Asymmetries in Electrical Impedance Tomography Lung Images

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Abstract: Electrical Impedance Tomography (EIT) uses a set of electrodes placed around the patient's body to apply current stimulation and measure the resulting potentials, from which an image of the internal conductivity distribution is calculated. Since EIT is sensitive to physiological phenomena which affect the conductivity, it has been used to image the thorax, to monitor the movement of blood and gas in the heart and lungs One key application of EIT is to determine the distribution of ventilation within the lungs, as this can help identify damaging patterns of breathing from lung ventilations. Thus, a key requirement for reliable interpretation of lung EIT is an understanding of if and when EIT images can produce inaccurate images which diverge from the true distribution of ventilation.

In this research, we show one scenario in which equally ventilated lungs can show unequal EIT images. Since the heart is conductive, current flows preferentially through the upper left thorax (heart) than the upper right (right lung). Because of this increased current, measurements are more sensitive to conductivity changes in the left than right lung. We verify this hypothesis through a simulation study. We built a 3D finite element model of thorax conductivity and simulated EIT images for different heart and lung conductivity, size and position. Overall, depending on the distribution of ventilation, the left lung shows up to 30% too large image. This result helps inform interpretation of lung EIT images.

1 Introduction

Electrical Impedance Tomography (EIT) uses a set of electrodes placed around the patient's body to apply current stimulation and measure the resulting potentials, from which an image of the internal conductivity distribution is calculated. Since EIT is sensitive to physiological phenomena which affect the conductivity, it has been used to image the thorax to monitor the movement of blood and gas in the heart and lungs. One key application of EIT is to monitor the ventilation distribution in mechanically ventilated patients, where it could help to identify damaging patterns of breathing and prevent ventilator-induced lung injury (VILI).

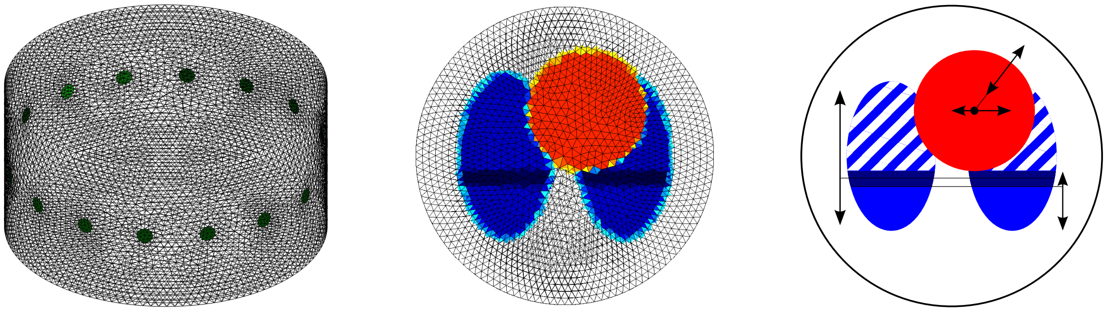
In such bed-bound patients, lung density and consequently regional ventilation are often distributed along the gravitational axis [1]. The dorsal region of the lung is often in a collapsed state and does not participate in ventilation. In contrast, the most ventral region could be overdistended, particularly in the presence of positive end-expiratory pressure (PEEP), and therefore have limited ability to accommodate tidal increases in air volume (compliance). Thus, ventilation in such patients is preferentially distributed to the central and ventral regions of the lungs.

Despite this known phenomenon, and the generally different electrical conductivity of the different tissues in the thorax, for the purpose of EIT image reconstruction, conductivity is often assumed to be uniform and the thorax is modelled by a simple geometric shape. We have previously shown the detrimental effect of shape mismatch on the quality of EIT reconstructions [2]. In the present study, we turn to the consequences of assuming a homogeneous background conductivity. We demonstrate through simulation that the asymmetric position of the heart can cause EIT images to show a false asymmetry between the left and the right lung and that the effect is particularly strong for a ventilation distribution typical of mechanically ventilated patients.

2 Methods

Using EIDORS 3.5[1], a cylindrical model with 16 circular electrodes was created with Netgen [3] as shown in Fig. 1a. Within the model, we defined two elliptical objects to represent the lungs and a circle for the heart, with tissue-to-background conductivity ratios ("conductivity") of 0.2 and 1.5. respectively, and simulated a voltage measurement with EIDORS's default forward solver. Subsequently, we decreased the conductivity in identically-sized regions in the lower central part of the two lungs to 0.18 (Fig. 1b) and repeated the simulation. The difference between the two measurements was reconstructed with the GREIT algorithm [4] (Fig. 2a) using a homogeneous cylindrical FEM with lower density than the one used for simulations.

[1]http://eidors3d.sourceforge.net/



(a) **(b)** **(c)**

Figure 1: Simulation models:(a) FEM used for simulations; (b) FEM with tissue conductivity values (top view); (c) parameters varied in the experiments. Colour code: red — heart; blue — lungs (striped part optional); navy — non-conductive contrast.

To investigate the possible causes of the asymmetry in the reconstructed image, the following parameters of the above reference set-up were systematically modified (Fig. 1c): the position, size and conductivity of the heart; the shape and conductivity of the lungs; the size and location of the contrast regions; and the current injection pattern. For each model variant, the deviation in left-right distribution of the reconstructed image was calculated as:

$$\Delta = \frac{L_{\mathrm{sol}} - R_{\mathrm{sol}}}{L_{\mathrm{sol}} + R_{\mathrm{sol}}} - \frac{L_{\mathrm{sim}} - R_{\mathrm{sim}}}{L_{\mathrm{sim}} + R_{\mathrm{sim}}} \tag{1}$$

where the values L_{sol} and R_{sol} represent the sums of the values of the negative pixels in the right and left half of the reconstructed image, respectively (medical orientation). L_{sim} and R_{sim} were calculated analogously from the difference of the two models used for simulation. Positive Δ indicates a distribution in the reconstructed image unduly skewed towards the left lung.

Additionally, we analysed the regional sensitivity and current distribution in the reference model. A sensitivity map was obtained by simulating a large number of small targets regularly distributed in the electrode plane, one at a time, reconstructing the images, and evaluating the total signal corresponding to each target in each image (amplitude response as defined in [4]). The current density in the entire 3D model was calculated based on the node voltages obtained from the forward solution; values in the electrode plane were analysed.

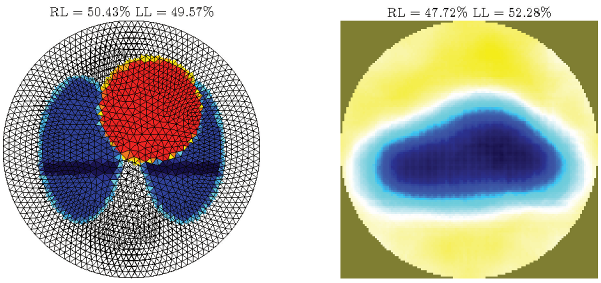
Finally, we included in the forward model used in the calculation of the GREIT reconstruction matrix [4] a conductivity distribution equivalent to that in the first simulated measurement (without the additional lung contrast).

3 Results

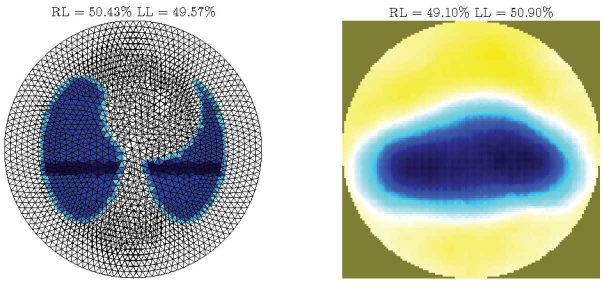
The deviation in left-right distribution Δ in the image reconstructed using the reference set-up (Fig. 2a) was 4.4%. Some examples of the investigated set-ups together with their solutions are presented in Fig. 2b–2d. Overall, Δ values up to 60% have been observed. The highest values have been obtained for conductivity changes in the ventral part of the lungs.

Fig. 3a shows the dependence of Δ on the position of the heart for three values of heart-to-background conductivity, including 1 i.e. no heart at all. The asymmetry in the reconstructed image increases as the heart is positioned more off-centre. Since the asymmetry in the reconstructed image is only slightly decreased by the absence of a conductive heart in the simulation, we conclude that the effect is primarily caused by the difference in shape of the two lungs. This is further supported by the symmetric reconstruction of the set-up in Fig. 2c. Based on results from the other analyses, we also conclude that the effect is increased by a bigger or more conductive heart (not presented) and is most pronounced for conductivity changes in the ventral part of the lung (Fig. 3b), while it is independent of the injection pattern insofar as the algorithm's sensitivity to changes in the different parts of the thorax does not change dramatically.[2]

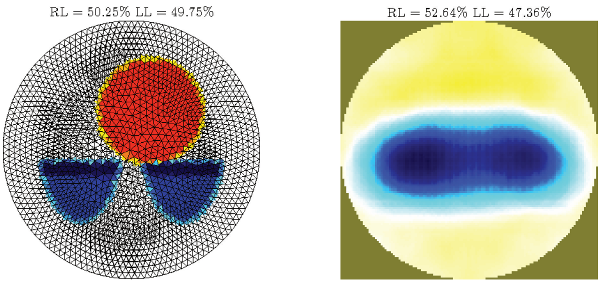
[2]This was not the case in our simulations for a one-step Gauss-Newton solver with the NOSER prior [5] which exhibited dramatically lower sensitivity in the centre of the thorax when used with adjacent stimulation pattern.



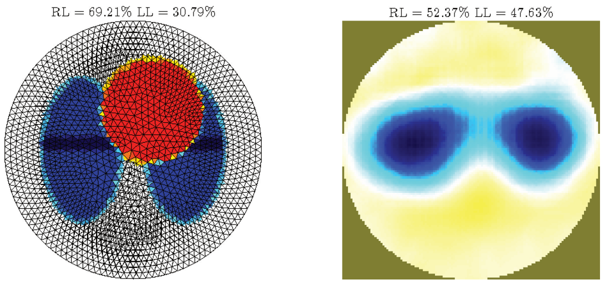
(a) $\Delta = 4.44\%$



(b) $\Delta = 2.66\%$

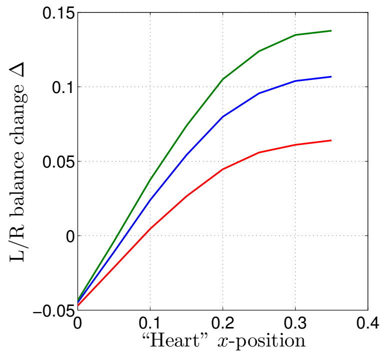


(c) $\Delta = -5.38\%$

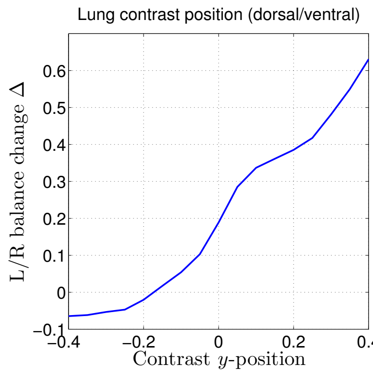


(d) $\Delta = 33.68\%$

Figure 2: Example results of simulations. Left: simulated measurement; right: reconstructed image.

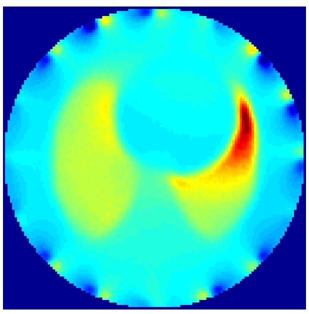


(a)

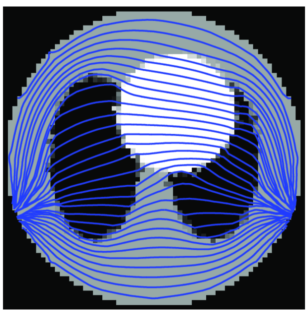


(b)

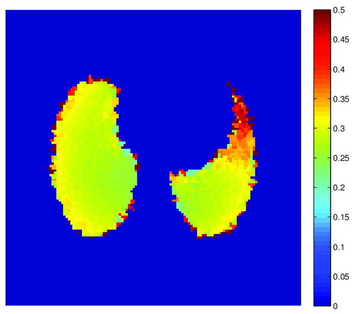
Figure 3: Deviation in left-right balance Δ as a function of (a) lateral heart position (positive to the right of the image) for heart-to-background conductivity ratios of 1.0 (red), 1.5 (blue) and 2.0 (green); (b) vertical position of the contrast (positive in ventral direction).



(a)

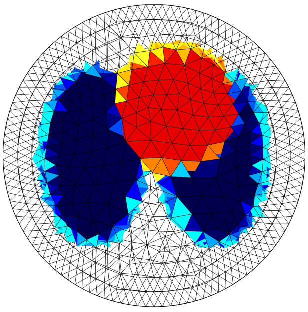


(b)

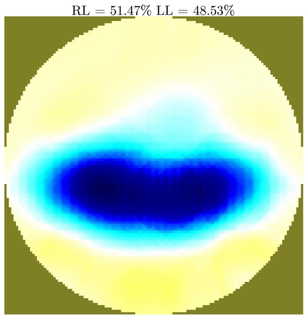


(c)

Figure 4: (a) Sensitivity map (red — high, blue—low);(b) Current streamlines showing more current flowing through the left lung than the right lung;(c) Current distribution in the lungs at the electrode level averaged over all 16 measurements (arbitrary units).



(a) Conductivity prior



(b) Reconstructed image

Figure 5: Reconstruction of data from Fig. 2a with true conductivity background. $\Delta = -2.08\%$

The asymmetry in the reconstruction of symmetric conductivity contrasts in the lungs is caused by increased sensitivity to changes in the left lung as shown in Fig. 4a. This, in turn, is explained by higher current flowing through the left as compared to the right lung, as evidenced by Fig. 4b and 4c. Because of the decreased thickness of the ventral part of the left lung, it attracts more current owing to smaller total impedance along paths crossing it.

Including the correct conductivity background in the calculation of the reconstruction matrix causes the reconstructed image to correctly show symmetric conductivity distribution as depicted in Fig. 5, which shows a reconstruction of the exact same data as Fig. 2a.

4 Discussion

The ventilation distributions in the two lungs are often compared in clinical studies (e.g. [6]), including those attempting to establish a single numerical index to indicate the quality of the ventilation distribution in a patient based on EIT images (e.g. [7]), which is very sought after in the clinical EIT community [8]. However, as demonstrated above, the ventilation induced changes in the left lung may habitually be over-estimated when homogeneous background conductivity is assumed by the EIT reconstruction algorithm, an effect particularly pronounced in the kind of ventilation distribution expected in mechanically ventilated patients.

The inclusion of a true background conductivity prior in our study removed the false asymmetry from the reconstructed images. In clinical practice, the shape of the internal organs in the electrode plane could be obtained from a CT or MRI image from which a conductivity prior could be constructed using average tissue properties from literature or by some transformation of tissue density or water content.However, this would only offer a partial solution. Because the lung density and hence conductivity is highly non-uniform and dynamic, such priors could never accurately reflect the true background conductivity distribution. Equal changes in less conductive lung areas will still produce smaller EIT signals than equivalent changes elsewhere in the lung. Thus, contrary to the common treatment of regional ΔZ (impedance change) values as being directly proportional to changes in air content, they necessarily also reflect mean local aeration (as well as liquid content), even when only tidal differences are considered.

A significant improvement in terms of the accuracy of reconstructed conductivity changes can be achieved by incorporating a conductivity prior in the reconstruction algorithm, and it remains to be investigated how doing so would affect the interpretation of EIT images. Meanwhile, when the underlying lung condition is known to be heterogeneous, extra care is required when interpreting EIT images. Ideally, information from other modalities would be incorporated in the analysis.

References

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