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# EVALUATION OF 3D CURRENT INJECTION PATTERNS FOR HUMAN LUNG MONITORING IN ELECTRICAL IMPEDANCE TOMOGRAPHY

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## ABSTRACT

Electrical impedance tomography (EIT) is a non-invasive imaging technique for monitoring the lungs continuously. During EIT Measurements, currents propagate intrinsically in 3D, since electrical current propagates diffusely in the human tissues, so a 2D EIT remains not sufficient to study the out-of-electrodes plane effects on the images. Until now, not enough effort has been made to evaluate the performance of 3D measurement patterns for lung monitoring. In this paper, to investigate 3D current injection patterns for 3D EIT, a 3D model mimicking the geometrical and electrical characteristics of the human thorax has been developed based on Finite Element Method (FEM) along with the Complete Electrode Model (CEM). Simulations have been performed with aligned ("planar," "zigzag", "square", "zigzag opposite", and "planar opposite"), and offset ("planar offset", and "zigzag offset") current injection patterns. Analysis shows the greatest current density diffusion results using the "zigzag opposite" current injection pattern.

***Index Terms –*** Electrical Impedance Tomography (EIT), lung monitoring, 3D injection patterns, Finite Element Method (FEM), Complete Electrode Model (CEM).

## 1. INTRODUCTION

Electrical Impedance Tomography (EIT) is a non-invasive medical imaging technique. It can monitor lung functions in real-time and over long periods. In most cases, 2D imaging is carried out, where one plane of equidistant electrodes is fixed on the human thorax to reconstruct a 2D image of the conductivity distribution in the same plane. 2D imaging is not sufficient to distinguish out-of-electrodes plane contributions or volumetric image effects. The volumetric images can be calculated using more than one electrode plane.

The main research toward 3D EIT has been led by A. Adler in [1, 2]. In this study, characterization and evaluation of several 3D injection patterns have been elaborated based on image reconstruction resolution. The previously mentioned studies has been performed on circular water tank phantoms. In [3], a circular water tank study has been conducted to investigate the 3D patterns using distinguishability criteria by calculating the Signal to Noise Ratio (SNR). The study in [4] explored experiments on the 3D patterns based on image reconstruction. Other studies evaluated the breast [5, 6] volumetric imaging and assessed 3D injection patterns based on the images quality metrics. In [7], the current density has been calculated to evaluate the heart activity to determine the ventilation ratio that serves in the heart and lungs monitoring.

In this work, an evaluation metric is performed based on the current density diffusion within the lungs model using FEM simulation results without the need of reconstructing the 3D images. This study seeks to gain time and effort for the evaluation and estimation of the most suitable injection pattern for lung monitoring, as well as the analysis and implementation of optimal and novel current injection patterns for lung volumetric imaging.

This paper is structured into four sections. The first section resumes the theoretical presentation of the EIT forward problem calculation. In the second section, the proposed realistic model as well as the evaluation metric are discussed. The third section shows the comparative study results of the 3D current injection patterns. And a final section for the conclusion and perspectives.

## 2. THEORETICAL BACKGROUND

The establishment of the EIT forward problem relies on Maxwell's equations, wherein a given conductivity distribution $\sigma$ and a specific current injection J through electrodes determine the potential distribution φ within the domain Ω, measured at the electrodes. To adhere to the quasi-static assumption, EIT employs low frequencies, allowing the neglect of inductive and capacitive effects. Under this condition, solving the forward problem involves finding the solution to the Laplace equation, represented by equation (1):

$$\nabla \cdot (\sigma \nabla \varphi) = 0 \tag{1}$$

Regarding the boundary condition, the current density injected through the electrodes, J, is described by equation (2):

$$\sigma \frac{\partial \varphi}{\partial \hat{\mathrm{n}}} = \mathrm{J} \tag{2}$$

Here, $\hat{n}$ represents the normal vector of the surface. To accurately formulate the EIT forward problem, the complete electrode model (CEM) is employed with FEM. The FEM-CEM is a widely used computational approach for solving the EIT forward problem. The CEM takes into account the complex geometry and electrical properties of the electrodes used in EIT measurements, providing a more accurate representation of the electrode interface. This model considers the contact impedance between the electrodes and the object under investigation, as well as the current spreading effect at the electrode boundaries. By incorporating these factors, the CEM improves the fidelity of the forward problem solution, enabling more precise predictions of the electrical potential or current distribution. Robin conditions are used to model shunting and conducting electrodes, as well as the contact impedance to formulate the CEM boundary condition as detailed in [8, 9].

## 3. PROPOSED APPROACH

This study was accomplished in two distinct parts. First, a thoracic and lung realistic geometry was developed to describe the anatomical shapes of the thoracic section. Then, a series of EIT FEM-CEM simulations have been conducted, followed by an evaluation metric that has been performed with the aim of investigating the most befitting current injection pattern for lung monitoring.

### 3.1 Realistic human thorax modeling

Designing a realistic geometry for EIT calculation requires careful consideration of both shape and electrical characteristics to ensure accurate FEM simulation results. The shape of the geometry should mimic the actual thorax region to be imaged, considering its size, contours, and internal structures. It is crucial to accurately represent the boundaries and interfaces within the geometry, as they significantly influence the propagation of electrical currents and impedance distribution. Furthermore, the electrical characteristics, such as the electrical conductivity σ and the relative permittivity $\varepsilon_r$, needs to be assigned to different regions within the geometry with precision. By meticulously designing the geometry with realistic shape and electrical characteristics, EIT calculations can provide reliable insights into impedance distribution. To achieve this, a combination of imaging techniques and computational modeling methodologies is employed. High-resolution computed tomography (CT) scans are used to acquire detailed 3D data of the chest region.

The acquired CT imaging data is then processed and converted into a digital 3D model using specialized software. This process involves segmenting the different anatomical structures present in the human chest, including the lungs, and soft tissues. Various imaging processing techniques, such as thresholding, region-growing algorithms, smoothing, and manual editing, are utilized to accurately isolate and delineate each anatomical component. The final true 3D model of the human thorax is composed of the skin, fat, muscle, and lungs, with a belt of 32 electrodes arranged in two belts, as shown in Figure 1. The electrodes are equally positioned around the human thorax model in two configurations, aligned and offset.

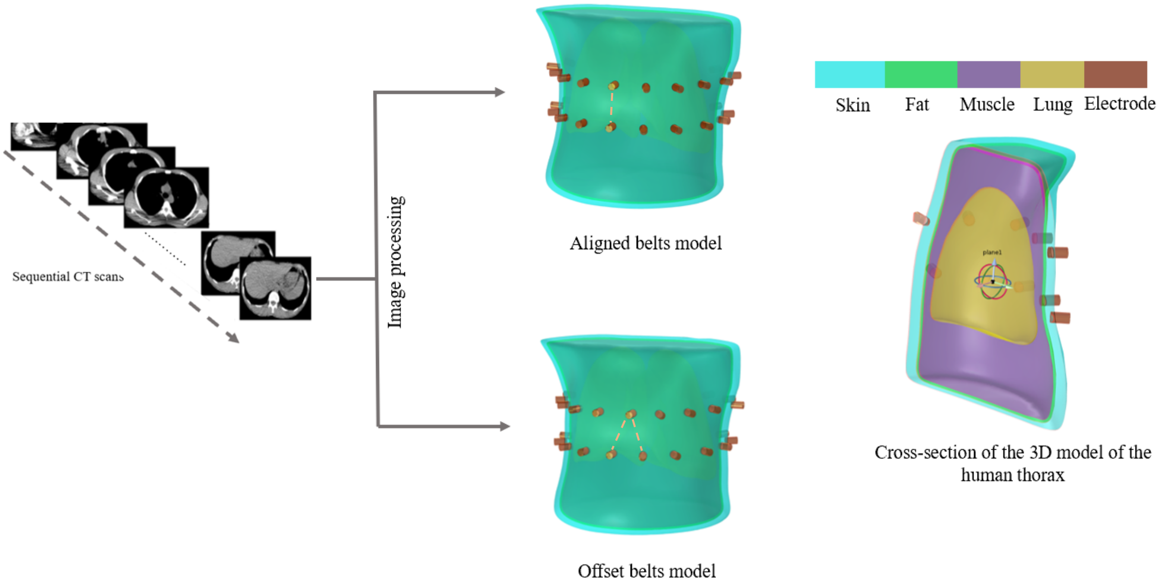


**Figure 1.** Thorax models established using sequential CT scans

Once the 3D model is created, it serves as the basis for constructing the FEM simulation model along with the CEM boundary condition. The model consists of a mesh composed of 437032 interconnected tetrahedral elements, each representing a discrete volume within the chest. The mesh is refined in areas of interest, such as regions close to electrodes, and regions of anatomical complexity, to capture finer details and ensure accurate representation.

Later on, a comprehensive evaluation of the FEM mesh quality, considering critical features mentioned in Table 1, before proceeding with FEM EIT simulations using COMSOL Multiphysics 6.1, as it is crucial to ensure accurate and reliable results. Poor mesh quality can make it difficult for the FEM solver to converge to a stable solution. In the following table, the optimal mesh quality features are represented which are obtained after remeshing and smoothing the model to converge the FEM solver. The mesh quality features should be less than 0.8. All the features are between 0.5 and 0.7 which is an acceptable range in our application. The final optimal mesh is represented in Figure 2.

**Table 1:** Mesh quality evaluation features

| | Skewness | Maximum angle | Growth rate | Condition number |
|---|---|---|---|---|
| **Description** | Refers to the degree distortion or asymmetry the elements of a mesh | Identifies the most acute or obtuse angle formed by the mesh elements | Measures the relative change in element size from one part of the mesh to another | Quantifies how sensitive the solution of a problem is to changes or perturbations in the mesh |
| **Value** | 0.65 | 0.7 | 0.61 | 0.5 |

(a) (b)

**Figure 2.** (a) Generated tetrahedral mesh model (b) Cross-section of the mesh model

Aiming to study and evaluate 3D current injection patterns used for volumetric imaging, the dielectric properties of the skin, fat, muscle, lungs, and electrodes are determined [9] for frequency $f = 50\ kHz$. An alternating current with a low amplitude of $I = 10\ mA$ is applied to the 32 attached electrodes. The contact impedance $Z_c = 10^{-6}\ \Omega.m^2$, as an initial value for investigations. Simulations are performed for both aligned ( “planar,” “zigzag”, “square”, “zigzag opposite”, and “planar opposite”), and offset (“planar offset”, and “zigzag offset”) current injection patterns as outlined in Figure 3.

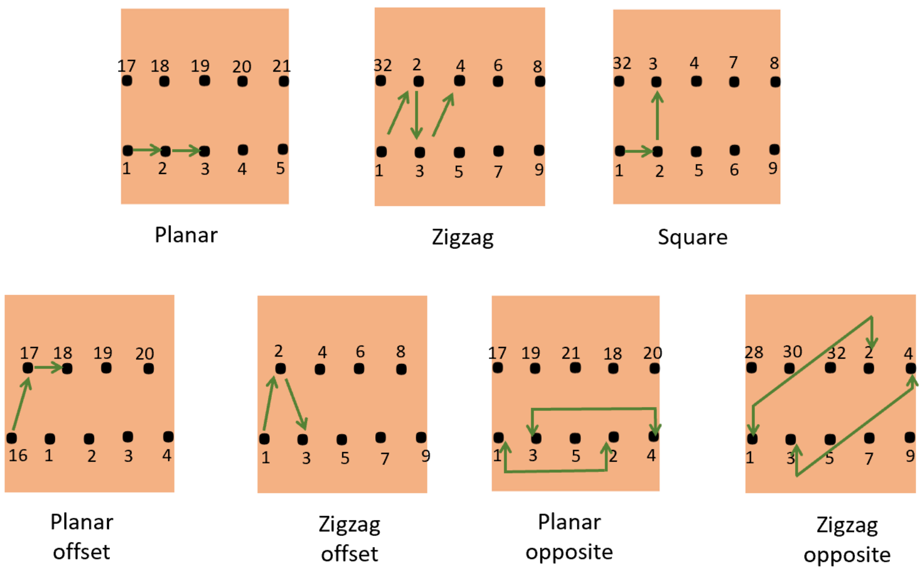


**Figure 3.** Electrode placement patterns consisting of two belts of both aligned and offset patterns

The previously mentioned injection patterns will be evaluated in the next section in terms of current density diffusion from the electrodes through the lungs.

### 3.2 Evaluation Metric: Current Density Ratio

In the evaluation of the EIT current injection pattern for human thorax application, a crucial proposed aspect lies in assessing the integral of the current density within the lungs and comparing it to that within the surrounding skin, muscle, and fat tissues. This analysis is imperative as it provides valuable insights into the effectiveness and specificity of the EIT technique in capturing thoracic lung activity. By quantifying the distribution and magnitude of current density, the degree of current penetration into the lungs can be determined and the corresponding influence on the volumetric image quality and diagnostic accuracy can be analyzed later. To evaluate the performance of the 3D current patterns, Current Density Ratio (CDR) is calculated as shown in the following equation (3):

$$\text{CDR}=\frac{\sum_{i=1}^{32}\int J_{Li}\,du}{\sum_{i=1}^{32}\int J_{Ti}\,du}\cdot 100 \qquad (3)$$

Where $J_{Li}$ is the current density in the lungs, $J_{Ti}$ is the current density in the skin, fat, and muscle, and $u$ is the model volume.

## 4 RESULTS AND DISCUSSION

Incorporating the real anatomical shape of the human chest into the FEM-CEM simulation model allows for more realistic and reliable EIT investigations. Comparing the current density in the lungs with that in adjacent tissues aids in distinguishing and minimizing potential unwanted effects in future work. CDR evaluation serves as a pivotal step in optimizing the EIT belt current injection pattern, enabling the refinement and advancement of EIT applications for thoracic imaging and physiological monitoring. The graph in Figure 4 presents a comparative analysis of the CDR for different 3D EIT injection patterns, revealing intriguing insight into their respective performances.

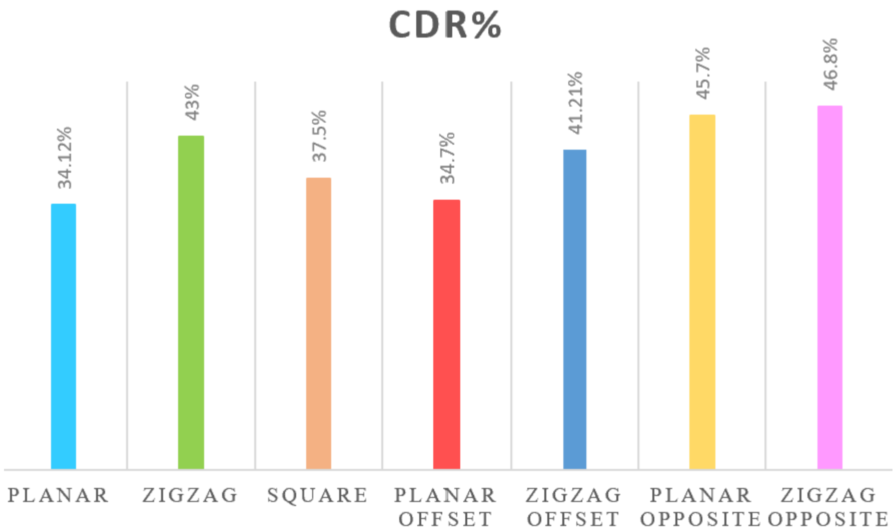


**Figure 4.** Current Density Ratio CDR in % of the 3D current injection patterns

Among the patterns examined, the highest CDR is observed in the "zigzag opposite" pattern, reaching an impressive 46.8%. Following closely behind is the "planar opposite" pattern, exhibiting a significant CDR of 45.7%. The "zigzag" pattern demonstrates a slightly lower but still notable current density ratio of 43%, while the "zigzag offset" pattern exhibits a further decrease to 41.21%. The "square" pattern showcases a comparatively lower CDR of 37.5%, while the "planar offset" and "planar" patterns demonstrate even lower ratios at 34.7% and 34.1%, respectively. Based on the graph, it is evident that the "zigzag opposite" and "planar opposite" injection patterns yield the highest CDRs, indicating their potential effectiveness in lung volumetric imaging.

Another evaluation indicator is the potential distribution resulting from FEM-CEM simulations. Figure 5 provides the potential distribution within the human thorax tissues, in addition to the current density streamlines penetration.

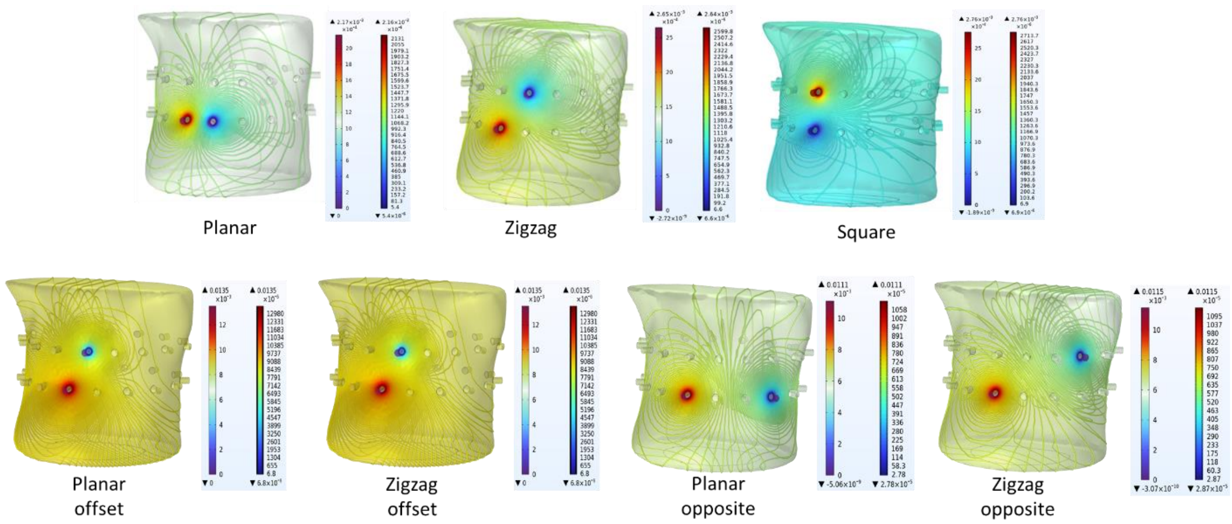


**Figure 5.** Potential distribution and current density streamlines within the human thorax model for the 3D injection patterns

The FEM-CEM simulation conducted provides significant observations regarding the current streamlines and their penetration characteristics in various 3D EIT injection patterns. Specifically, it reveals that the "zigzag opposite" pattern exhibits the highest current penetration and the least potential distribution within the outside skin. This implies that a larger proportion of the potential is effectively reaching the lungs. Additionally, the evaluation highlights that both the "planar offset" and "zigzag offset" patterns demonstrate higher penetration compared to other patterns. This suggests that these two injection patterns are particularly effective in ensuring greater current flow and potential distribution toward the lungs.

## 5 CONCLUSION AND PERSPECTIVES

This paper explores the FEM-CEM simulation capability of evaluating and characterizing the 3D EIT measurement protocol for lung monitoring. This study shows a good performance of the ”zigzag opposite” injection pattern compared to the rest of injection patterns based on the current density diffusion in the human thorax. Simulations reveals that the "zigzag opposite" pattern exhibits the highest current penetration by a CDR equal to 46.8%, with a noticeable streamlines distribution compared to the rest of the explored patterns. The initial results from the simulation present a compelling starting point for further investigation and application of these injection patterns in the context of lung-related studies. Further studies, such as the implementation of novel injection patterns,more complex human thorax geometry, and lung injury assessment can be investigated based on the proposed CDR metric.

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