

The Effect of Breathing on Stroke Volume Estimation in Patients with Implanted Cardiac Device using Parametric Electrical Impedance Tomography

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Abstract

Correlating changes in the thoracic conductivity distribution with the volume changes of the heart can help providing a non-invasive Stroke Volume (SV) quantification method.

Electrical Impedance Tomography is a non-invasive non-ionizing imaging technique in which tissues can be differentiated based on their electrical properties. The method uses measured surface potentials in order to reconstruct information of the spatial conductivity distribution within the thorax. In the current study, parametric EIT (pEIT) scheme was applied in a high-resolution 4D model of the human thorax to determine the left ventricular volume (LVV) at different cardiac cycle phases. The effect of breathing is examined by allowing both heart and respiratory motions.

The results emphasize the fact that the estimation of the LVV using pEIT is affected by breathing. About 10% change in the lungs' volume causes 8% change in the estimated SV. The contribution of both motions to the change of potential distributions can be separated. The separated potential distributions are used to estimate the LVV while neutralizing the effect of breathing. The preliminary results show a decrease in the SV estimation error; 3% compared to 12% without using the correction algorithm.

The results suggest that the LVV can be estimated using pEIT method while neutralizing the effect of respiratory motion and that the method has the potential to be used for monitoring purposes.

1. Introduction

Cardiac Stroke Volume (CSV) is a direct indicator of the cardiac pumping efficiency yet it is a primary determinant of the global oxygen transport from the heart to the body therefore measuring CSV is of a great clinical value. A wide range of methods have been developed and used for the determination of the CSV. The main requirement of such methods is to be accurate enough to identify clinically relevant changes in the CSV. Furthermore, measurements of CSV need to be taken

repetitively for monitoring purposes of hemodynamically unstable patients. At the present time, part of the available methods requires the invasive procedure of right heart catheterization. Another part of methods is non-invasive yet is either expensive or use ionizing radiation to achieve its main intended purpose. Due to the mentioned limitations, the experience of using the mentioned methods for monitoring patients with cardiovascular conditions has been limited to hospitalized patients.

In [1, 2] a new method for estimating the CSV has been introduced. The method is based on the fact that the blood pool has high electrical conductivity relative to the surrounding tissues. During the cardiac cycle, big changes in the thoracic conductivity distribution occur simultaneously. These changes might be a result of changes in the fluid content of the vascular bed or changes in the lungs' volume due to breathing [3-6]. Relating changes in thoracic conductivity to cardiac blood volume can help providing a noninvasive CSV quantification method. One method that can do so is Electrical Impedance Tomography (EIT). The method reconstructs information of the spatial conductivity distribution within the thorax making it possible to estimate the CSV more accurately than other global conductivity distribution based methods (such as Impedance Cardiography). Electrical impedance tomography is a noninvasive imaging and monitoring technique that is based on the fact that different tissues have different electrical properties. The method involves applying alternating electrical current to the body and measuring the electrical potential differences between electrodes. These potential measurements are used to reconstruct the impedivity value of each tissue within the body. The method consists of two main problems, forward problem (FP) and inverse problem (IP). For more technical information about EIT please see [1].

The objective of this paper is to develop a new method for the elimination of the contribution of breathing to the thoracic conductivity changes hence allowing more accurate CSV estimation using EIT.

2. Methods

As mentioned in the introduction, changes in the

thoracic conductivity distribution are composed from changes in the lungs' volume and changes caused by the volumetric changes in the heart. In order to be able to estimate accurately the CSV we need to eliminate the contribution of the lungs to the conductivity changes and we will be left with the changes to the conductivity distribution caused by changes in the volume of the heart only. The conductivity distribution affects the thoracic potential distribution map. This effect is well-described by the governing Poisson equation:

$$\begin{cases} \nabla(\sigma\nabla\phi) = \begin{cases} -I_s & \text{on electrodes} \\ 0 & \text{other wise} \end{cases} \\ \sigma \frac{\partial\phi}{\partial\hat{n}} \Big|_{\partial\Omega} = 0 \end{cases} \quad (1)$$

σ [$S\text{m}^{-1}$] is the total conductivity of the tissue, ϕ [V] is the electric potential, I_s [Am^{-3}] is the injected electric current per unit volume and \hat{n} is the perpendicular vector to the boundary. This equation defines the FP of EIT. (*the equation, along with the boundary conditions, is rewritten to suite our needs.)

In the inverse problem of EIT, a conductivity distribution is reconstructed using a measured set of potentials. In parametric EIT, a small number of parameters are reconstructed; these parameters model an anatomical or physiological phenomenon. In the current study, the Left Ventricle (LV) is modeled as a tri-axial semi ellipsoid. The parameters that model the volumetric change in the LV are radii, center of mass and rotation angles:

$$\mathcal{P} = \{\mathcal{R}_1, \mathcal{R}_2, \mathcal{R}_3; C_x, C_y, C_z; \phi, \theta, \psi\}$$

The reconstruction is done by using Levenberg-Marquardt non-linear optimization technique. The optimization was made in order to ensure that the ellipsoid built from the reconstructed parameters is the best to model the LV at each cardiac cycle phase. The iterative reconstruction procedure can be described using the following equation:

$$\mathcal{P}^{k+1} = \mathcal{P}^k - [\mathfrak{J}^T \mathfrak{J} + \lambda^k \text{diag}(\mathfrak{J}^T \mathfrak{J})]^{-1} \cdot [\mathfrak{J}^T \cdot (\varphi_c(\mathcal{P}^k) - \phi^m)] \quad (2)$$

Here \mathcal{P}^k are the ellipsoid's parameters at the k^{th} iteration. $\varphi_c(\mathcal{P}^k)$ is the calculated electrodes potential difference vector for the k^{th} conductivity distribution, ϕ^m is the 'real' electrodes potential difference vector (measured set of potentials), λ is the damping factor and $\text{diag}(\blacksquare)$ is the diagonal of a matrix. The Jacobian matrix, $\mathfrak{J}(\mathcal{P}^k)$, is defined as:

$$\mathfrak{J}(\mathcal{P}^k) = \frac{\partial\varphi_c(\mathcal{P}^k)}{\partial\mathcal{P}^k} \quad (3)$$

The iterative procedure is terminated when the error energy function

$$E(\mathcal{P}^k) = \|\varphi_c(\mathcal{P}^k) - \phi^m\|_2^2 \quad (4)$$

reaches a local minimum.

As we can see from equation #2, the reconstruction

procedure depends on the potential distribution. In order to eliminate the effect of breathing on the thoracic potential distribution map, we need to separate the contributions of the heart and the lungs. Let $TC(t)$ be the total thoracic conductivity distribution and $\varphi_{TC}(t)$ be the appropriate potential distribution map. We assume that only the heart movement and breathing contribute to the total thoracic conductivity change hence:

$$TC(t) = H(t) + L(t) \quad (5)$$

Using the superposition principle (due to the linearity of Poisson's equation) we can write:

$$\varphi_{TC}(t) = \varphi_H(t) + \varphi_L(t) + \varphi_C \quad (6)$$

Here φ_C is a constant potential value produced by the other tissues.

3. Results

One potential measurement is shown in figure #1. The figure shows the changes in the potential during the cardiac cycle and the respiratory cycle. The green line (line with circles) shows the changes in the potential due to the contraction of the heart only. The red line (line with dots) shows the changes in the potential due to respiratory motion only (the heart is steady). The blue line (line with crosses) shows the changes in the potential when allowing both motions (cardiac and respiratory).

The simulation results emphasize the fact that the estimation of the LVV using pEIT is affected by breathing. About 10% change in the lungs' volume (during tidal breathing) causes 8% change in the estimated CSV. In order to neutralize this effect a new algorithm was developed. By assuming that the respiratory rate is lower than the heart rate, the contribution of both motions to the change of potential distributions can be separated. The separated potential distributions are used to estimate the LVV while neutralizing the effect of breathing. The preliminary results show a decrease in the SV estimation error; 3% compared to 12% without using the correction algorithm.

4. Discussion

The total potential distribution depends on all of the organs that comprise the volume conductor (the chest in our case). In this article we showed that other movements like the movement of the lungs (aka breathing) change the potential distribution including the potential on electrodes. The change is in the amplitude of the potential signal and in the morphology of the signal.

The assumption that during the cardiac cycle only the heart moves can be incorrect. Due to the fact that if the potential has a small error the LVV estimation results will be faulty (seen in equations #2, #3 and #4) one should consider these other movements and integrate their effect in the reconstruction procedure. In order to eliminate the

effect of breathing we developed a new algorithm which takes into account the movement of the lungs. The preliminary simulation results showed that the algorithm has a great potential for solving the problem. The estimation error of the SV using the pEIT method decreased by $\sim 75\%$ when the preliminary correction algorithm is used.

Future work will include, inter alia, improving the correction algorithm and incorporating other motion artifacts like electrodes motion and heart translation during the cardiac cycle.

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Contribution of heart and respiratory motions to the potential on one electrode

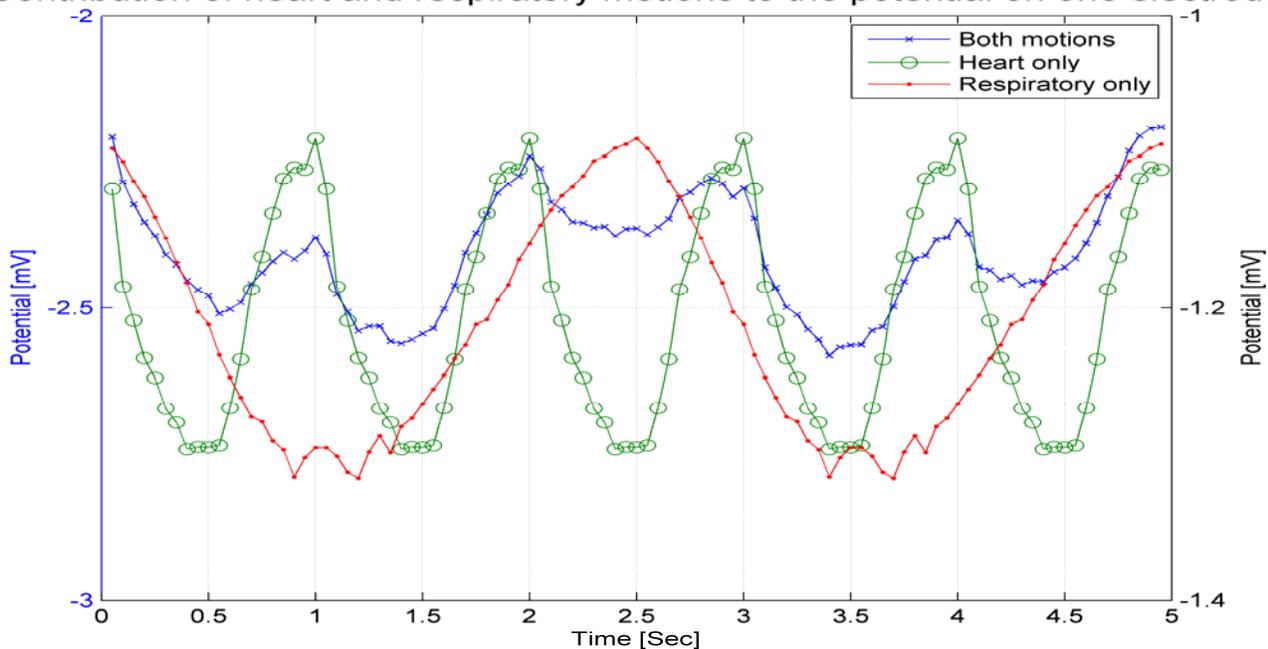


Figure 1: Contribution of the motions to the potential. Green line with circles shows the potential oscillations due to the heart contraction only, red line with dots shows the potential oscillations due to the lungs motion only and blue line with crosses shows

