decomposes the function of one variable (time) \( f(t) \) in the 2D space (time and scale space) as

\[
W(a,b) = \frac{1}{a} \int_{-\infty}^{\infty} f(t) \psi\left(\frac{t-b}{a}\right) dt,
\]

where \( t \) is the time, \( b \) is the time shift (wavelet position), \( a \) is the oscillation scale which has the dimension of time and corresponds to the inverse of the frequency \( \nu = 1/a \), and \( \psi(x) \) is the oscillating function termed the analyzing wavelet. We use here the function, known as the Morlet wavelet,

\[
\psi(x) = \exp(2\pi ix)\exp(-x^2/2)
\]

which is represented as a product of two functions \( \phi(x) = \exp(2\pi ix) \) and \( \xi(x) = \exp(-x^2/2) \).

The wavelet image \( W(a,b) \) of the analyzed function \( f(t) \) will be complex because we use the complex analyzing wavelet. Since the signal has finite length, the gaps on its boundaries produce artifacts. These boundary effects are caused by the violation of the admissibility condition

\[
\int_{-\infty}^{\infty} \psi(x) dx = 0
\]

when part of the wavelet goes outside of the interval under study, or when it overlaps the gap in the signal.

In order to remove artifacts caused by boundary effects, we propose the use of the gapped wavelet technique [5]. When the wavelet is disturbed by a boundary or a gap, the admissibility condition is restored by including a constant shift, \( A \), in the oscillatory part of the wavelet as

\[
\int_{-\infty}^{\infty} \left(\phi(x) + A\right)\xi(x) dx = 0.
\]

The parameter \( A \) can be determined for each scale, \( a \), and position, \( b \), with

\[
A(a,b) = \int_{-\infty}^{\infty} \psi\left(\frac{x-b}{a}\right) dx \left(\int_{-\infty}^{\infty} \xi\left(\frac{x-b}{a}\right)\right)^{-1}.
\]

The mathematical properties of the gapped wavelet technique were studied in detail in work [6]. The gapped wavelets not only suppress the noise caused by gaps and boundaries, but also improve the accuracy of frequency determinations for short or strongly gapped signals.

2.3 Wavelet cross-correlation
Let us consider two functions \( f_1(t) \) and \( f_2(t) \). The cross-correlation function of their wavelet-transforms is defined as a normalized scalar production
\[
C(a) = \int_{-\infty}^{\infty} W_1(a,b) W_2^*(a,b) db \left( \int_{-\infty}^{\infty} W_1^2(a,b) db \int_{-\infty}^{\infty} W_2^2(a,b) db \right)^{-\frac{1}{2}},
\]

where \( W_1(a,b) \) and \( W_2(a,b) \) are the corresponding wavelet transforms and \( * \) stands for conjugation.

The cross-correlation function \( C(a) \) is complex; its modulus shows the level of correlation of oscillations at the given scale (frequency) and takes on a value in the segment \([0:1] \), and the phase of \( C(a) \) indicates the mean phase shift of oscillations of the given scale. The wavelet cross-correlation (6) was firstly introduced in [3] for the analysis of correlations of different characteristics of solar activity.

3. Results and discussion

The typical integral wavelet spectra of thoracic impedance oscillations and wavelet-correlations \( z(t) \) and HRV signals obtained with the use of gapped wavelets are given in figure 1.

![Typical integral wavelet spectra of thoracic impedance oscillations and wavelet-correlations](image)

\[\text{Figure 1. Typical integral wavelet spectra of thoracic impedance oscillations (a) and wavelet-correlations (b) obtained with the use of gapped wavelets.}\]

For wavelet spectra, five characteristic frequency intervals were defined: I (0.0095-0.02 Hz), II (0.02-0.05 Hz), III (0.05-0.14 Hz), IV (0.14-0.5 Hz), V (0.5-2 Hz). The modulus of wavelet-correlation function shows the level of correlation and the phase indicates the mean phase shift of oscillations at the given scale (frequency). The upper bound in the HRV spectrum is about 1 Hz, and therefore, the wavelet correlations are defined within the range 0.5 – 0.0095 Hz. For comparison, the mean values of correlation were calculated for 15 pairs of noise signals generated according to the Gauss distribution. To verify the hypothesis concerning the difference between the mean values, the non-parametric U-criterion by Mann/Whitney was applied. The statistically valid difference (\( p<0.01 \)) between the values of correlation of the measured signal and those of the noise signals was found for I and IV frequency intervals.

Rhythmic changes in the heart beat within the range 0.14-0.5 Hz are known as RSA (respiratory sinus arrhythmia) show the high values of correlation with ICG signals. It is seen that within this range for ICG signals, the wavelet-spectra have the highly pronounced maximum, which is also caused by the influence of respiratory waves. Of particular interest is a high correlation of signals in the range 0.0095-0.02 Hz. This frequency range has not been extensively studied, and it is supposed to be responsible for rhythmic metabolic activity, in particular, the activity of the endothelium. The mean
phase shift over the whole measurement interval of the examined oscillations with a high correlation value ranges from -2.7 to 2.4 radians. The supplementary wavelet analysis methods demonstrate that during measurements the dynamics of the phase shift variation is changed. We can observe different variants of these changes, which may lead to the phase coincidence of the signals and to the motions out of phase. To gain insight into the reason of these differences, it is necessary to conduct additional studies including examination of different functional tests.

4. Conclusions
We have investigated the wavelet-spectra of ICG signals and determined the reliable high values of correlation of these signals with the HRV signals within the frequency range corresponding to the respiratory wave and metabolic activity. Probably, the phase shift of oscillations within these frequency ranges is related to the peculiarities of parasympathetic and neuro-humoral regulation of a cardiovascular system. The proposed approach can be used in clinical practice for early diagnostics of cardiovascular system remodelling in the course of different pathologies. The early detection system for cardiac insufficiency can be offered to practitioners.

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