Optimized Electrode Placement for Regional Impedance Measurements in the Lung

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Abstract—Bioimpedance Spectroscopy (BIS) and Electrical Impedance Tomography (EIT) are both impedance based techniques that have a great potential in biomedical engineering. While BIS is able to identify and distinguish between different tissue types, EIT has the advantage of providing spatial resolution. In this paper, we present electrode combinations, which combine the advantages of both modalities. We show results of a simulation study evaluating different electrode setups to focus impedance measurements to specific lung regions.

I. INTRODUCTION

Bioimpedance Spectroscopy (BIS) has proven to be a powerful tool, for example to detect fluids inside the lungs. However, one major drawback of this measurement technique is the lack of local information. In contrast, Electrical Impedance Tomography (EIT) provides local information, but can currently only display impedance changes in time and is mainly used in ventilation monitoring. Our approach is to modify the common BIS setup (2 injection and 2 measurement electrodes) to focus on specific lung regions. By doing so, we try to identify local pathologies in these regions. To achieve this focusing, we use both electrodes at the boundaries of the body and inside the trachea, which can be easily integrated into an endotracheal tube. One crucial aspect is an optimized electrode placement at the boundary, which will be analyzed in this paper. We use the sensitivity definition to evaluate various electrode setups. It was shown in previous studies that the position of injection and measurement electrodes have a high impact on the sensitivity and the measurement results [1] [2]. To calculate results without making invalid assumptions, we chose a brute force approach: We use a finite element model of the human body and place 66 electrodes on the boundary. In addition, we place two electrodes inside the trachea, which has been successfully investigated in a previous study [3]. We simulate current densities for all possible injection and measurement combinations and evaluate the results using two objective criteria.

II. MATERIALS AND METHODS

A. Simulation

The simulations were performed using CST EM Studio (CST AG, Darmstadt, Germany) and the Victoria 4 model (provided by DAZ3D Studio, Salt Lake City, USA). In this model, 66 electrodes were placed on the boundary and 2 electrodes were placed inside the trachea. The injection frequency was set to 100 kHz. Current densities for all injection and measurement possibilities were calculated using the electro-quasistatic solver. Fig. 1 shows the electrode positions on the boundary.

B. Sensitivity

From the exported current densities, the sensitivity distribution inside the body can be calculated. If the conductivity is constant, the impedance measured in a four-terminal-sensing setup can be expressed according to eq. (1):

$$ Z = \int_{\nu} \frac{1}{\sigma} J_{LE} \cdot J_{LI} \, d\nu, $$

where $\sigma$ is the electrical conductivity, $\nu$ the volume of the body, $J_{LE}$ is the lead field of the voltage measurement electrodes and $J_{LI}$ the lead field of the current feeding electrodes [4]. The sensitivity distribution $S$ is then obtained by eq. (2):

$$ S = J_{LE} \cdot J_{LI}. $$

A high sensitivity means, that a change in conductivity in this area has a high impact on the measurement result. In this paper, this definition is used for evaluation of different electrode positions.

C. Evaluation Methods

To evaluate and rank different electrode configurations, various parameters were calculated based on the sensitivity data. The global goal is, to focus on a specific Region of Interest (ROI) and to separate it from the rest of the lung. One example for a ROI is highlighted in Figure 2. In this figure, the top back region of the lung is emphasized.
In general, the optimal result would be a high, homogeneous sensitivity inside the ROI and a zero sensitivity elsewhere. However, this is not possible, especially not with a single four point measurement. The sensitivity is usually highest close to the electrodes. This is obvious, since the current flows out from the electrodes creating a high current density field close to them. Since the sensitivity is defined as the dot product of two current density fields (see Equation 2), this leads to a high sensitivity in this area. Furthermore, the sensitivity is highly dependent on the tissue conductivity. Areas with a high conductivity usually have a higher current density field than areas with a low conductivity. Since the conductivity of the lung is low compared to muscle conductivity and the electrodes are not directly connected to lung tissue, the desired binary sensitivity distribution is impossible. Thus, we defined two criteria to evaluate the measurement setups. Let $S_{ROI}$ be the sensitivity inside the Region of Interest and $S_{Lung}$ be the sensitivity in the rest of the lung. We define two evaluation criteria:

$$ Sel = \frac{\text{mean}(S_{ROI})}{\text{mean}(S_{Lung})} > TH_{Sel} \tag{3} $$

and

$$ Hom = \frac{\text{std}(S_{ROI})}{\text{mean}(S_{ROI})} < TH_{Hom}, \tag{4} $$

where $TH_{Sel}$ and $TH_{Hom}$ are thresholds. A high $Sel$ means, that the mean sensitivity inside the ROI is higher than the mean sensitivity in the remainder of the lung (see Equation 3). This can be interpreted as the selectivity. The $Hom$ value represents the homogeneity inside the lung. The lower the $Hom$-Value, the lower the standard deviation compared to the mean sensitivity inside the ROI (see Equation 4).

### III. RESULTS

The criteria introduced in Section II-C were applied to the top back region of the lung with the thresholds $TH_{Sel} = 5$ and $TH_{Hom} = 1$. Out of 285439 analyzed electrode setups, only 114 setups fulfilled the requirements. A setup that combines a high selectivity and a high homogeneity is shown in Figure 3. This setup uses one electrode in the trachea and three electrodes on the boundary. The mean sensitivity inside the ROI is 6.5 times higher than in the remainder of the lung. In addition, the ration between standard deviation of the sensitivity and the mean sensitivity is 0.334, which indicates a homogeneous distribution. Interestingly, this uses electrodes in the trachea which shows that, depending on the Region of Interest, the measurement results can be improved using internal electrodes.

However, some issues should be investigated in future work. Simulations were performed using an injection frequency of 100 kHz only. Thus, no spectroscopy was performed. Since the electrical properties of body tissue vary over frequency, the results should be confirmed using different frequencies. In addition, neither electrode positioning errors nor noise were added to the simulation. However, the presented results indicate that a focused bioimpedance spectroscopy inside the lung is possible.

### IV. CONCLUSION

In this paper, we presented the results of a simulation study. A total of 66 electrodes on the boundary and two electrodes in the trachea were investigated to focus impedance measurements on specific regions inside the lung. The results were evaluated using two main criteria: the ratio between the mean sensitivity inside the Region of Interest and the remainder of the lung and the homogeneity of the sensitivity inside the Region of Interest. For a Region of Interest in the top back of the lung, the best results were achieved using both electrodes inside the trachea and on the boundary.

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### REFERENCES


