

An EIT system for monitoring lung conductivity in CHF patients

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ABSTRACT: The principles of EIT are implemented in a novel, lung conductivity monitoring system ("CardioInspect" Ramot LTD). The system is to be utilized in the clinic or at home, for daily monitoring of patients suffering from congestive heart failure (CHF). The developed system consists of an 8-electrode belt designed to be worn around the thorax, an electronic unit containing analogue and digital boards, and a portable PC with a designated software to analyze the data. A Newton-Raphson algorithm is employed for the optimization of the left and right lung conductivities, making use of the voltage measurements retrieved from opposite current injections. In this preliminary study, 13 healthy volunteers and 30 CHF patients were measured with the system during tidal respiration, and the ability to monitor the respective lung conductivities was assessed. A mean left and right lung conductivities of $[0.17\pm 0.01, 0.16\pm 0.01]$ for the control group and $[0.20\pm 0.02, 0.19\pm 0.02]$ for the CHF group was found, indicating a significant ($p < 0.0005$ for both lungs) separation between the two groups. The system specificity was found to be 85%, and its sensitivity was found to be 80%. A comprehensive study with a larger subject group is planned in a further research.

Keywords: electrode-belt, CHF monitoring, lung conductivity, EIT

1. INTRODUCTION

Congestive Heart Failure (CHF) is a disease originating from an inadequacy of the heart to maintain blood circulation, resulting in congestion and edema in the body tissues. Cardiogenic Pulmonary edema (CPE) is a symptom of CHF, arising from the accumulation of excessive amount of watery fluids, transferred from the pulmonary capillaries to the pulmonary interstitium or into the alveoli. Monitoring the development of CPE is crucial, since it can rapidly deteriorate to cause acute respiratory distress. Current monitoring techniques include mainly X-ray CT and weighing, the former of which cannot be performed on a frequent basis due to the ionizing radiation involved, while the latter is far from being accurate. The electrical impedance tomography (EIT) technique seems to be a suitable CPE monitoring modality. First, the technique is proven sensitive to the amount of lung fluids [1-4], as their increase results in an increase in the lungs' specific conductivity. In addition, it is non-invasive and does not incorporate ionizing radiation. A general scheme of an EIT system consists of an electrode-array, attached to the body, through which the electrical current is injected in various combinations of source and sink and the voltage measurements are performed. The measurements, for each current injection combination, are then processed using an inverse-problem algorithm to produce an estimation of the internal conductivity distribution that led to the observed surface voltages. Since there is a large differentiation in the electrical properties of different biological tissue types, the resulted conductivity distribution is essentially of anatomical information. Another aspect concerns the medicinal treatment of CHF patients, which is intended to control the excessive retention of salt and water. The latter purpose is achieved by giving diuretic agents, however, over-treatment with diuretics must be avoided, since the resultant hypovolemia may reduce cardiac output, interfere with renal function and produce lethargy. Diuretics might also reduce the concentration of important ions in the blood circulation, causing phenomena such as hypokalemia. These symptoms are accompanied with ECG waveform changes, mostly a prolongation of the QT interval [5].

In this work, a portable EIT system ("CardioInspect", Ramot LTD), with integrated ECG measuring capabilities was designed and built, and its performance in monitoring CHF patients was assessed. The system provides information regarding the electrical conductivities of the left and right lungs using the bio-impedance measurements, and the QT interval duration using the ECG measurement. The

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combination of these indicators is believed to improve the diagnostic capabilities of this illness, and help the physicians to better adjust the proper medication dosage on a frequent basis.

2. METHODS

2.1 Hardware Design

A block diagram of the experimental system is presented in figure 1. The system comprises of an 8-electrode belt, designed to be worn around the thorax, with an additional reference electrode to be attached on the waist for minimizing baseline drifts. A current source circuit generates a 3mA, 20kHz current, which is injected through a switch matrix to the body in an opposite configuration. For each injection, five differential voltages are measured, sampled and stored to be off-line processed in a PC. The system also measures the ECG signal, using two of the eight electrodes, for a period of 5 seconds. The entire system is power supplied from a rechargeable battery for safety considerations.

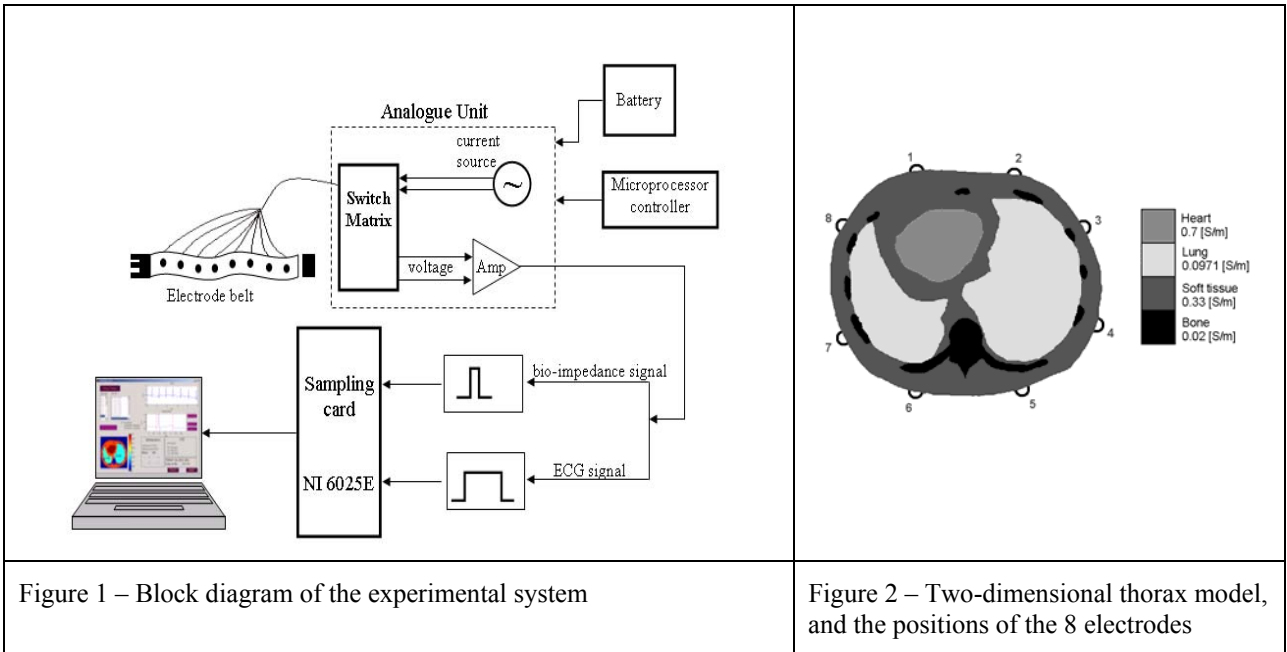


Figure 1 – Block diagram of the experimental system

Figure 2 – Two-dimensional thorax model, and the positions of the 8 electrodes

2.2 Software Design

2.2.1 Lung Conductivity Estimation

An iterative optimization scheme, based on the second-order Newton-Raphson method, was implemented for estimating the left and right lung conductivities, each of which was assumed constant in its respective lobe domain. The method comprises of guessing an initial conductivity for each lung lobe, calculating the expected surface potentials due to the injected currents for all four source and sink configurations, and comparing them to the appropriate measured surface voltages from the thoracic electrode belt. Then, at each iteration, new conductivity values for the two lungs are calculated so that the error between the calculated and the measured surface potentials is reduced. The surface potentials are calculated at each iteration by solving the following governing Laplace equation and Neumann type boundary condition, using the two-dimensional thorax model shown in figure 2:

$$\nabla \cdot (\sigma \nabla \psi) = 0 \quad (1)$$

$$\sigma \frac{\partial \psi}{\partial \vec{n}} = \begin{cases} \vec{J}, & \text{on electrode positions} \\ 0, & \text{elsewhere} \end{cases} \quad (2)$$

where σ [$\Omega^{-1} \cdot m^{-1}$] is the tissue conductivity, ψ [Volt] is the electrical potential, \vec{J} [$A \cdot m^{-2}$] is the injected current density and \vec{n} is a unit vector, normal to the surface. In the physical model, from which equation (1) is derived, several assumptions were applied, including the quasi-static approximation and linearity and isotropy of the biological volume conductor. The finite-volume method was employed for the discretization and numerical solution of the integral presentation of the governing equation. A comprehensive formulation of the numerical solution for the forward and inverse problems is given in our previous works [6-10].

2.2.2 QT interval Calculation

An R-wave detection algorithm is applied on the 5 seconds long ECG signal, which employs a BPF to differentiate the QRS-complexes from the rest of the ECG, and a threshold-based pick-detection method to locate the picks of the R-waves. The ECG-signal beats are then averaged, using the detected R-wave picks as synchronizing points, to determine the average RR interval. The QT interval, defined as the time from the beginning of the QRS-complex to the end of the T-wave (representing the total ventricular activity composed of the repolarization and depolarization periods), is measured on the averaged beat. Finally, the corrected QT-RR, which is normalized to a fixed heart-rate of 60bpm, is calculated using Bazet's formula: $QTc = QT / \sqrt{RR}$, where QTc [sec] is the corrected QT interval and RR [sec] is the mean time period between sequential R-waves.

2.3 Experimental Procedure

A preliminary study was conducted at the CHF clinic, the department of cardiology, Rabin medical center, and was approved by a Helsinki ethics committee. The inclusion criteria for subject participation in the study were: (1) inexistence of a cardiac pace maker, and (2) subject who agreed to sign an informed consent. The study was performed on two subject groups, the first of which was a control group consisting of 13 healthy subjects (37 ± 10 years old), while the second group comprised of 30 CHF patients (57 ± 14 years old), regularly monitored at the clinic, with various stages of illness. For both study groups the measurements were taken at rest, during tidal respiration.

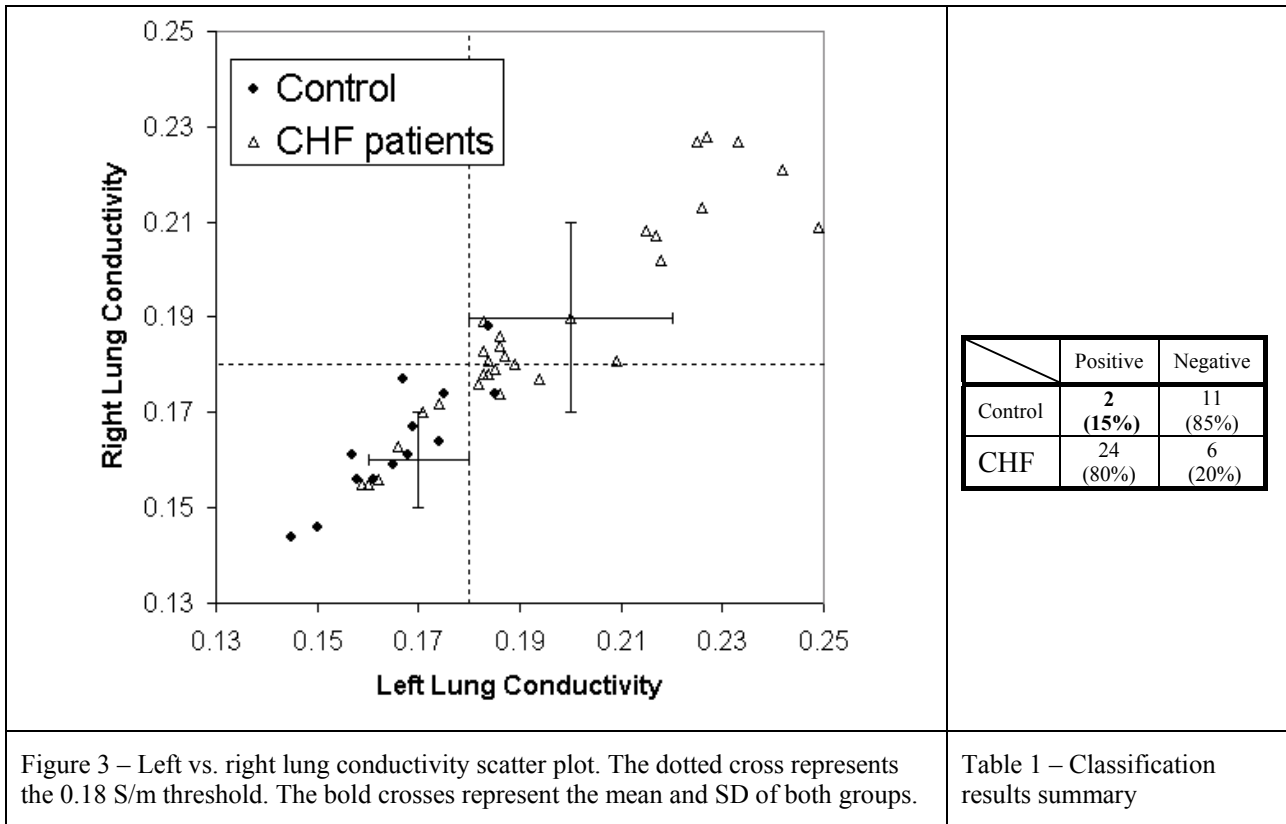
3. RESULTS

The reconstruction results for the lung conductivities of the two groups are shown on a scatter plot in figure 3. A clear separation between the two group types can be seen, where the higher lung conductivity values belong to the CHF patients, indicating larger fluid volumes in their lungs. The mean left and right lung conductivities for the control group is $[0.17 \pm 0.01, 0.16 \pm 0.01]$ and for the CHF group $[0.20 \pm 0.02, 0.19 \pm 0.02]$. An unpaired two-sample t-test proved this separation to be significant ($p=0.0002$ and $p=0.0005$ for the left and right lungs respectively). A threshold value of 0.18 S/m was set as a diagnostic criterion for classifying the examinee condition to be either normal (negative) or fluid-congested (positive). Using this threshold, the system's specificity was shown to be 85%, and its sensitivity 80% (table 1).

4. DISCUSSION

In this work, preliminary results that demonstrate the feasibility of a novel EIT system to discriminate between healthy and CHF subjects were presented. The system monitors lung conductivity changes using the bio-impedance principles and inverse-problem techniques. A significant separation of means between the two groups' typical lung conductivities was found, as well as a sensitivity of 80% and a specificity of 85%. These values can be actually slightly altered by changing the 0.18 S/m threshold that was used to classify the examinee condition; however, this chosen value, in addition for representing a normal tidal value for the lung conductivity, was found to well balance the system's sensitivity and specificity. It should be noted that in this stage of the study, all CHF patients, although inner-classified into various illness degrees, were considered a homogenous group. In addition, the exact condition of the CHF patients

on the trial date, regarding the degree of lung fluid accumulation, was not referred to in the performances analysis. These assumptions surley tend to lower the sensitivity of the system, and should be addressed in later study.



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