Wavelet analysis of the impedance cardiogram waveforms

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Abstract. Impedance cardiography has been used for diagnosing atrial and ventricular dysfunctions, valve disorders, aortic stenosis, and vascular diseases. Almost all the applications of impedance cardiography require determination of some of the characteristic points of the ICG waveform. The ICG waveform has a set of characteristic points known as A, B, E \((dZ/dt)_{\text{max}}\) X, Y, O and Z. These points are related to distinct physiological events in the cardiac cycle. Objective of this work is an approbation of a new method of processing and interpretation of the impedance cardiogram waveforms using wavelet analysis. A method of computer thoracic tetrapolar polyrheocardiography is used for hemodynamic registrations. Use of original wavelet differentiation algorithm allows combining filtration and calculation of the derivatives of rheocardiogram. The proposed approach can be used in clinical practice for early diagnostics of cardiovascular system remodelling in the course of different pathologies.

1. Introduction

Impedance cardiography (ICG) is a simple and cheap method for acquiring hemodynamic parameters. Unfortunately, not all physiological influences on the ICG signal have yet been identified. It has been confirmed that the main contributions to ICG signal come from ventricles, atria, aorta, and lungs. The relations between these components have been found to be dependent nonlinearly on spatial conductivity distribution. As a result, reliable and reproducible measurements of stroke volume (SV) using ICG are impossible [1]. Nevertheless, ICG can be used to monitor relative changes of SV in all cases where the spatial distribution of conductivity and geometry of the subject, during the examination, is preserved. Recent advances in waveform morphology analysis and pattern recognition software have allowed the development of reliable baseline-independent devices that can produce signal-averaged ICGs. 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 [2].

The ICG waveform has a set of characteristic points [3] known as A, B, E \((dZ/dt)_{\text{max}}\) X, Y, O and Z, as shown in figure 1. These points are related to distinct physiological events in the cardiac cycle.
Figure 1. Characteristic $\Delta Z$, $dZ/dt$ and ECG signal, where A is the downward deflection due to the contraction of the atria, B is the start of ejection of blood by the left ventricle, E $((dZ/dt)_{\text{max}})$ the major upward deflection occurring during systole, X the closure of the aortic valve, Y the closure of the pulmonic valve, O the diastolic upward deflection, Z wave describes a decreasing following the O wave, and it is associated with a third heart sound.

The A point occurred on the impedance cardiogram during the interval between the end of the P wave and the beginning of the QRS complex on the electrocardiogram, the A point occurred simultaneously with the beginning of the fourth heart sound. This wave is associated with the atrial contraction and its amplitude is correlated with the ejection fraction of the left atrium, A-wave is not observed when atrial fibrillation occurs [4]. The B point was synchronous with the maximal deflection of the first heart sound at the apex. Sometimes identifying the location of the B point is problematic because the characteristic upstroke that serves as a marker of this point is not always apparent [5]. The E point placed on the top position of the curve reflecting the maximal speed of the change in the impedance. It is associated with the maximal velocity of the ejection measured by using ultrasound methods [6]. The X point corresponds to the closure of the aortic valve (and second heart sound) and the Y point corresponds to the closure of pulmonic valve. The O wave is associated with changing of the volume during the diastolic phase of the cycle and opening snap of the mitral valve. The early diastolic O wave increases with mitral regurgitation, volume overload and increased left atrial pressure [7]. And, finally, Z wave describes a decreasing following the O wave, and it is associated with a third heart sound.

Objective of this work is an approbation of a new method of processing and interpretation of the impedance cardiogram waveforms using wavelet analysis.

2. Measuring technique and data analysis algorithm

2.1. Measurements

Ten healthy men at the age of 19 to 22 and five patients with essential hypertension participated in the study. A method of computer thoracic tetrapolar polyrheocardiography was used for hemodynamic registration [8]. For six people (three healthy and three patients), functional test with an isometric load was carried out. Static force is created by holding a raised patient’s leg at an angle of 30 degrees to the horizontal plane. For twelve persons Doppler echocardiographic early $E_D$ and late $A_D$ diastolic waves were obtained at the mitral valve tips. Measurements were performed off-line using the average of 3 consecutive cycles.

2.2. Wavelet analysis

Wavelet transform presents a kind of “local” Fourier transform, allowing us to isolate a given structure in physical space and the Fourier space. Let us define the wavelet transform of the
analyzing function $F(t)$ as

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

where $\psi(t)$ is the analyzing wavelet, $a$ defines the scale and $b$ defines the position 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. [9])

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

The reconstruction formula (2) exists under condition that

$$C_\psi = \frac{1}{2} \int_{-\infty}^{\infty} \left| \hat{\psi}(k) \right|^2 dk < \infty. \hspace{1cm} (3)$$

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

Let us suppose that the function $F(t)$ is given by its derivative $G(t)$. Applying differentiation by part to equation (1) we have

$$w_G(a, t) = \frac{1}{|a|} \int_{-\infty}^{\infty} G(t') \psi^* \left( \frac{t' - t}{a} \right) dt' = \frac{1}{|a|} \int_{-\infty}^{\infty} F(t') \chi^* \left( \frac{t' - t}{a} \right) dt', $$  \hspace{1cm} (4)$$

where $\chi(t) = -\psi'(t)$ is another wavelet. So the wavelet transform with wavelet family $\chi(t)$ gives the wavelet coefficients of the derivative of the analyzing function $w_G(a, t)$. Use of original wavelet differentiation algorithm [10] allows to combine filtration and calculation of the derivatives of rheocardiogram. We use as the analyzing wavelet the so-called Mexican hat $\psi(t) = (1 - t^2) \exp(-t^2/2)$ for higher resolution of separated picks in time and the wavelet Morle $\psi(t) = \exp(-t^2/2 + 2i\pi t)$ for better spectral resolution.

3. Results and discussion

The basic idea of the suggest approach is to define the characteristic points in the wavelet coefficient distribution $w$ which are corresponds to ones are shown in figure 1. Typical distribution of wavelet coefficient is presented in figure 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 (red) 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. For the chosen case in Fig. 2 wave A has no well pronounce feature on the wavelet coefficient map but the local extremum can be found anyway for the fixed scale $a$.

For further analysis we take three amplitudes of wavelet coefficient $A_w$, $E_w$ and $O_w$ which correspond to A, E and O waves. For twelve subjects Doppler echocardiographic registration of the diastolic transmitral blood flow was carried out. The first phase of the Doppler echocardiograms caused by the movement of blood through the mitral valve during the phase of rapid filling (peak $E_D$). The second phase (peak $A_D$) corresponds to the left atrium systole. Wavelet coefficient $O_w$ correlated with Doppler peak $E_D$ (r=0.65), and wavelet coefficient $A_w$ did not correlate with Doppler peak $A_D$ (r=0.23).
Figure 2. Wavelet coefficient map (top) of DR (bottom). Positive/negative values correspond the red/blue area. Black means maximum absolute values and white means values close to zero. Characteristic points A, E and O are shown by green points.

Hemodynamic response to isometric functional test in healthy subjects characterized by a significant linear increase in stroke volume with increasing velocity and pressure of the left atrium filling during early diastole and increased pressure in the left atrium during atrial systole (A, E and O waves). At the end of the load, indices have decreased to normal values during the first minute of recovery period (Fig. 3a). 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. For the patients an isometric stress did not cause any changes in cardiac output or diastolic left ventricular filling, which indicates the absence of compensatory mechanisms of the immediate adaptation to hemodynamic stress (Fig. 3b).
4. Conclusions
The proposed approach can be used in clinical practice for early diagnostics of cardiovascular system remodelling in the course of different pathologies. Isometric functional test with hemodynamic ICG monitoring and its subsequent wavelet analysis can be used to correct diagnosis of heart failure in hypertensive patients. The early detection system for cardiac insufficiency can be offered to practitioners.

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