Reinhard Fuchs*, Michael Unger, Andreas Wolfgang Reske and Thomas Neumuth

# Landmark registration in CT for lung model approximation in EIT

https://doi.org/10.1515/cdbme-2024-1006

**Abstract:** For the visualization of pulmonary ventilation with Electrical Impedance Tomography (EIT), most devices rely on generalized reconstruction models. Yet, fixed thorax dimensions, predetermined electrode locations, and standard lung shapes lead to multiple sources of EIT imaging distortion. The following work compares reconstructions of a library model, a practical model based on landmark fitting, and a detailed model based on manual segmentation. CT images of five pigs were segmented into torso surface, electrode positions, and lung borders. Practical models were created with reduced data, registration, and fitting. Detailed models were created by using the complete segmentation data. After EIT reconstruction and tidal image calculation, the overlap of CT lung segmentation and ventilated voxel was calculated. Compared with the results of a standardized model, the practical model reached an average ventilation/segmentation-overlap difference of an additional 12 %, and the detailed model achieved an average difference of 10 %. In conclusion, the shift of reconstructed impedance towards the segmented lung region is similar in both models when compared to the standard model, while the practical model requires a considerably less amount of information.

**Keywords:** Model generation, Emergency medicine, Landmark registration, Electrical Impedance Tomography

## 1 Introduction

In the prehospital or emergency setting, injuries to the chest (thorax) represent one of the most common types of injury [1]. Any occurring injury to the lung and resulting ventilation issues are examined by auscultation and, if available, mobile ultrasound devices. Restricted availability of modern devices, a high level of ambient noise, e.g. in scenarios with high traffic intensity, and the small thorax portion that can be monitored with available methods limit their effectiveness. Monitoring of one-sided lung problems, i.e. a post-traumatic pneumothorax, requires constant manual effort and is susceptible to surrounding noise-sources. Electrical Impedance Tomography (EIT) systems provide an alternative option for regional analysis of pulmonary functions, independent of the user's expert level. It approximates the source of electrical impedance changes, e.g. ventilation or perfusion, in a cross-section of the lung in real time while enabling an objective analysis of regional temporal changes over time [2-4].

EIT is a non-invasive and radiation-free imaging technique that uses small electrical currents applied to the patient via an electrode belt. When the belt is fixated on the upper body, inner-thoracic changes in tissue conductivity can be measured as voltages between electrode pairs and used for inverse calculation of low-resolution reconstruction images [3, 5]. The technique is defined as an inverse mathematical problem since measured voltages are used to approximate the cause of their change [6]. Regional conductivity changes are calculated by using a 2.5D or 3D model to solve inverse problems and determine differences in tissue impedance [7].

Sufficient accuracy of the EIT reconstructions relies heavily on an accurate representation of the patient's anatomy and the location of the attached electrodes in the reconstruction model [8]. Many systems for clinical use provide standard reconstruction models that most likely contain deviating characteristics from the actual thorax, while electrode positions are usually pre-determined. This can lead to major impedance shifts, causing improper assessment of lung behavior. Inaccurate dimensions of the lung area or electrode positioning can rotate and shift impedance changes, thereby falsely displaying

* **Reinhard Fuchs:** Innovation Center Computer Assisted Surgery, University of Leipzig, Semmelweisstr. 14, 04107 Leipzig, Germany, e-mail: Reinhard.fuchs@medizinuni-leipzig.de
**Michael Unger, Andreas W. Reske, Thomas Neumuth:** Innovation Center Computer Assisted Surgery, University of Leipzig, 04107 Leipzig, Germany
**Andreas W. Reske:** Department of Anaesthesiology, Intensive Care, Emergency Medicine and Pain Therapy, Heinrich-Braun-Klinikum, 08060 Zwickau, Germany

a one-sided overextension of the lung, dead-spaces, shunts, or other misbehavior.

Acquiring all the necessary information to create an accurate model of the patient and electrodes is time-intensive and not feasible in emergency scenarios. There are mobile model creation methods, but to reach that goal efficiently, necessary data needs to be left out [9]. The following work focuses on the improvement of EIT reconstructions when only a limited amount of data is available. It is hypothesized that a selection of the electrode positions, the approximation of thorax shape via an elliptical fit, and an estimation of the lung dimension based on four landmarks can provide a practical reconstruction model, whose results are superior to a standard model while comparable to a detailed model created with more segmentation data.

# 2 Materials and Methods

## 2.1 Materials

In compliance with the 3R's for reduction of animals in research[1], we used suitable data from an existing institutional database. The original experiment received approval by the governmental animal ethics committee (Landesdirection Leipzig, reference number TVV38/11). From the database, we randomly obtained 5 EIT files and the corresponding CT data.
EIT measurements during the study were done using the commercially available EIT-device PulmoVista 500 (Drägerwerk AG & Co. KGaA, Lübeck, Germany). Data analysis and EIT reconstruction were done with MATLAB 2018b (The MathWorks, Inc., Natick, Massachusetts, United States) and EIDORS [10], an open-source toolbox providing functions for the forward and inverse modeling of EIT. Model generation was done with NETGEN[2].

## 2.2 Model generation

For the generation of inverse reconstruction models, 6mm CT-slices of each pig were used to create segmentations of the thorax, the lung, and the electrode positions on the surface of the pig. Segmentation information consisted of voxel addresses necessary to generate the desired shape boundary. Electrode positions consisted of 16 points close to the skin, while thorax and lung shapes contained a maximum of 40 points to avoid overload during model optimization. For lung and thorax segmentations a CT slice was chosen, which already contained a highly detailed segmented lung mask, created by a medical expert. For electrode positioning, multiple CT slices were overlapped since the EIT belt could extend over multiple slices. The detailed model was created from all segmented points.

The practical model generation used a fraction of the provided segmentation points as the basis for elliptic fitting and shape registration (lung and electrodes). The lung shape was reduced to four voxel points/landmarks acquired from the thorax/lung CT slice for the full individualized model. The four points were placed on the ventral left, ventral right, dorsal left, and dorsal right boundary of the lung area. The lung shape of the standard model was used as a template, and the counterparts of the four landmarks were chosen manually. Through a registration process between the selected landmarks in the CT and the landmarks in the template lung shape a registration process was performed with the *projective fitgeotrans* algorithm (provided by MATLAB and based on the works of A. Goshtasby [11]). The template lung shape was transformed to the desired position, rotation, and extension.

Thorax shape approximation was done by leaving out all segmented thorax points that lay below the most dorsal lung shape landmark. The remaining points were used for the least-squares elliptic fit using the algorithm of Fitzgibbon et al. [12] and create the new thorax shape. Electrode positions were reduced to eight positions, with only the ventral electrodes (#1 to #4 and #13 to #16) being used for the following fitting process. Positions of the chosen electrodes were used to calculate a transformation matrix that transforms a standard electrode shape with equidistant positioning, approximating the remaining eight electrodes' position. The algorithms for registration and transformation were the same as for the lung shape. From the transformed positions, the angle of the electrodes in relation to the thorax's center was used for the electrode localization on the surface.

A practical and detailed model was created for each pig and used for 2.5D forward model generation as well as inverse model training with GREIT [13]. As the standard model, *pig_23kg_16el_lungs* of the EIDORS toolbox was chosen.

## 2.3 Reconstruction and analysis

EIT reconstruction was done for data collected during times of mechanical ventilation after the application of blunt force thorax trauma to the ventral right part of the pig's thorax. At a sample rate of 50 frames per second, the reconstructed

[1] https://www.nc3rs.org.uk/the-3rs, Accessed 15 May 2024

[2] https://ngsolve.org/, Accessed 15 May 2024

data consisted of 5000 frames. The reference frame for reconstruction was created automatically by averaging the three frames with the lowest global voltage within the first 500 frames. After reconstruction, the tidal images of all inspirations were calculated and averaged. The values of voxels, whose magnitude does not exceed 15 % of the maximal value of the respective mean tidal image, were set to zero. For the calculation of the overlap of the mean tidal image with the lung segmentation from the CT, the sum of all ventilated voxels within the lung segmentation was divided by the total sum of ventilated voxels. Correct positioning of the CT lung mask was achieved by deleting image regions outside a bounding box, whose boundaries were the most left, most right, most ventral, and most dorsal electrodes.

# 3 Results

## 3.1 Model generation

Model generation based on the practical and detailed approach resulted in two models per pig dataset, which were used in addition to the library model provided by EIDORS. The models for dataset 381132 are presented in Figure 1. It shows the library model to the left, the practical model in the middle, and the detailed model to the right.

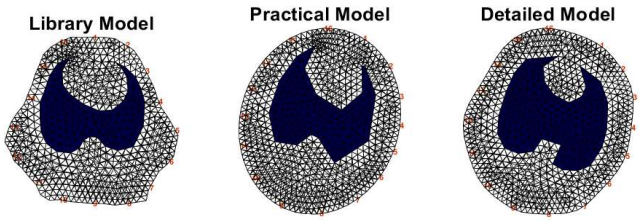


**Figure 1:** FEM model comparison for 381132; Left: EIDORS library model for pig thorax with lungs (blue); Middle: Practical model achieved with partial segmentation and fitting; Right: Detailed model achieved through complete segmentation.

## 3.2 Reconstruction and analysis

Each model was the basis for one mean tidal image, resulting in three mean tidal images per pig, i.e., fifteen tidal images. Figure 2 shows the CT image data closest to the EIT belt for dataset 381132 and its segmentation mask (far left). The mask has been reduced to its boundaries, which are shown in white. From the middle left to the far right, the figure then shows the mean tidal image of the library model, the practical model, and the detailed model respectively, each in addition to the boundaries of the segmentation mask (white) and the boundaries of the mean tidal image (light blue).

The mean tidal image of the library model shows a bigger ventilation area than the practical or detailed model, which is shown by the extension of the blue line. Results of the practical and the detailed model are comparable. The tidal image of the practical model and the mask boundaries share greater similarities in this instance. In total, the process was done for five datasets; 381128, 381129, 381132, 381135, and 381140. The results in Table 1, show the ventilation/segmentation overlap as well as the difference between the library model results and each of the models with a segmentation basis. The average difference between the ventilation/segmentation-overlap of the practical models and the library model is 12 %. The detailed models achieve an average ventilation/segmentation-overlap difference of 10 %. The maximum difference between library reconstruction and any other approach was the practical reconstruction of 381132 with 18 % more overlap.

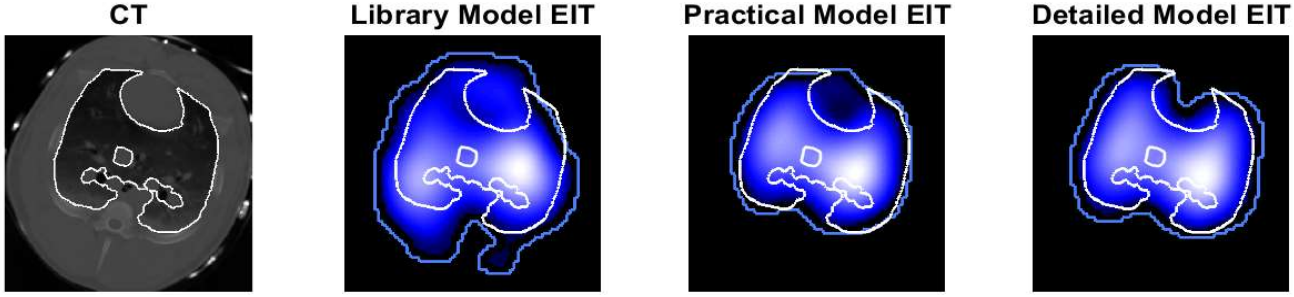


**Figure 2:** Lung area and tidal image overlap for 381132; Left: CT image in grayscale; Middle Left: Tidal image calculated with the library model of EIDORS and dataset 381132; Middle Right: Tidal image calculated with the practical approach and dataset 381132; Right: Tidal image calculated with the detailed model and dataset 381132; Ventilation boundaries are highlighted with a blue line, CT lung segmentation boundaries with a white line.

**Table 1:** Overlap between lung segmentation and active tidal image voxel for each model type with their respective differences to the library model

| Model 3811... | 28 | 29 | 32 | 35 | 40 | Mean | Std. |
|---|---|---|---|---|---|---|---|
| **Library** | 45 % | 47 % | 51 % | 50 % | 70 % | 52 % | 9 % |
| **Practical** | 62 % | 53 % | 69 % | 57 % | 80 % | 64 % | 9 % |
| Δ Library | 17 % | 6 % | 18 % | 8 % | 10 % | 12 % | 5 % |
| **Detailed** | 55 % | 54 % | 68 % | 55 % | 80 % | 63 % | 10 % |
| Δ Library | 10 % | 7 % | 17 % | 5 % | 11 % | 10 % | 4 % |

# 4 Discussion

The results of the fitting process in Figure 1 visualize how already a small amount of thorax information and electrode positions can result in a far better reconstruction model. Despite missing information, the practical model shows considerable similarities with the detailed model. This is shown especially in the position, dimension, and rotation of the lung area as well as electrode rotation. With only four registration points used for transforming an existing lung shape, the distances between the thorax surface and the lung area are improved significantly. The reconstruction results and their overlap with the lung segmentation prove the benefit the practical approach can have for the analysis of EIT data. Every reconstruction displayed ventilation data, being shifted into the lung area, which can be considered as an information gain. The maximal ventilation/segmentation overlap was reached with the practical approach instead of the detailed model.

One explanation might be that, due to the nature of the EIT reconstruction, ventilation reconstruction does not stop at the lung border (see Figure 1, blue voxels) but extends into its neighboring areas, i.e., tissue with higher conductivity (see Figure 1, white areas). The fitting process of the practical model created an elliptic pig thorax with a larger volume and used a lung shape with a larger heart region, resulting in a more compact reconstruction that focuses on the segmented lung area. This provides a bigger overlap but less resolution.

Overall, the initial hypothesis that a small amount of data can provide a superior construction model when compared to a standard model is proven. The chosen fitting algorithms approximate a sufficient shape to gain a significant shift in image ventilation data and allow for tidal images that correspond more with image data acquired with CT.

**Author Statement**

Research funding: The author states no funding was involved. Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

## References

[1] Höfer C, Lefering R (2020) Annual Report 2020 (in german). In: TraumaRegister DGU. https://www.traumaregister-dgu.de/fileadmin/user_upload/TR-DGU_Jahresbericht_2020.pdf. Accessed 14 May 2024

[2] Teschner E, Michael I, and Steffen L, 'Electrical Impedance Tomography: The Realisation of Regional Ventilation Monitoring', 152

[3] Frerichs I et al., TREND study group (2017) Chest electrical impedance tomography examination, data analysis, terminology, clinical use and recommendations: consensus statement of the TRanslational EIT developmeNt stuDy group. Thorax 72:83–93.

[4] Muders, Thomas, Henning Luepschen, and C. Putensen, 'Regional Ventilation Delay Index: Detection of Tidal Recruitment Using Electrical Impedance Tomography', in Yearbook of Intensive Care and Emergency Medicine 2009, 2009, pp. 405–12

[5] Brown BH (2003) Electrical impedance tomography (EIT): A review. J Med Eng Technol 27:97-108,.

[6] Barber DC, Brown BH (1984) Applied potential tomography. J Phys [E] 17:723–733.

[7] Holder DS (2004) Electrical Impedance Tomography: Methods, History and Applications. CRC Press

[8] Schilling T, Bauer M, Biskup C, Haverich A, Hassel T. Engineering of biodegradable magnesium alloy scaffolds to stabilize biological myocardial grafts. Biomed Eng-Biomed Tech 2017;62:493–504.

[9] Dussel N, Fuchs R, Reske AW, and Neumuth T, 'Automated 3D Thorax Model Generation Using Handheld Video-Footage', International Journal of Computer Assisted Radiology and Surgery, 17.9 (2022), 1707–16

[10] Adler A, Lionheart WRB, Uses and abuses of EIDORS: An extensible software base for EIT, Physiological Measurement, 27(5) 25-42 (2006)

[11] Goshtasby A "Image Registration by Local Approximation Methods." Image and Vision Computing 6, no. 4 (November 1988):S 255–61.

[12] Fitzgibbon A, Pilu M, and Fisher RB, 'Direct Least Square Fitting of Ellipses', IEEE Transactions on Pattern Analysis and Machine Intelligence, 21.5 (1999), 476–80

[13] Adler A et al., 'GREIT: A Unified Approach to 2D Linear EIT Reconstruction of Lung Images', Physiological Measurement, 30.6 (2009), 35–55.