RAD Conference Proceedings, vol. 8, pp. 59–63, 2024
ISSN 2466-4626 (online) | DOI: 10.21175/RadProc.2024.12
www.rad-proceedings.org

OPTIMIZATION OF THE ACCURACY OF THE ELECTRICAL IMPEDANCE TOMOGRAPHY IMAGES OF THE LUNG

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Abstract. *Electrical impedance tomography (EIT) is a non-invasive method for monitoring of lung ventilation at the bedside. To improve the personalization and increase the information value of the method, optimization of the accuracy of the lung EIT images must be achieved. The main goal of the study was to develop a methodology for individualized reconstruction of the EIT images. The investigation includes computer tomography (CT) and electrical impedance tomography (EIT) data of two mechanically ventilated trauma patients with pulmonary contusion, admitted to the Department of Anesthesiology and Intensive care, University hospital "St. George" (Plovdiv, Bulgaria). Following a CT scan analysis, a fem mesh is used for determination of the contour of the patient's thorax. Subsequently the raw EIT data is reconstructed in the resulting individualized contour. A protocolized approach to the individual patient is created. As a result of a comparative analysis between the lung areas on the CT image and the reconstructed EIT image taken at the corresponding thoracic level, the spatial morphological sensitivity of the EIT is determined (% of overlapping conformity > 82%). Thus, overcoming the limitations for placing the EIT electrodes at different than initially recommended positions, enables the clinical application of EIT in conditions characterized by heterogeneously disseminated or solitary lesions occur. The personalized approach reveals the EIT potential to provide sufficient spatial resolution and image accuracy to support the optimization of mechanical ventilation, especially in case of heterogeneously disseminated or solitary lesions. It enables EIT practical application as a hybrid method for image diagnostics and monitoring of the pathophysiological changes in ventilation and perfusion in pulmonary contusion.*

Keywords*:* *EIT, electrical impedance tomography, lung ventilation monitoring, personalized monitoring*

1. INTRODUCTION

Electrical impedance tomography (EIT) is a non-invasive method [1] for personalized monitoring [2],[3] of lung ventilation at the bedside. The EIT devices are significantly informative [4] about the characteristics [5] of lung function, caused by different heterogeneous pathological conditions [6]–[9] leading to inadequate gas flow distribution. Electrical impedance tomography (EIT) is used to evaluate lung mechanics [10] and support mechanical ventilation [11]. The informational value of the method is significantly reduced [12] since there are no guidelines for sufficient personalization of the acquired data. Another reason is the lack of clear recommendations for optimal placement [13] of the EIT electrodes. It results from the absence of instructions on determining the level of interest. Thus, there is no possibility to correct the data of the raw EIT images in accordance with the patient's anatomic characteristics and create reliable images with high resolution. Nevertheless, the application of the EIT at certain levels [14] of the thorax restricts its ability to assess the pathological process development if it is located elsewhere. To improve the personalization and increase the information value of the method, optimization of the accuracy of the lung EIT images must be achieved.

2. METHODS AND MATERIALS

The investigation is made on anonymized raw data from the EIT monitor (Swisstom BB2 EIT Monitor and Drager PulmoVista 500) in comparison with thoracic CT scans (Siemens Somatom Definition AS) of two mechanically ventilated trauma patients with pulmonary contusion, admitted to the Department of Anesthesiology and Intensive care, University hospital "St. George" (Plovdiv, Bulgaria). In our protocol we have chosen the CT as a reference method. Following a CT scan analysis, the level of interest was defined as the most significant intersection between the injured lung zones and the electrodes' plane. In order to optimize the accuracy of the EIT images on an individualized thoracic contour, we implemented a dedicated two-dimensional (2D) finite element method (FEM) mesh-based reconstruction process. Subsequently the raw EIT data was processed within this personalized contour, followed by a reconstruction of the raw EIT image, reflecting patient anatomical characteristics.

3. RESULTS AND DISCUSSION

The pathological processes could cause heterogeneous lung tissue [15] alteration, which could not correspond to the recommended levels [13] for

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positioning of the EIT electrodes thus compromising the results [16]. To overcome this limitation, we provide researchers with methodology for optimization of the accuracy of the electrical impedance tomography images of the lung.

3.1. Process description

A personalized approach to the individual patient was created. Based on the CT scan analysis we define the level of interest (topographically described with skin markers and angles) as the slice containing the largest intersection area of the investigated pathological process (Fig. 1A and 1B). Fig. 1A presents a thoracic CT scan of a patient with lung contusion. This level (indicated in green) is significantly higher than the recommended by the vendor V intercostal space (indicated in red). Therefore, in patients with lung contusion at a level different than V intercostal, the standard placement of the EIT electrodes would not provide reliable information about the distribution of lung ventilation in the injured zones.

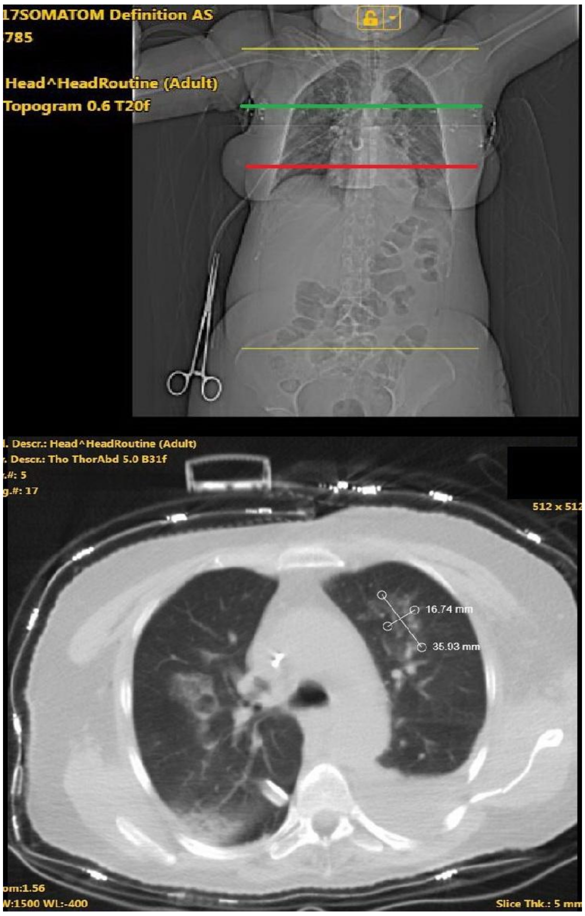

Figure 1A. A CT scan of the thorax of patient 1

On Fig. 1B is presented a 3D reconstruction of a patient's thorax. As a result of severe trauma there is a significant deformity of the chest wall on the right side and lung contusions. According to the study protocol the level at which was the largest intersection with the injury was selected. The radiologist proposed topographic markers for optimal electrode placement (Fig. 1B). Such positioning ensures that the raw EIT image will contain the information required for the analysis of the injured zones.

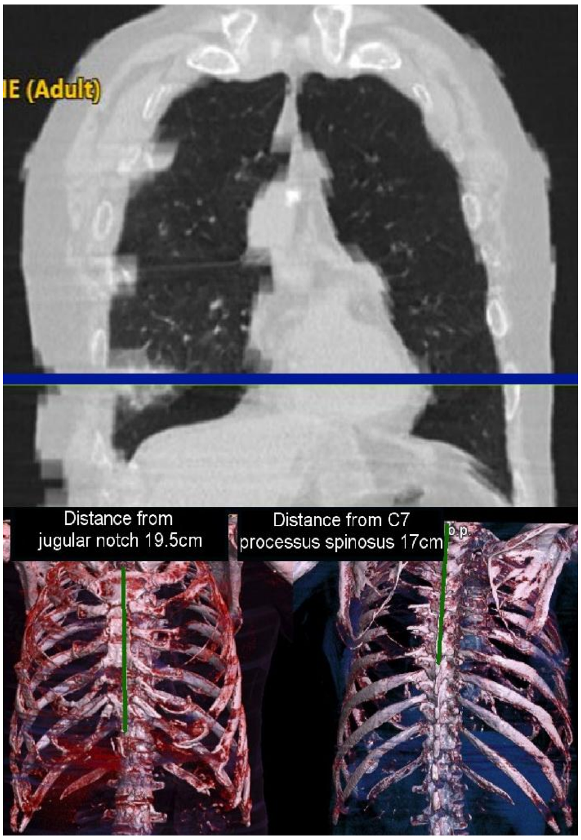

Figure 1B. A CT scan and 3D reconstruction of the thorax of patient 2

The initial EIT image by default has a circular shape (Fig. 2). Therefore, the primary signal in every pixel of the raw image would not correctly represent the impedance values generated in the patient's thorax. The resolution of the EIT image is low and there is no correspondence to the real anatomy of the patient's thorax.

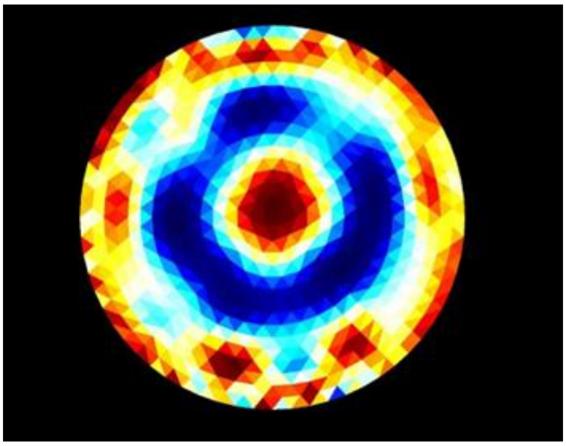

Figure 2. Initial non-personalized EIT image of patient 1

To support the EIT image reconstruction optimization, a two-dimensional fem mesh was created together with a rationale how to use it for precise matching of the intersection of the patient thorax obtained by CT with the EIT image and increase the informational value of the EIT images at the unconventional level of interest.

The EIT data reconstruction algorithm could be summarized in the following steps:

- Input acquisition and pre-processing

The raw EIT signals from the Swisstom BB2 and Dräger PulmoVista 500 devices consist of voltage measurements collected from electrode arrays placed around the thoracic perimeter.

Simultaneously, a CT scan slice corresponding to the level of interest is selected to obtain the patient-specific thoracic contour, which serves as a basis for the FEM mesh generation.

- Mesh generation

A 2D FEM mesh comprising approximately 22,600 elements, at a nominal resolution of 5×5 mm is employed.

Key anatomical landmarks identified on the CT slice are used to place 16 Cartesian points along the outer contour. Four points define the antero-posterior and transverse thoracic diameters, while the remaining twelve points ensure proper curvature along each quadrant without overfolds.

- Model constraints and boundary conditions

The center of the mesh is fixed based on the intersection of the horizontal and vertical diameters identified on the CT slice.

Boundary conditions assume equipotential reference nodes at the electrode level.

- Reconstruction approach

The EIDORS open-source routines are adapted to incorporate the patient-specific mesh coordinates.

A back-projection GREIT iterative solver is applied to estimate the impedance distribution within the patient-specific topographic mesh. Once numerical stability is confirmed, the final output is a color-coded 2D representation of conductivity changes mapped onto the individualized patient contour.

- Output and validation

The resulting reconstruction provides an EIT image that more accurately reflects the patient's thoracic anatomy at the selected level. Mesh constraints prevent topological overlaps, ensuring that each element corresponds to a distinct region of the thorax.

In contrast to the majority of the EIT reconstruction protocols a new topography for nonlinear approximation is applied.

The fem-mesh (1) is over-imposed on the referent image corresponding to the level of interest, and the points of the mesh are placed on the contour of the patient's thorax, resulting in spatial definition of the thoracic borders (Fig. 3).

As the fem mesh is set the raw data from the EIT device is imported and a new static EIT image is generated.

The result is a color-coded two-dimensional fem diagram representing the body composition of the patient in that specific slice and reflecting the electrical impedance sensitivity to water and air. It contains no patient identification or protected data information.

3.2 Protocol application

The application of the personalized approach for reconstruction of the EIT images, resulted in significant conformity between the CT scan and the EIT image taken at the same thoracic level (Fig. 3).

The location and the extent of contusions, pleural effusions, or infiltrates seen in the CT images are compared to the corresponding low-impedance regions in the EIT images. By applying this patient-specific reconstruction algorithm, the spatial accuracy of EIT-based assessments is enhanced, particularly when the standard electrode plane does not coincide with the region of clinical interest.

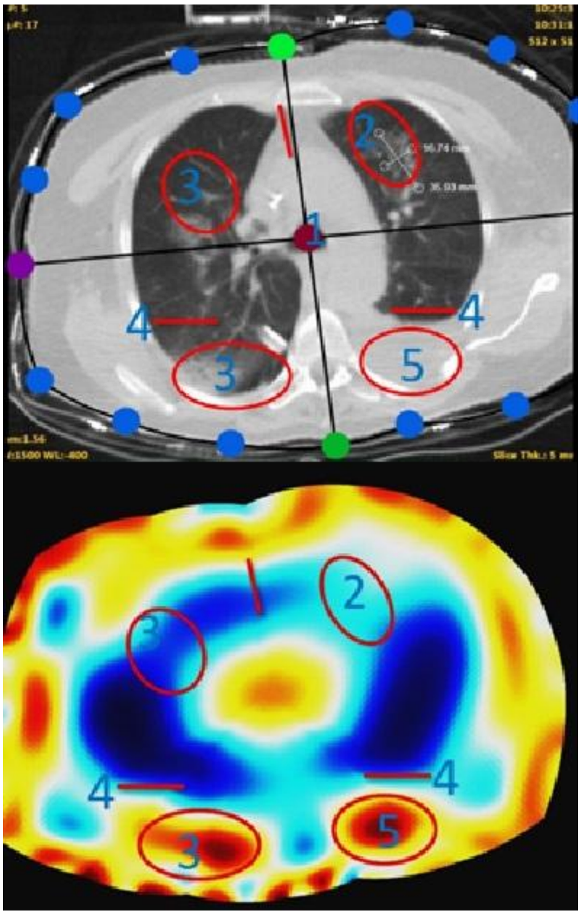

Figure 3. Comparison between CT scan image and the personalized reconstructed EIT image of patient 1

The impedance was not equally distributed. Several abnormality zones were marked and compared with the corresponding zones of the CT image (1 – fem mesh, 2 – lung contusion, 3 – infiltration, 4 – hydrostatic level, 5 – pleural effusion). The visual analysis revealed considerable sensitivity of the EIT to gas and water distribution [17], [18].

Dorsally and bilaterally on the EIT image an impedance abnormality with horizontal ventral border was observed. On both sides of the CT scan, signs related to water accumulation were visible. On the left there was pleural effusion (5) and on the right infiltrative process (3). It is important to point out that the ventral margin of the pleural effusion on the CT scan matched the change in the impedance distribution (4) on the EIT image. In contrast, the ventral margin of the infiltrative process was lower than the corresponding change in the impedance (4), suggesting that the electrical impedance tomography provides higher sensitivity to the changes in water distribution than the CT scan but lower resolution. EIT abnormalities reflect the tissue function alteration and visualize prospective changes prior to organized structural changes [19]. Different factors affect water accumulation and the impedance changes in these two pathological focuses. Pleural effusions are poor of biological membranes in the liquid [20]–[22] and gravity is a major factor. The infiltration is related to inflammation that results in water accumulation in the lung tissue due to changes in biological membrane permeability and is dependent on gravity and lung tissue architecture (vascularization and ventilation in the segments). In these regions restricted distribution of ventilation [23], [24] is observed on dynamic images. Considering the differences in pathophysiology further investigation should be carried out.

Due to the thoracic deformation standard and personalized EIT images differ significantly (Fig. 4A).

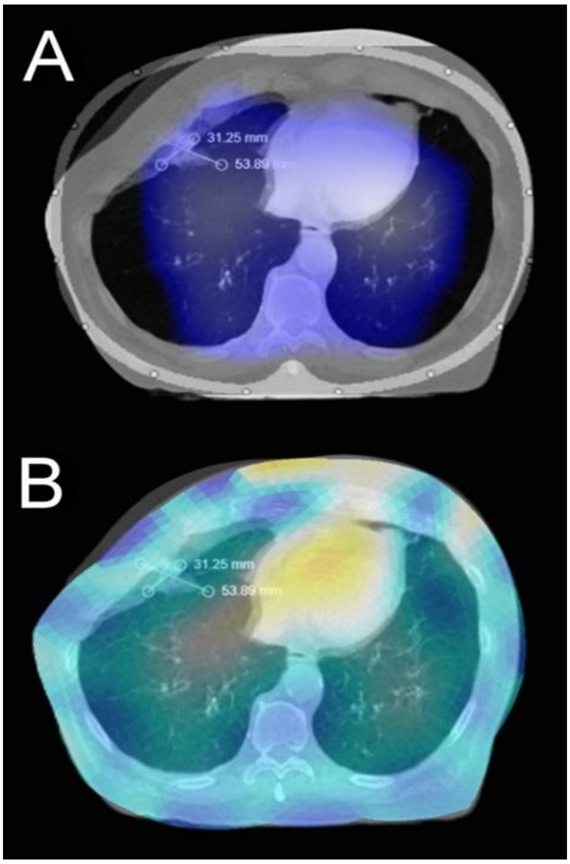

Figure 4. Comparison of spatial conformity between a standard EIT image/CT scan and a personalized EIT image/CT scan of patient 2

The altered chest and lung mechanics are not correctly represented on the standard EIT image, where a standardized contour of the "patient's" thorax and a blend present unreliable image with low spatial resolution that gives a very simplified idea of what and where it happens. Although the chest deformation suggests impaired ventilation in the ventral region of the right lung, on the standard EIT image (Fig. 4A) the ventilation in this area is visualized better than in the dorsal region.

This personalized static EIT image should "perfectly" fit over a CT scan obtained at the same level of interest. As a result of a comparative analysis between the lung areas on the CT image and the reconstructed EIT image taken at the corresponding thoracic level, the spatial morphological sensitivity of the EIT is determined (% of overlapping conformity > 82%) (Fig. 4).

Thus, results in increased informational value concerning the spatial resolution of the images. The color coding of impedance distribution improves structural recognition and spatial evaluation of gas flow distribution, reflecting patient's anatomic characteristics.

Overcoming the limitations for placing the EIT electrodes at different levels than initially recommended [13], [16], reveals potential for broader clinical application of EIT [15].

4. Conclusion

The personalized approach reveals the EIT potential to provide sufficient spatial resolution and image accuracy. It significantly improves EIT clinical application for monitoring and optimization of mechanical ventilation.

In addition, new indications for clinical application of EIT in conditions characterized by heterogeneously disseminated or solitary lesions occur.

Furthermore, it enables EIT practical application as a hybrid method for image diagnostics and monitoring the dynamics of pathophysiological changes in ventilation and perfusion following pulmonary contusion at the bedside.

Acknowledgements*: The paper is a part of the research done within the Project BG05M2OP001-1.002-0005 - Competence Center "Personalized Innovative Medicine (PERIMED)", financed by Operational Program "Science and Education for Smart Growth", EU, ESIF and Project NO-08/2021 "Investigating the capabilities of EIT as a clinical method for monitoring lung injury dynamics in patients with thoracic trauma", MU-Plovdiv.*

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