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Evaluation of different stimulation and measurement patterns based on internal electrode: Application in cardiac impedance tomography

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ABSTRACT

The conductivity distribution around the thorax is altered during the cardiac cycle due to the blood perfusion, heart contraction and lung inflation. Previous studies showed that these bio-impedance changes are appropriate for non-invasive cardiac function imaging using Electrical Impedance Tomography (EIT) techniques. However, the spatial resolution is presently low. One of the main obstacles in cardiac imaging at the heart location is the large impedance variation of the lungs by respiration and muscles on the dorsal and posterior side of the body. In critical care units there is a potential to insert an internal electrode inside the esophagus directly behind the heart in the same plane of the external electrodes. The aim of the present study is to evaluate different current stimulation and measurement patterns with both external and internal electrodes. Analysis is performed with planar arrangement of 16 electrodes for a simulated 3D cylindrical tank and pig thorax model. In our study we evaluated current injection patterns consisting of adjacent, diagonal, trigonometric, and radial to the internal electrode. The performance of these arrangements was assessed using quantitative methods based on distinguishability, sensitivity and GREIT (Graz consensus Reconstruction algorithm for Electrical Impedance Tomography). Our evaluation shows that an internal electrode configuration based on the trigonometric injection patterns has better performance and improves pixel intensity of the small conductivity changes related to heart near 1.7 times in reconstructed images and also shows more stability with different levels of added noise. For the internal electrode, when we combined radial or adjacent injection with trigonometric injection pattern, we found an improvement in amplitude response. However, the combination of diagonal with trigonometric injection pattern deteriorated the shape deformation (correlation coefficient $r=0.344$) more than combination of radial and trigonometric injection (correlation coefficient $r=0.836$) for the perturbations in the area close to the center of the cylinder. We also find that trigonometric stimulation pattern performance is degraded in a realistic thorax model with anatomical asymmetry. For that reason we recommend using internal electrodes only for voltage measurements and as a reference electrode during trigonometric stimulation patterns in practical measurements.

1. Introduction

For medical diagnostic purposes there is an increasing need for non-invasive or minimally invasive techniques for evaluating the functional status of the heart. The current gold standard techniques for measuring cardiac ejection fraction, such as MRI, CT and echocardiography, are expensive and do not offer continuous monitoring. Electrical Impedance Tomography (EIT) was presented in 1987 by Brown and Seagar [1,2]. As a non-invasive technique, this method has the potential for real-time bedside assessment of electrical impedance changes within the human body. One of the current medical applications of EIT systems is monitoring conductivity changes of the thorax related to breathing [3]. In addition to impedance changes related to ventilation within the thorax area, cardiac-related impedance changes related to cardiac stroke volume (SV) also arise with major diagnostic value. Dynamic imaging (difference imaging) of changes related to the cardiac cycle show only relative changes in impedance and include a composite of cardiac and respiratory components. As the respiratory component is much larger than the cardiac component, resolution of cardiac changes is low and may be assisted by minimally invasive techniques such as inclusion of internal electrodes or use of contrast agents. In order to localize and separate the cardiac signal from the respiratory

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signal, extensive research has been conducted. Eyuboglu et al. [4] found that by averaging over 100 ECG gated cardiac cycles cardiac related impedance changes could be revealed. Brown et al. [5] mixed 10 ml of 0.9% saline (1.66 s/m) with a typical blood volume of 5000 ml (0.62 s/m) to improve the cardiac conductivity changes near 0.23%. They showed that electrical impedance imaging can be used to investigate the human vascular system by using saline as a tracer (contrast agent). Vonk Noordegraaf et al. [6] studied the electrode configuration to improve cardiac imaging. They analyzed MRI scans of two healthy subjects and proposed electrode measurements on an oblique plane at the level of the ictus cordis anteriorly and 10 cm higher posteriorly for better visual separation between the ventricles and atria. Patterson et al. [7] studied sixteen electrodes in three transverse planes around the thorax at the level of the second intercostal space, at the level of the xiphisternal joint, and midway between the upper and lower locations. In order to remove the respiration signal, they collected data with controlled lung air volume using a breath holding procedure. They reported that middle electrodes most consistently show an increase in impedance in the region of the heart during systole. Zlochiver et al. [8] studied the feasibility of a parametric EIT algorithm for measuring stroke volume in simulation and in a clinical study. They estimated the lengths of the major and minor axes of an elliptic model of the left ventricle based on an iterative parametric optimization scheme. They reported a correlation of 0.86 between parametric EIT and impedance cardiography measurements in 28 healthy patients. Deibele et al. [9] developed a dynamic filtering method for the online separation of pulmonary and cardiac changes based on principle component analysis and frequency domain filtering. The method does not depend on ECG or other a priori knowledge and they reported that the results are superior to frequency domain filtering and in good agreement with signals averaged over several cardiac cycles. Sokolovsky et al. [10] simulated the forward problem using a realistic 3D hybrid phantom of human thorax. They analyzed the simulation of the cardiac cycle of normal patients and patients suffering from cardiogenic pulmonary edema and reported that the forward problem is most sensitive to the stroke volume when the current injects from the right breast toward the left scapula ($-0.021\ \mu V\ ml^{-1}$). They also reported that both the heart volume and the lung conductivity effect the voltage change; therefore, in stroke volume estimation the lung conductivity and heart volume should be jointly estimated. Despite all efforts, the non-invasive measurement of stroke volume by means of EIT is still inaccurate for clinical applications. The spatial resolution of EIT systems is comparably low and relies on many parameters such as limited number of independent measurements, electrode configuration, contact impedances, noise artefacts, and stimulation patterns. Resolution can be increased if more electrodes are used. However, this is inappropriate in most clinical settings. In critical care units, EIT electrodes could potentially be inserted in the esophagus bringing them closer to the heart with a ten-fold reduction in their contact impedance in comparison with skin electrodes [11,12]. In addition, by inserting an extra electrode in this area directly right behind the heart (Fig. 1) we aim to reduce the high impedance areas related to the lungs and deep back muscles.

The aim of the present study is to evaluate different stimulation patterns including an internal electrode and external electrodes. Analysis is performed for a circular arrangement of 15 electrodes around a simulated 3D tank and a pig thorax model with 1 internal electrode located at the center of the models [13]. The finite element models (FEM) were created by Netgen [14]. Simulations were performed with Electrical Impedance Tomography, Diffuse Optical Tomography Reconstruction Software (EIDORS) which is a linear finite element solver written in Matlab.

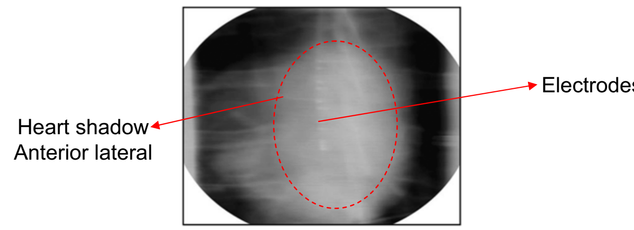

Fig. 1. Fluorescence image of the pig thorax, which shows the shadow of the heart and the catheter with 10 electrodes located inside the esophagus right behind the heart.

This software was developed to promote collaboration between research groups working on EIT and diffusion based optical tomography, in medical and industrial settings [15]. For quantitative evaluation of the stimulation patterns, we implemented methods based on distinguishability [16], sensitivity [17], and the merit figures in GREIT (Graz consensus Reconstruction algorithm for EIT) [18].

GREIT is linear reconstruction algorithm designed for EIT, since early discussions took place at the International Conference on Electrical Bioimpedance (ICEBI) 2007 in Graz, Austria. The aim of GREIT is to develop standard evaluation parameters of EIT images, which have broad agreement from experts in the mathematical, engineering, physiological and clinical EIT communities.

This paper is organized as follows: first, we describe the simulation and illustration of voltage and current distribution with the internal electrode. Second, we describe the evaluation of a cylindrical tank model with a small perturbation for characterizing detectability, and GREIT parameters for different stimulation patterns. Third, we provide an analysis of the sensitivity of stimulation patterns in the pig thorax model, considering lungs, spinal cord, and small changes related to the heart conductivity. Finally, the effect of changes in lung conductivity in these images is evaluated.

2. Simulated FEM with internal electrode

Our simulation is based on the conventional arrangement of 16 surface electrodes encircling the medium in a single plane ($z=1$). For an internal catheter electrode, we removed the surface electrode located at the furthest point from the heart, and placed this internally. The left image in Fig. 2 shows a CT scan of the pig thorax. This was segmented and meshed to develop the 3D FEM mesh model (right image in Fig. 2). The FEM includes regions relating to the heart, lungs (green), spinal cord (large, posterior, white cylinder) and small regions of the heart for modeling conductivity changes. The red cylinders show the location of the surface electrodes including electrode 9 (most anterior) which was moved internally. The small empty cylindrical area with 0.1 unit diameter in the middle of the lungs is the location of this internal electrode (electrode 9). The perturbation of interest was a small variation of conductivity within the heart region, represented by the small blue 0.05 unit diameter cylinder (inner area of the heart). The simulated conductivities are given in Table 1. In order to make the simulations more realistic we add zero mean Gaussian noise with an SNR equal to 3. SNR is defined in terms of power $SNR=||signal||/||noise||$. We simulate the measured difference voltage between homogenous voltages (v_h) (background) and inhomogeneous voltages (v_i) caused by a 10% change in the small perturbations of interest related to the heart. We included lung conductivity changes of (0.1%, 1%, 10%, and 20%) to represent different breathing conditions from apnoeic to free