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Beat-to-beat cardiovascular hemodynamic parameters based on wavelet spectrogram of impedance data

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ABSTRACT

Impedance cardiography (ICG) is an attractive non-invasive tool for determining cardiac output, systemic vascular resistance and stroke volume (SV). New methods of improving the signal to noise ratio and data processing can infuse new life into this technique. In the present paper, wavelet transform is used to find solutions to two interrelated problems: (1) filtering of tetrapolar thoracic rheography signals (ICG, electrocardiogram and phonocardiogram (PCG)) to suppress random noise and respiratory variation; (2) quantitative description of the ICG and PCG parameters based on the analysis of two-dimensional time-frequency distributions of wavelet coefficients. The wavelet images provide an illustrative representation of the results obtained and allow us to define the ejection time and to control beat-to-beat changes in cardiac parameters in the systolic and diastolic phases of the cardiac cycle. The advantage of the wavelet-based approach is demonstrated by an example of determining the SV variation during the respiratory cycle. Wavelet-based processing of impedance cardiography signals reduces the influence of artifacts and the interference of breathing modulation, and displays the morphological features of cardiac cycles.

1. Introduction

In cardiovascular therapy, impedance cardiography (ICG) has long been recognised as an effective non-invasive method of determining cardiac output and systemic vascular resistance. It enables researchers to obtain one of the key hemodynamic parameters, the stroke volume (SV). The principle underlying the rheography method, according to which changes in the electrical resistance of a particular domain of the body to high-frequency alternating current are proportional to variations in blood volume in this domain, has been known for over 50 years. H. Mann published the results of his early impedancemetry studies of the human body in 1937. Kedrov first proposed a method to determine SV using bipolar body rheography in 1948 [1]; Nyboer et al. independently did so in 1950 [2]. According to Nyboer's study, the area under the rheogram curve can be related to the amount of blood ejected into the systole, i.e., the SV.

The tetrapolar thoracic rheography method, developed for NASA by a team of researchers under the guidance of Kubicek, was introduced in medical practice in the 1970s. Following this method four electrodes (two current-carrying and two potential probe electrodes) are placed on the neck and chest. This research led to the development of the Minnesota Impedance Cardiograph and a new formula [3], which relates the SV to the maximum value of the first derivative of the impedance waveform and the Left Ventricular Ejection Time (LVET) as

$$SV = C\,\mathrm{LVET}\left(\frac{dZ}{dt}\right)_{\max}, \qquad (1)$$

where C is a parameter which depends on blood resistivity, distance between receiving electrodes and basic impedance of the body segment limited by receiving electrodes.

In a rather short period of time, the tetrapolar thoracic ICG was widely applied in practical medicine and highly rated by cardiologists in the 1970s and 1980s. However, during this time researchers (and especially practicing physicians) lost interest in this technique for a number of objective reasons, including the imperfection of measurement devices used for impedancemetry and a lack of digital techniques for processing ICG signals, which complicated the interpretation of the obtained results. Nevertheless, impedance cardiography techniques, in particular the tetrapolar thoracic ICG method, were still rather attractive to specialists due to their simplicity, low cost and probability of obtaining sufficiently

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accurate and reproducible express-results [4–8]. The application of advanced equipment and new methods of data processing can infuse new life into this technique.

Under ideal condition, the recorded ICG signals should reflect only physiological processes and allow one to determine the parameters of the permanent and variable component of the impedance. In practice, bioimpedance measurements are very sensitive to external electromagnetic effects and different risk factors (loose electrodes, patient movement, etc.). Such disturbances (artifacts) introduce large errors into hemodynamic parameters, and therefore real physiological processes can be lost among these artifacts.

Recently various denoising techniques were applied for suppressing the respiratory and motion artifacts in ICG, e.g., discrete wavelets, LMS-based adaptive filtering technique and EEMD denoising [9–11]. Denoising of signals with real respiratory and motion artifacts indicated effective suppression of artifacts without any significant signal distortion. Note, that the respiratory wave is mainly considered as an artifact, which should be excluded for valid estimation of SV. However, the SV modulation during different respiratory phases can provide important information about the function of the heart [12]. Wavelet spectrograms allow us not only to separate the respiratory and pulse waves, but also to analyse the variation of pulse wave parameters with the phase and depth of breathing. This is the main difference between the approach employed in the present study and the existing techniques.

In some cases, random errors in estimation of the sample mean can be reduced by increasing the size of the sample, but the contribution of the noise and artifacts persist in statistical characteristics such as variance or correlation. However, the variability of the hemodynamic parameters (e.g., the respiratory variation in SV) opens considerable scope for diagnosis of pathologies. Studying the variability, one should distinguish between the regular variability, which actually affects each cycle (due to the respiration or some functional tests), and the variability, which occurs during extraordinary and rare cycles that differ significantly from most cardiac cycles. The latter changes can be used to diagnose heart rhythm disturbances (for example, ventricular extrasystole) and chronic cardiac insufficiency [13]. Therefore, we aim to develop robust computational techniques for calculating a hemodynamic parameter for each tested cardiac cycle of ICG signals.

Among the mathematical techniques developed last decades for analysis of nonstationary multiscale processes, wavelets are a promising tool, particularly for analysis of cardio-related signals [14–18]. Unlike the Fourier transform, in which the basis functions cover the entire signal range, the wavelet analysis deals with the local time-scale features of the signal. We have carried out preliminary signal processing in order to find the self similar cardiac cycles. Then the wavelet transform of the signal has been used to solve two problems. The first one is a standard wavelet filtration of the tetrapolar thoracic rheography signals (impedance cardiogram, electrocardiogram and phonocardiogram) to suppress random noise and respiratory variation. The second problem concerns the determination of quantitative parameters of impedance cardiograms and is solved by analysing the two-dimensional time-frequency distributions of wavelet coefficients. Wavelet images provide an illustrative representation of the obtained results and allow us to control beat-to-beat changes of cardiac parameters in the systolic and diastolic phase of the cardiac cycle.

2. Wavelets

The signals that characterise cardiovascular activity (electrocadiograms, phonograms, impedance cardiograms, etc.) have an implicit quasi-periodic character. Note that analysis of the state of the cardiovascular system involves evaluating both the frequency variability of the main cardiac cycle and the structure variability of the signal inside a single cycle. It is also interesting that the characteristics obtained for patients at rest and those obtained during different functional tests are equally important. Clearly, investigations in this field require an appropriate mathematical apparatus that will allow the study of non-stationary quasi-periodic signals (especially when changes in the character of signals occur at times that are comparable with the fluctuation period). The wavelet analysis (WA), which has received wide recognition in the past 20 years (see, e.g., [19,14,20]), proves to be a very effective tool for considering the local aspects of a signal.

The wavelet transform is a kind of local Fourier transform, which allows us to isolate a given structure in the physical space and in the Fourier space. The wavelet transform of the function $F(t)$ can be defined as

$$w_F(a,t) = \frac{1}{|a|}\int_{-\infty}^{\infty} F(\tau)\psi^*\left(\frac{\tau - t}{a}\right)d\tau, \tag{2}$$

where $\psi(t)$ is the analysing wavelet, a defines the scale and t defines the position of the wavelet in time. The coefficient w_F specifies the contribution to the function F of the corresponding structure of scale a at time t. Any wavelet must have a zero mean value (this is the admissibility condition) and be localised in both physical and Fourier spaces. The choice of the analysing wavelet is very important and depends on the aim of the analysis. We use two popular analysing wavelets, shown in Fig. 1: the so-called Mexican hat wavelet $\psi(t) = (1 - t^2)\exp(-t^2/2)$, which provides good time resolution of separated peaks, and the Morlet wavelet $\psi(t) = \exp(2\pi i t - t^2/2)$, which ensures better spectral resolution. In our study the Morlet wavelet was used for analysis of phonograms, in which the carrier frequency is rather high comparing with the cardiac rhythm. Analysing the impedance cardiogram we used the Mexican hat which allowed to treat an isolated cycle.

The function $F(t)$ can be reconstructed from its wavelet coefficients $w_F(a,t)$ using the inverse transform (see, e.g., [21]), which implies in principle integration over infinite range of scales a. In fact, the inverse transform is done over a specified range of scales $a_{min} < a < a_{max}$ performing a spectral filtration of the signal.

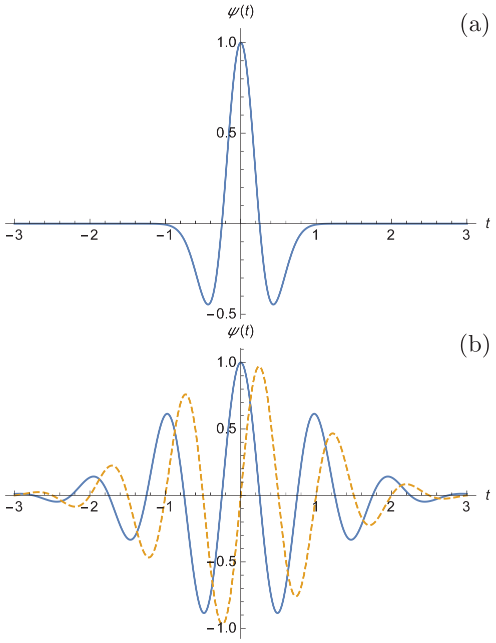

Fig. 1. Analysing wavelets used in this paper: (a) the Mexican hat; (b) the Morlet wavelet (solid line – real part, dashed line – imaginary part).