NOVEL APPROACH TO CHEST IMPEDANCE SIGNAL ANALYSIS

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Abstract: New wave of development of more informative and reliable diagnostic methods substituting classical Impedance Cardiography introduced by Sramek in the 1960's was inspired by rapid development of IT based devices in medicine. We illustrate approaches of multivariate analysis of chest impedance signals in aim to reveal parameters reflecting detail pattern of functions of cardiovascular system.

1 INTRODUCTION

The electrical resistivity of human body organs varies about 100-fold from about 1.6 Ωm in blood to about 170 Ωm in bone. Within the soft tissues the variability is about 10-fold, with about 20 Ωm in the lung and in fat (Malmivuo 1995). Physiological processes in chest result in the permanent changes in chest impedance. Activity of the heart and respiratory movements play major roles.

The amount of blood in the thorax changes as a function of the heart cycle. During systole, the right ventricle ejects an amount of blood into the lungs which equals the stroke volume. At the same time blood flows from the lungs to the left atrium. The effect of these changes in the distribution of blood in the thorax as a function of the heart cycle can be determined by measuring the impedance changes of the thorax. The amount of air in the thorax is changing as function of the respiratory cycle. It also results in the impedance changes of the thorax. Permeability of lung alveoli to the blood flow is affected by air pressure in the lungs, i.e. it is changing as a function of respiratory cycle. Taking into account all mentioned facts we can state that chest impedance changes reflect several interacting processes and quantitative evaluation of the features of it could be of great diagnostic importance.

Impedance cardiography has been introduced by Sramek in the 1960's as a simple and non-invasive measurement of cardiac output which is used till nowadays. Very simple decomposition of the chest impedance signal (ICG) or ΔZ by determining of first derivative (dZ/dt) of it extracts only the component reflecting blood volume changes (BVC) in the thorax caused by heart activity. Cardiac output is proportional to the amplitude of dZ/dt. However, measured data in some cases remain controversial. This is highly expressed in the states causing low cardiac output syndrome cardiogenic shock, severe arrhythmias as well as in healthy obese patients. Rapid development of devices of digital registering of biomedical signals and availiability of comparatively cheap computational resources for their proccessing have inspired new wave of development of methods for processing of such signals. The aim of it is to reveal more informative features of the signal and to elaborate more reliable diagnostic methods. Extraction of other parameters then ejected blood volume is reported in (Ernst 1999). Respiratory movements representing component of the chest impedance signal was reconstructed by integration of first derivative dZ/dt of the ICG registered by means of standard equipment. Acording to the biophysical models (Malmivuo 1995) chest impedance signal carries much more diagnostic information than it is used today. Our previous studies have shown that structural analysis of simultaneously recorded ICG and ECG is able to separate two major components of chest impedance signal – BVC and respiratory movements reflecting component. Quantitative estimates of the shape of cardiocycles of the extracted BVC also correlate with blood volume ejected by heart (Tamosiunas 2006). Moreover component reflecting BVC reflects a result of left

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and right ventricle outputs, so it is also a complex signal. Decomposition of which could realize a possibility to evaluate separately the efficiency of functions of both ventricles. It could have a great value for monitoring of cardiac output in acute phase of myocardial infarction. Such decomposition could be realized if additional blood flow reflecting signal could be registered somewhere apart from the chest. Then multivariate analysis methods applied for simultaneously recorded signals from the chest and e.g. limbs together with ECG leads could reveal parameters reflecting detail pattern of functions of cardiovascular system. The aim of this paper is to present several illustrations of application of advanced signal processing methods used to extract parameters representing detail status of central hemodynamics.

2 METHODS

2.1 Signal Registration

Clinical recordings of the signals for investigation we performed during 24h follow up of the patients hospitalized in the acute phase of myocardial infarction in Cardiology Clinics of Kaunas University of Medicine (Permission of Kaunas Region Ethics Committee for Biomedical Research Nr. 169/2004). Chest impedance signal together with one lead ECG was recorded by means of Heartlab™ system (Dregunas 1999) (certificate No. LS. 08.02.1957) using 12 bit resolution A/D conversion at 1000 Hz sampling rate. 250 recordings from patients in various states of severity of myocardial infarction were used in the study. Ten recordings we made from healthy volunteers in addition simultaneously recording spirogram by means of spirometer "VMax-229" (Sensomedics USA). Another 10 recordings we made also from healthy volunteers in addition simultaneously registering limb pulse wave.

2.2 Signal Processing

2.2.1 Chest Impedance Signal Decomposition

Method for the ICG signal decomposition is based on combined structural analysis of synchronically registered ECG and ICG signals. The principle of the method is illustrated on fig.1. Automatic detection of fiducial point of every cardiocycle – peak of ECG R-wave (marked with crosses on the upper trace) is made in two steps. Preliminary detection finds time points where filtered derivative of the ECG signal exceeds certain threshold. Final detection is made maximizing cross-correlation of the sliding R-wave template with current ECG signal in the region of preliminary detected point. R-wave template is constructed from first 10 cardiocycles of the recording and updated after every processed cardiocycle. Fiducial time points are always pointing to the same phase of the ICG signal component reflecting blood flow (solid line of trace A on fig.1). So respiratory movements caused component of the signal is restored by means of cubic spline interpolation between the samples of the ICG signal at these time points (dotted line of trace A on fig.1). Subtraction of this component (trace B on fig.1) from the ICG signal gives the component reflecting only blood volume changes in the chest vessels (trace C on fig.1).

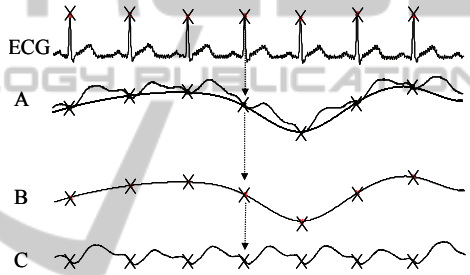

Figure 1: ICG signal decomposition: (A) cubic spline interpolation between samples of ICG signal corresponding to peaks of ECG R-wave, the fiducial points of cardiocycles; (B) - reconstructed respiratory movements reflecting component; (C) – extracted blood volume changes reflecting component of the ICG signal.

The 180 samples of ICG signal starting from fiducial point is considered as samples of one cardiocycle and is used to construct a matrix representing all cardiocycles of one recording.

2.2.2 Quantitative Evaluation of the Shape of the Chest Impedance Signal

Samples of the extracted cardiocycles give redundant but comprehensive representation of the signal shape. We used Principle Component Analysis (PCA) (Jollife 2002) to reduce the dimensionality of the representations. Samples of ICG cardiocycles formed two-dimensional array:

$$\mathbf{X} = \begin{matrix} x_{1,1} & x_{1,2} & \dots & x_{1,n} \\ x_{2,1} & x_{2,1} & \dots & x_{2,n} \\ \dots & \dots & x_{i,j} & \dots \\ x_{p,1} & x_{p,2} & \dots & x_{p,n} \end{matrix}, \quad (1)$$

where $x_{i,j}$ is the i[th] sample of the j[th] cardiocycle. The PCA transforms the original data set into a new set of vectors (the principal components) which are uncorrelated and each of them involves information represented by several interrelated variables in the original set. Every vector $\boldsymbol{x}_i$ representing ordinary ICG cardiocycle or ECG T-wave is then represented by the linear combination of the principal components φ_k multiplied by coefficients $w_{i,k}$:

$$\mathbf{x}_i = \sum_{k=1}^{p} w_{i,k}\boldsymbol{\phi}_k \ . \quad (2)$$

The calculated principal components are ordered so that the very first of them retain most of the variation present in all original variables. Thus it is possible to perform a truncated expansion of ICG cardiocycles by using only the first several principal components. We expected to get one or mostly several principal components reflecting desirable changes. We calculated the basis functions (principal components) as eigenvectors of the covariation matrix $\boldsymbol{R}_x$:

$$\mathbf{R}_x = \mathrm{E}\left[\mathbf{X}\cdot\mathbf{X}^T\right] . \quad (3)$$

Calculation of the covariation matrix was performed using MatLab[TM] function "COV" which gave mathematical expectation E after removing the mean from each column. Variation or trend of coefficients $w_{i,k}$ represents changes of the shape of evaluated ICG cardiocycles. It is expected that the dynamics of cardiac output will be reflected by the shape changes of ICG cardiocycles and represented by changes of one or several coefficients.

2.2.3 Extraction of Components of Chest Impedance Signal by Means of Independent Component Analysis

Independent component analysis is able to separate independent source signals from the mixtures which are linear combination of them. The minimal amount of the mixtures given for ICA should be equal to the number of independent source signals we want to extract. Detailed description of the method of Independent Component Analysis is given in (Hyvärinen, 2001). BVC reflecting component of chest impedance signal consists of two components which reflect: a) pulmonary (lesser) blood circulation; b) systemic (greater) circulation. It was used as first mixture. Pulse wave signal simultaneously registered from the limb, which mainly reflects systemic (greater) circulation was used as second mixture. ICA we used to extract two independent components and afterwards we used averaged cardiocycle excerpts of them as basis functions for decomposition of every single cardiocycle of BVC reflecting component of the chest impedance signal.

BVC reflecting component of signal $\boldsymbol{x}$ is represented as following:

$$\mathrm{x} = As = \begin{pmatrix} a_{11}, a_{12} \\ a_{21}, a_{22} \end{pmatrix} \times \begin{pmatrix} s_1 \\ s_2 \end{pmatrix} = \begin{pmatrix} x_1 = a_{11}s_1 + a_{12}s_2 \\ x_2 = a_{21}s_1 + a_{22}s_2 \end{pmatrix}, \quad (4)$$

Where x_1 and x_2 are two registered signals: chest impedance and pulse wave from the limb. Then estimated independent components will be:

$$s_1 = w_{11}x_1 + w_{12}x_2 , \quad (5)$$

$$s_2 = w_{21}x_1 + w_{22}x_2 , \quad (6)$$

where $W=A^{-1}$.

3 RESULTS

3.1 Adequacy of Extracted Signal Components

Result of the adequacy test of extracted respiratory movement representing signal component is shown on fig.2. The extracted signal is visually identical to the signal registered by means of spirometer during normal breathing. Limited frequency characteristics of the ICG registering device caused inadequacy of the respiratory component during forced and sustained breathing. However such cases were comparatively rear in analyzed recordings.

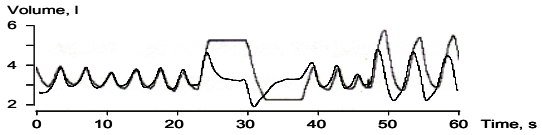

Figure 2: Illustration of the adequacy test of respiratory movement representing signal (dashed line). Control signal (solid line) is registered by means of spirograph. Forced breathing starts at 21 second of the test.

3.2 Chest Impedance Signal Shape

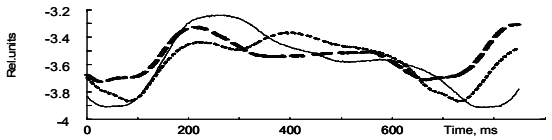

Figure 3: Variety of the shapes of the ICG component reflecting blood flow during various phases of respiratory movement. Full inhale – solid line, full exhale – dotted line and medium position – dashed line.

Variety of the shapes of the ICG component reflecting blood flow during various phases of the respiratory movement is presented in fig.3.

The quantitative estimates of shape of the decomposed ICG signal component obtained by means of PCA showed significant correlation with reference cardiac output estimates obtained by means of intermittent thermodilution. The most important fact was that correlation coefficients of the first and the second principal component showed significant correlation ($r= 0.6$ $p<0.001$ and $r= 0,75$ $p<0.001$ respectfully) in cases when standard method of the evaluation of the cardiac output by means of first derivative of ICG failed.

3.3 Independent Component Analysis of Chest Impedance Signal

Independent components calculated from the cardiocycles of synchronically recorded chest impedance signal and pulse wave from the limb are presented on fig. 4. The linear combination of them was used for representation of cardiocycles of recorded chest impedance signal.

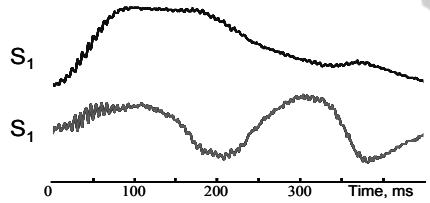

Figure 4: Independent components calculated from cardiocycles of synchronically recorded chest impedance signal and pulse wave from limb.

Coefficients of these basis functions reflect shape changes of the signal during the whole recording. We expected that changes of only one of them will be correlating with respiratory movements. If so, we can expect that especially this component will be reflecting pulmonary (lesser) circulation (changes in permeability of the lung alveoli will affect it). Results on fig.5 illustrate that.

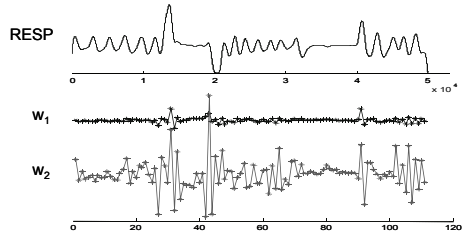

Figure 5: Coefficients of independent components (lower traces) together with reference respiratory movements representing signal.

4 DISCUSSION AND CONCLUSION

Results presented in this article illustrate only the preliminary investigations which already gave promising results. A lot of investigations is needed till estimates obtained by means of ICA or PCA will give the conventional estimates of cardiac output for clinicians. However even from these results we can expect that at least dynamics of the estimates will be shown what sometimes is of great diagnostic value. We hope that novel approach to chest impedance signal analysis started by (Ernst 1999) will be continued including applications of advanced signal processing methods. Hopefully the result will be less invasive and more reliable methods for the evaluation of detail pattern of functions of cardiovascular system.

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