USE OF TEMPERATURE AS A CONTRAST AGENT IN ELECTRICAL IMPEDANCE TOMOGRAPHY

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Abstract: Electrical Impedance Tomography (EIT) images conductivity changes within a body from electrical measurements at the body surface. There is significant interest in using EIT to measure cardiovascular parameters, such as blood perfusion. Currently, a hypertonic bolus of saline is injected into a central vein, producing an increase in conductivity which is visualized. Unfortunately, hypertonic saline has undesirable effects in large doses, and cannot be used for continuous monitoring. We propose the use of temperature contrasting isotonic saline as a new contrast agent for EIT, suitable for repeated measurements. The experiments were carried out on a cylindrical tank filled with a saline solution having a conductivity of 1 S/m and the temperature of 22.6 °C. A 280 ml saline bolus with the conductivity of 1 S/m and temperature difference Δt was injected at the tank center. We selected 5 different temperatures for the bolus. Subsequent EIT image analysis demonstrated that the temperature contrast can be successfully reconstructed. A quantitative analysis revealed that reconstructed impedance values were correlating linearly with temperature. Our initial results show the suitability of EIT for real-time noninvasive temperature contrast imaging.

INTRODUCTION

Electrical impedance tomography (EIT) is a low cost, real-time, portable and non-invasive method to image conductivity distributions within a body. EIT has emerged as a potential new functional imaging method for clinical monitoring (e.g. respiratory monitoring, blood perfusion) [1]. Since tissue conductivity changes with temperature with a known temperature coefficient of 2 % per °C [2], electrical impedance measurements can be carried out from the boundary of a body and used as a tomographic thermometry instrument.

Previous literature mostly from the early 1990's suggested electrical impedance measurements and imaging as a means for carrying out non-invasive thermometry for the monitoring of hyperthermic treatment [2]. Hyperthermia is used for the treatment of malignant tumors, which are heated by laser radiation or ultrasound. However, EIT met a lot of challenges at that time for this type of monitoring applications due to its insufficient spatial and contrast resolution [2]. Currently, EIT instruments for biomedical application can achieve image rate of 20 to 50 (image) frames per second which allows the time resolution needed by most of the physiological events.

There is a clinical need for the non-invasive and real time monitoring of cardiovascular parameters. In this paper, we propose the use of temperature contrasting saline as a contrast agent for cardiovasular EIT imaging. Typically in clinical practice, the cold temperature of an indicator bolus is dissipated in the surrounding tis-

sue as a function of their heat capacity given by the water content. We propose that a saline bolus of physiological concentration (0.9%) at temperatures significantly different from that of the surrounding body tissue be injected into a central vein and EIT difference images be analyzed to derive cardiovasular parameters and identify structures of interest such as heart chambers and the aorta [3]. Temperature contrast can be safely applied repeatedly to a patient, while a repeated bolus of hypersaline with salt concentrations as high as 5 to 20 times that of blood risks disturbing a patients electrolyte balance, resulting in a high sodium load and adverse effects such as hypertension and additional strain on the kidneys. Our aim is to investigate the suitability of EIT for temperature contrast imaging in real-time.

METHODOLOGY

Our approach is to investigate temperature contrast imaging using EIT. EIT measurements are carried out from the boundary voltage resulting from electrode-pair current injections. Time difference imaging produces conductivity distribution images that reflect conductivity changes between a reference measurement and the measurement of interest (i.e. between two points in time). If such changes are generated by local temperature changes a temperature difference map can be generated.

Temperature and Conductivity

The electrical conductivity in ionic solutions depends on the mobility of ion species. In human biology, the ion species that occur most are sodium and potassium ions. They allow the electrical current to flow throughout both intracellular and extracellular volumes [2]. The conductivity of a solution depends on the ionic mobility, which depends on the solution temperature. This effect can be modeled within a limited temperature range around temperature T_0 using the following linear approximation:

$$\boldsymbol{\sigma}(T) = \boldsymbol{\sigma}_0(1 + a(T - T_0)) \tag{1}$$

where $\boldsymbol{\sigma}(T)$ is the electrical conductivity at the temperature T, a is the temperature coefficient of conductivity (empirical parameter), T_0 is the reference temperature that can be used for calibration, and $\boldsymbol{\sigma}_0$ is the electrical conductivity at the temperature T_0.

Image Reconstruction

We want to measure the changes in conductivity $\boldsymbol{\sigma}(T)$ due to temperature changes based on a background (or reference) conductivity $\boldsymbol{\sigma}$ and obtain a conductivity change $\mathbf{x} = \boldsymbol{\sigma}(T) - \boldsymbol{\sigma}$, which can be modeled as a linear function of difference measurements, y, as follows [5]:

$$\mathbf{y} = \mathbf{J}\mathbf{x} + \mathbf{n}, \tag{2}$$

where $\mathbf{n}$ is the noise and $\mathbf{J}$ is the Jacobian (sensitivity) defined as [5]

$$[\mathbf{J}]_{i,j} = \frac{[\partial F(\boldsymbol{\sigma})]_i}{[\partial \boldsymbol{\sigma}]_j} \tag{3}$$

where F is a (linear) forward model operator.

From EIT measurements $\mathbf{y}$, the estimate of conductivity change image $\hat{\mathbf{x}}$ is reconstructed from a linearized difference EIT reconstruction algorithm [5], using a priori information and introducing forms of filtering as

$$\hat{\mathbf{x}} = (\mathbf{J}^T\mathbf{J} + \lambda^2\mathbf{R})^{-1}\mathbf{J}^T\mathbf{y} \tag{4}$$

where λ is the regularization parameter, $\mathbf{R}$ is the regularization matrix based on the discrete Laplacian (with $\lambda = 0.005$). The normalized difference measurement vector is given by $\mathbf{y}$ ($[\mathbf{y}]_i = ([\mathbf{v}]_i - [\mathbf{v}_r]_i)/[\mathbf{v}_r]_i$), where $\mathbf{v}$ and $\mathbf{v}_r$ are the current and reference measurements respectively.

Experimental Design

System description: The experimental system consists of a cylindrical tank filled with a saline solution, a set-up for bolus injection and an EIT measurement system. The EIT measurement system is the Sigma Tome II EIT system (École Polytechnique Montréal, Canada), which used adjacent current injection and (voltage) measurement patterns on pairs of adjacent electrodes. The operating frequency of the system is 50 kHz (applied alternating current). The cylindrical tank has a radius of 14.5 cm and a height of 36 cm. A long neck plastic funnel was fixed

on to the tank just above the water level. The temperature of saline bolus was adjusted using Thermo Scientific temperature controller system (model: NESLAB RTE-7).

Saline solution: During the measurement, the conductivity and the temperature of the tank solution and the injected saline bolus were monitored using a conductivity meter (model: ECTestr) and a thermometer (model: TEMARS TM-362), respectively. We designed the experiment such that the ionic concentration of the solution in the tank is the same as the one in the saline bolus. The tank was filled with 11 liters of saline solution (filled up to the middle of the tank) with conductivity of 1 $S{\cdot}m^{-1}$. Saline bolus of 280 ml was prepared at 5 different temperatures (at 5, 15, 25, 35 and 45 °C) and poured into the tank perpendicular to the surface level of the electrode plane for about 6 seconds. The temperature of the saline was kept approximately at 22.6 °C manually. However, the room temperature fluctuated from 23 °C to 24.2 °C during the measurement, and the temperature of the saline also varied by around 0.2 °C.

Additionally, we took measurements with various cubic and spherical non-conductive objects with the volume sizes of 100, 50 and 10 ml in order to calculate the size of conductivity contrast and compare it with the saline bolus. Those objects were placed at the same location where the saline bolus was poured.

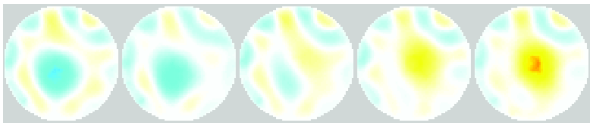
Data Processing

We used the one-step Gauss-Newton solver with a Gaussian high pass filter image prior and movement compensation [6]. For the calculations, we used a 2D circular forward model with 1024 elements from EIDORS 3.6 [7].

An image amplitude metric(A_r), is defined as the sum of all pixel values of the reconstructed images inside the region of interest (ROI). The ROI was calculated based on a full width at half maximum (FWHM) - a $\frac{1}{2}$ threshold of the maximum value of image amplitude. This has the advantage of avoiding the contamination by low amplitude noise far from the ROI. However, the noise amplitude larger than this threshold will still be included in the calculation of A_r.

RESULTS

Fig. 1 shows the reconstructed temperature contrast image. The conductivity images reflect the expected cross-sectional temperature distribution. When the bolus temperature is close to the temperature of the tank solution, the conductivity contrast is weak. This can be observed for the measurement done with bolus at 25 °C. Pouring the saline bolus at the water surface created small waves, which affected the EIT measurement and subsequently produced undesired motion related conductivity changes.



5 °C 15 °C 25 °C 35 °C 45 °C

Figure 1: Reconstructed images showing temperature contrast of the saline bolus at 5 different temperatures (5, 15, 25, 35 and 45 °C) poured in the off-center position. The tank saline temperature was 22.6 °C.

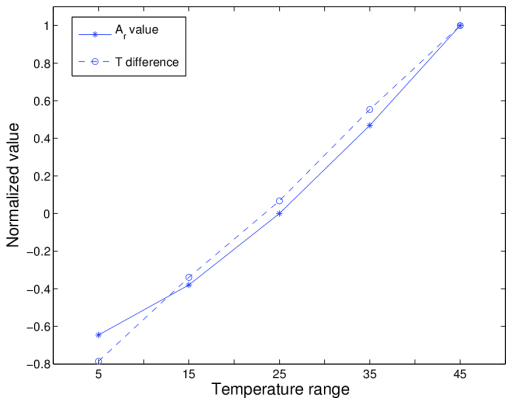


Figure 2: Graph showing the normalized A_r values of the reconstructed images for the different temperatures from 5 to 45 °C.

Fig. 2 shows normalized values of A_r and temperature difference (T difference). A global threshold value was calculated from the recon-

structed images of poured saline bolus at the temperature of 5 °C and fixed for all other cases to calculate appropriate A_r values. The temperature differences between the tank saline and the poured saline were -17.6, -7.6, 1.5, 12.4 and 22.4 °C respectively. Furthermore, the conductivity change based on eq. (1) showed that the normalized conductivity difference calculated from the reference conductivity using $\Delta\boldsymbol{\sigma}(T) = \boldsymbol{\sigma}(T) - \boldsymbol{\sigma}_0$ gave identical values as the normalized temperature difference in Fig. 2. Overall, the normalized A_r values for the different temperatures from 5 to 45 °C follows the trend predicted by the conductivity variation model presented in eq. (1). Nevertheless, we observed variation to the linear model likely due to changes of the saline temperature, quick temperature dissipation of the poured saline bolus, and water motion.

The results (not shown here) based on A_r indicated that 280 ml of saline bolus at 15 °C corresponds to a 10 ml non-conductive spherical object. However, the A_r values of the cubic object (10 ml) varied according to the corner orientation due to the direction asymmetries compared to the spherical object. Thus, the temperature contrast is about 3.5 % (10/280) of an equivalent non-conductive contrast. In a clinical scenario for instance, the temperature contrast is high with 4 °C in saline bolus and 37 °C for a human body. For this maximal temperature contrast, the estimated contrast ratio is 15 %.

DISCUSSION

In this paper, we investigated temperature contrast imaging by EIT. Temperature contrast can potentially be used as an EIT contrast agent for the measurement of cardio vascular parameters.

Conductivity images were successfully reconstructed from the measurements acquired based on 280 ml saline with 5 different temperatures (5 °C to 55 °C) poured in the tank. The image reconstruction in EIT is sensitive to system instabilities primarily from the movement disturbance caused by the pouring of water, which creates measurement errors and subsequent image artifacts. We used one-step Gauss-Newton algorithm integrating movement compensation [6]. EIT images reconstructed from test data were evaluated in terms of A_r, which corresponded with the calculated difference conductivity and the temperature changes.

Although more sophisticated experiments in vitro and in vivo are necessary to draw meaningful conclusions about the potential of EIT-based temperature tracking as a means to determine blood perfusion, our initial results showed the suitability of EIT for using temperature as a contrast agent for real time imaging.

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