Assessment of Systolic Heart Function byWavelet Analysis of the Impedance Cardiogram

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Abstract—

Impedance cardiography (ICG) can be used to obtain one of the key hemodynamic parameters - stroke volume (SV). The SV is proportional to the left ventricular ejection time (LVET) and the maximum value of the first derivative of the recorded impedance (E wave) during the given cycle. Traditional ICG technique does not enable unambiguous detection of the LVET time between onset of the aortic valve opening and closing process. Objective of this work is investigation the possibilities of wavelet analysis (WA) approach to determine the parameters of the SV, in particular LVET. We can define LVET as the scale corresponding to the E wave maximum on 2D wavelet representation of the ICG data. Wavelet estimation of the LVET is well correlated (0.8) with the time interval between first and second heart sound, defined with usage of phonocardiogram. The proposed approach demonstrates the ability of ICG-WA technique to adequate assessment of SV parameters, including LVET and can be used in clinical practice.

Keywords— **impedance cardiography, wavelet analysis, hemodynamic parameters**

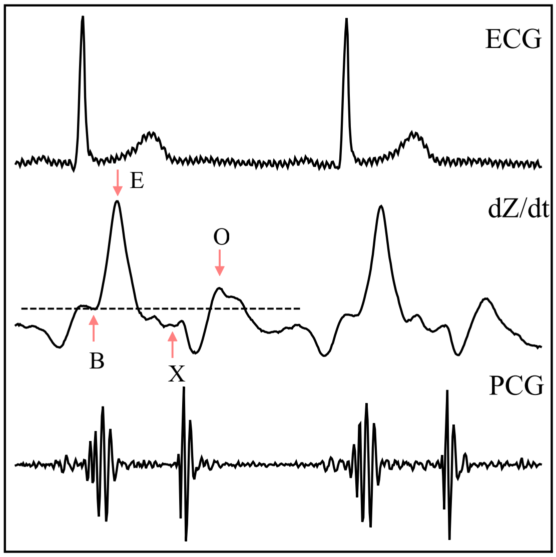

Fig. 1: Characteristic electrocardiogram (ECG), dZ/dt and phonocardiogram (PCG) signals, where B is the start of ejection of blood by the left ventricle, E is the major upward deflection occurring during systole, O is related to the diastolic phase, X the closure of the aortic valve.

I. Introduction

Impedance cardiography (ICG) is a simple, inexpensive, noninvasive technique for acquiring hemodynamic parameters. The impedance rheography method based on changes in the electrical resistance of a particular area of the body to high-frequency alternating current. These changes are proportional to variations in blood volume in the area at any given point in time. ICG can be used to obtain one of the key hemodynamic parameters: stroke volume (SV). In addition to the continuous hemodynamic monitoring of patients in intensive care, recognition of the different ICG patterns allows the rapid detection of cardiac dysfunction and the need for further cardiac evaluation. Compared with the standard ECG, the different patterns of ICG waveform are relatively easy to recognize and require considerably less time and skill to interpret than Doppler echocardiography [1].

There are several characteristic points which are usually considered to describe the ICG waveform [2]. These points are used to distinguish the physiological particularities of cardiac cycles. Figure 1 shows so called B, E ($(dZ/dt)_{\max}$) X, O points.

The points B and X correspond to the first and second heart sounds. They are synchronous with the maximal deflection at the apex and the closure of the aortic valve, respectively. In some cases the identification of the B point location is difficult because the characteristic upstroke that provides a marker of this point is not always pronounced [3]. The E point is defined by the peak of dZ/dt curve which reflects the maximal derivative in the impedance. Ultrasound method measurements confirm that the E point may be associated with the maximal velocity of the heart ejection [4]. For ICG the first maximum (i.e. E-wave) is related to the systolic phase of the cardiac cycle and the second maximum with a smaller amplitude (O-wave) is related to the diastolic phase. The amplitude of the E-wave is proportional to the SV, and the am-

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plitude of the O-wave correlates to a change in the volume of the left auricle during a short-term diastolic phase. In some cases the amplitude of the O-wave proves to be an important diagnostic parameter [5, 6]. Following the Kubicek formula [7], the stroke volume SV is proportional to the ejection time and the maximum value of the first derivative of the recorded impedance $Z(t)$ during the given cycle.

The left ventricular ejection time (LVET) is defined as the time interval of left ventricular ejection, which occurs between the opening of the aortic valve and its subsequent closure. However, as stated in some studies [8] there is evidence that ICG does not enable the detection of the onset of the aortic valve opening and closing process. Most of the ICG algorithms for LVET computation exhibit very low correlation coefficients and very high systematic estimation errors and dispersions [9]. Objective of this work is an demonstration of the wavelet transform for processing and interpretation of the impedance cardiogram waveforms and investigation the possibilities of this approach to determine the parameters of the SV, in particular LVET. For consistency we reproduce here some results of our previous study where the wavelet transform is suggested for an estimation of blood ejected velocity into the systole [10].

II. MEASUREMENTS AND ITS PROCESSING ALGORITHM

We used the method of computer thoracic tetrapolar polyrheocardiography for simultaneous registration ECG, ICG and phonocardiogram (PCG) [11]. Participants group consists of eight healthy men of 20 to 25 years old and four patients, men of 50 to 55 years old, with diagnose of the essential hypertension. During polyrheocardiogram registration the functional test (isometric load) were performed for all participants. Patient's legs were held raised at an angle of 30-40 degrees to the horizontal in order to create a static force. Also all participants passed the thoracic tetrapolar polyrheocardiography without the functional test for comparison analysis.

Advanced signal processing techniques provides more elaborated approaches to the analysis and interpretation. In our study, we continue to promote the use of a continuous wavelet transform. We believe that its higher computational complexity are comparable to the Fourier transformation but the continuous wavelet transform makes the convenient assessment of amplitude, scale and phase of signal oscillations. Wavelet transform allows us to isolate a given structure in time and frequency space. Let us define the wavelet transform of the analyzing function $F(t)$ as

$$w_F(a,b) = \frac{1}{|a|}\int_{-\infty}^{\infty} F(t')\psi^*\left(\frac{t'-b}{a}\right)dt', \qquad (1)$$

where $\psi(t)$ is the analyzing wavelet, a defines the scale (inverse to a frequency) and b defines the position in time of the wavelet. Then the coefficient w_F gives the contribution of corresponding structure into the function F.

The function F can be reconstructed using the inverse transform (see, e.g. [12])

$$F(t) = \frac{1}{C_\psi}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \psi\left(\frac{t'-t}{a}\right) w_F\left(a,t'\right)\frac{da\,dt'}{a^2}. \qquad (2)$$

The reconstruction formula (2) exists under condition that

$$C_\psi = \frac{1}{2}\int_{-\infty}^{\infty}\frac{|\hat{\psi}(\omega)|^2}{|\omega|}d\omega < \infty. \qquad (3)$$

Here $\hat{\psi}(\omega) = \int \psi(t)e^{-\imath\omega t}dt$ is the Fourier transform of the analyzing wavelet $\psi(\phi)$.

Let us define the wavelet transform of analysing function $G(t)$ which is derivation of measured function $F(t)$ as following

$$w_G(a,b) = \frac{1}{|a|}\int_{-\infty}^{\infty} G(t')\psi^*\left(\frac{t'-b}{a}\right)dt'. \qquad (4)$$

Applying differentiation by part to equation (4) one can write

$$w_G(a,b) = \frac{1}{|a|}\int_{-\infty}^{\infty} F(t')\xi^*\left(\frac{t'-b}{a}\right)dt', \qquad (5)$$

where $\xi(t) = -\psi'(t)$ is the differentiating wavelet. Then the wavelet coefficients of the derivative of the analyzing function $w_G(a,b)$ is obtained the wavelet transform with wavelet family $\xi(t)$. The advantage of original wavelet differentiation algorithm [13] is a combination of filtering and differentiating procedures to process the rheocardiogram. We use as the analyzing wavelet the so-called Mexican hat $\psi(t) = (1-t^2)\exp(-t^2/2)$ for higher resolution to separate characteristic points (see Fig. 1) in time. The wavelet Morle $\psi(t) = \exp\left(-\frac{t^2}{2} + 2i\pi t\right)$ were used for better spectral resolution.

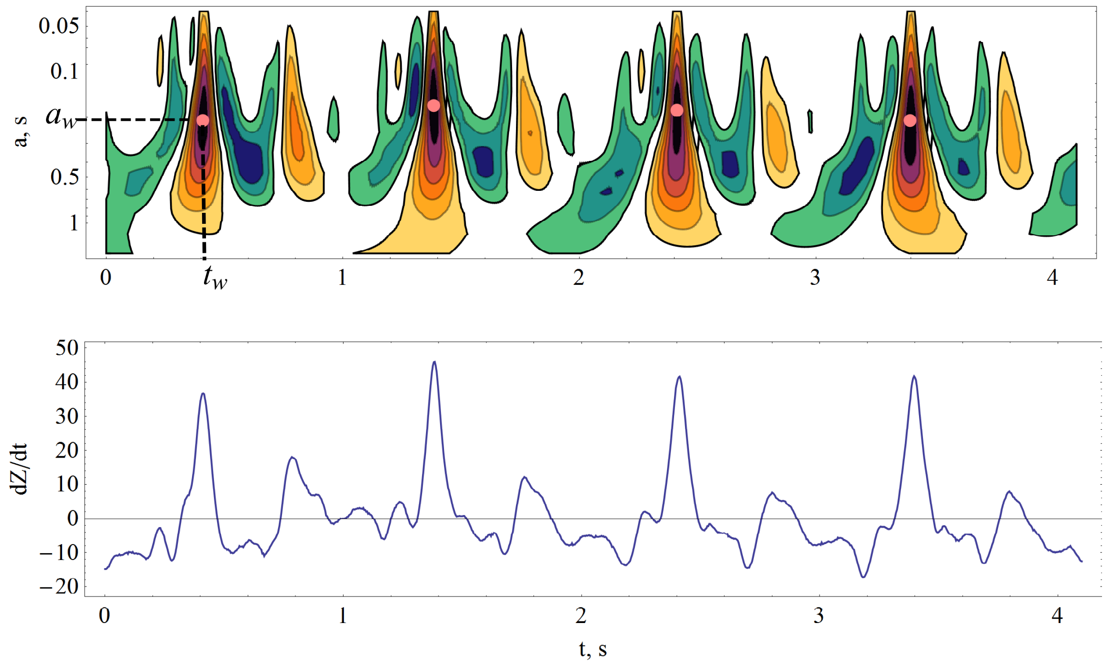

Fig. 2: 2D distribution of the wavelet coefficients (top) and analysing signal (bottom). The warm/cold colours denote positive/negatine values. White area corresponds to values close to zero. Characteristic E points are shown by pink points.

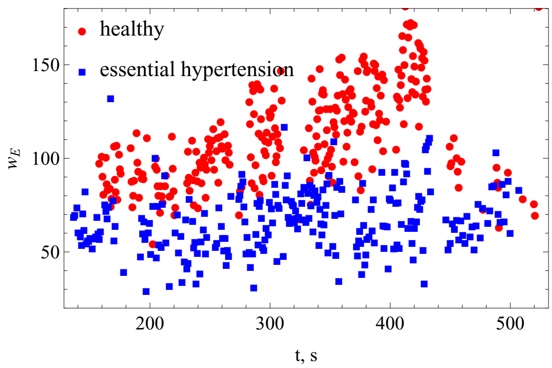

Fig. 3: Typical changes of the amplitudes E-wave waves after starting of the postural test (lifting leg at an angle of 30-40 degrees from horizontal until t=450 s) for healthy subject (red) and for the patient with hypertension (blue) (55 years old, hypertension in conjunction with coronary artery disease, with fixed dilation of the left atrium and concentric left ventricular hypertrophy).

III. RESULTS

Typical distribution of ICG wavelet coefficient (using the Mexican hat) is presented in Fig. 2. Principal difference between analysis of ordinal signal and its wavelet representation is that waves produce the local extremum in time and scale in 2D map. One can see positive defined (yellow) areas which correspond to E and O waves in each in the cardiac cycle. It is possible to define time, scale and amplitude for each extremum point. We focus on the amplitude w_E and the scale a_w corresponding to the E wave maximum which can be defined for each cardiac circle. For verification conformity w_E and stroke volume we used hemodynamic response to isometric functional test (Fig. 3). In healthy subjects results characterized by a significant linear increase in stroke volume with increasing w_E. At the end of the load, indices have decreased to normal values during the first minute of recovery period. This response to the load is explained by the action of the Frank-Starling mechanism, which allows to implement an adequate hemodynamic response to stress. Changes in cardiac output were not found during isometric stress for for the patients with the essential hypertension. This means that the compensatory mechanisms of the immediate adaptation to hemodynamic stress is absent. All participant of each group show similar behaviour w_E as in Fig. 3.

The scale a_w of each extremum point with amplitude w_E characterizes an extension of E wave in time. It can be used for estimation the LVET. Let's consider the time interval between the first and second heart sounds as reference value. We defined it using the wavelet transform (using the Morle wavelet) of the phonogram which is recorded simultaneously with the impedance cardiogram. Then we calculate time interval between B and X points on the impedance cardiogram

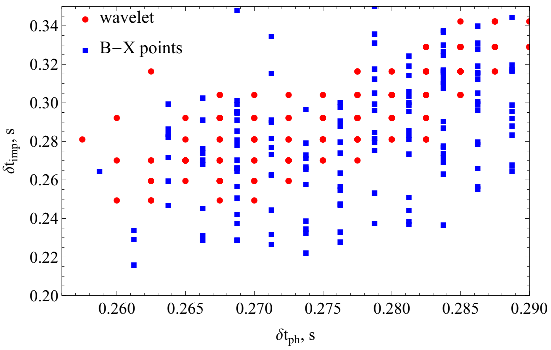

Fig. 4: Phonogram LVET vs impedance cardiogram LVET for selected healthy participant: δt_{ph} is defined as time interval between the first and second heart sounds, δt_{imp} is defined as B-X points interval (blue squares) or as the wavelet scale a_w of E-wave maximum (red points).

for each cardiac circle. The comparison of the LVET defined with usage of phonogram and impedance cardiogram for selected healthy participant is shown in Fig. 4. One can see that the wavelet estimate is well correlated with the time interval between first and second heart sound. The correlation coefficient calculated over 163 cardiac circles is 0.8. The classical estimate using B and X points agrees only with correlation coefficient equals 0.45. Similar correlations are found for the patient with hypertension. Averaged value correlation coefficients over all participants are 0.78 ± 0.07 for ICG-WA technics and 0.42 ± 0.12 for classical estimate using B and X points in ICG. We note that performing of the postural test is important to archive a significant variation of the heart rate. However the same condition can be provided by the deep breathing.

IV. Conclusions

The proposed approach demonstrates the ability of ICG-WA technics to adequate assessment of SV parameters, including LVET and can be used in clinical practice for early diagnostics of cardiovascular system remodelling in the course of different pathologies. We demonstrate an advantage of the wavelet transform not only as a common tool for filtration but also as an approach for introducing the new parameters defined by wavelet coefficients itself. Computational costs of the wavelet transform are comparable with ones for the fast fourier transform. So that required calculation are affordable using any laptops and the most of mobile gadgets, like phones and tablets.

Conflict of Interest

The authors declare that they have no conflict of interest.

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