Sensitivity analysis of thorax imaging using two-dimensional Electrical Impedance Tomography (EIT)

L Andiani¹, A Rubiyanto¹, Endarko*¹
¹Department of Physics, Institut Teknologi Sepuluh Nopember, Kampus ITS Sukolilo-Surabaya 60111, East Java, Indonesia

E-mail: endarko@gmail.com

Abstract. Electrical Impedance Tomography (EIT) is a non-invasive medical imaging technique which estimates the electrical impedance distribution within some tissue. The study aimed to assess the performance of the EIT system in a thorax imaging by analysis of sensitivity distribution. Sensitivity distribution was visualized using COMSOL Multiphysics simulation in a human thorax represented as an elliptic cylinder phantom consisting of homogeneous and inhomogeneous medium with varying different dimensions of 16 electrode EIT system. Current density distribution was collected for sensitivity analysis using the neighboring method. The sensitivity distribution at each position in the phantom is different. It is caused by the interaction of current density from transmitter and receiver terminal. The different varying parameter of the system can also influence sensitivity distribution. The sensitivity of inhomogeneous phantom is very non-uniformly distributed. The performance of systems was assessed by analysis of the change of sensitivity with the change of electrode dimensions in the homogeneous and inhomogeneous medium.

1. Introduction
Electrical Impedance Tomography (EIT) is an imaging technique which estimates the electrical impedance distribution within some medium [1]. In the medical field, EIT is a non-invasive medical imaging technique in which current is applied to the surface of the body through contact electrodes, and the resulting surface voltages are used in the reconstruction of images. It is a new safe methodology for use in medical applications because it does not use harmful radiations [2]. The basic principle of EIT uses a mapping of the immittance distribution (tomography) from the measurement of some passive electrical properties of tissue named bioimpedance [3]. Electrical impedance in tissues is a function of variables such as ion concentrations, cell geometry, and organ geometry, so it is easy to imagine that sensitivity to different changes in these variables may be detectable. This sensitivity imaging is used in the reconstruction of an image from EIT. The sensitivity distribution from current density of the system is affected by the layers of tissue and the dimension of electrodes. The quality of EIT image is dependent on the dimension of electrodes which is adapted to the condition of tissue that will be imaged [4].

Through sensitivity distribution analysis we can know the performance of the EIT system in medical imaging. Here we propose sensitivity distribution analysis to compare the performance of 16 electrode EIT systems in a thorax imaging with varying different dimensions of the electrode. Sensitivity distribution of EIT system is visualized considering an elliptic cylinder phantom represents a human thorax which consisting of the homogeneous and inhomogeneous medium using COMSOL Multiphysics and Matlab.
2. Sensitivity Distribution Analysis

Sensitivity is the fractional change of transfer impedance with a change of conductivity inside a particular region [4]. Sensitivity distribution of an impedance measurement gives a relation between the measured impedance $Z$ change caused by a given conductivity distribution change. If conductivity change is not involved, the measured impedance can be calculated using equation [5]:

$$Z = \int_{V} \frac{1}{2} J_{LE} \cdot J_{LI} \, dv$$  \hspace{1cm} (1)

Where $J_{LE}$ and $J_{LI}$ are the current density fields associated with the current injection and voltage measurement leads. This equation gives the contribution from each volume to the total $Z$, and the dot product of the two fields expresses the sensitivity to conductivity changes throughout the volume conductor [5].

From Shuvo’s research (2016) conducted that the sensitivity distributions showed much-localized areas of high sensitivity between the receive electrode pair and low sensitivity between the drive and receive electrode pairs at a lower depth. From the current density, the sensitivity was computed for both the homogeneous and inhomogeneous medium. At homogeneous and inhomogeneous medium, these regions of high sensitivity started diminishing, and low sensitivity region became dominant between the receive electrode pairs for higher depths down the surface as shown in figure 1. Electrical properties of tissue layers at the inhomogeneous medium influence the sensitivity [4].

![Figure 1](image1.png)

**Figure 1.** Shows the change of (a) mean sensitivity at homogeneous medium and (b) the integrated sensitivity at inhomogeneous medium with EIT system [4].

Here we use the neighboring method as the measurement method of the EIT system. The current was applied through adjacent electrodes, and the measured voltage is recorded successively from all other adjacent electrode pairs without the pairs containing one or both the current electrodes. The neighboring method shows a high sensitivity distribution near the electrode of the current source [6].

3. Material and Methods

For the 16 electrode EIT system, the sensitivity distribution is computed in several stages, namely modeling, simulation, data iteration, and data processing.

3.1. Modeling

In this study, the geometry models created were the geometry of the human thorax and the geometry of the electrode of the EIT system. All design geometries were created using COMSOL Multiphysics. Parameters design for the geometry of the human thorax represented as an elliptic cylinder phantom used the average circumference of a grown man’s thorax, which is around 1.10 m. For EIT system, design parameters for the electrode were used which consists of 16 electrodes with varying different dimensions $2 \times 2 \text{ cm}^2$ and $4 \times 4 \text{ cm}^2$. The electrode was placed according to the phantom geometry as shown in figure 2a. It is due to the limitations of the software which cannot detect two adjacent geometries. The design geometry represents the homogeneous medium in the phantom.
For inhomogeneous medium, the manufacture of the phantom with the layers of thorax tissue was created as shown in figure 2b. The layers given (from outside to inside) are skin dry with a thickness 0.01 m, muscle with a thickness 0.025 m, bone with a thickness 0.015 m, pleura with a thickness 0.02 m and lung with a diameter 0.15 m placed at coordinates (0.09;0;0) and (-0.09;0;0).

Figure 2. Design geometry of phantom at (a) homogeneous medium and (b) inhomogeneous medium.

3.2. Simulation
The simulation stage was performed using the theoretical approach of electrical current. All physical parameters used in the simulation are executed using COMSOL Multiphysics with appropriate subdomain setting, boundary setting, the solver parameter, and free mesh parameter. The physical parameters and the subdomain setting stage will be used on the design geometry and involved the setting of the material type, respectively. The relative permittivity \( \varepsilon_r \) and electrical conductivity \( \sigma \) for a frequency of 20 kHz used in this study are summarized in table 1.

| Material               | Relative Permittivity | Electrical Conductivity (Sm\(^{-1}\)) |
|------------------------|-----------------------|--------------------------------------|
| NaCl                   | 5.6                   | 9.86                                 |
| Copper                 | 1                     | \( 5.998 \times 10^7 \)               |
| SkinDry                | 1131.7                | \( 2.1417 \times 10^4 \)              |
| Muscle                 | 15521                 | 0.34488                              |
| Bone                   | 374.18                | \( 2.8959 \times 10^3 \)              |
| Body Fluid (Pleura)    | 98.837                | 1.5                                  |
| LungInflated           | 9111.3                | \( 9.7131 \times 10^2 \)              |

The limit of the extension of the capacitive electrodes was performed using boundary setting, EIT electrodes based on neighboring method. Meanwhile, the accuracy of the simulation data was done by setting the free mesh parameter. In this study, we used the normal size on the free mesh parameter. In the solver stage, the parameter is set to regulate the simulation parameters related to the study stage and physics. The purpose of this simulation was to obtain the current density distribution, so we used electrical current (ec) as the physics parameter and stationary as the study parameter. The current density values were obtained by gridding method with 32 voxels for X-axis.

3.3. Data Iteration
Data iteration stage is performed to obtain the current density values for each looping of the transmitter which connected to the current source 16 times. The iteration result was used to obtain the sensitivity distribution of the EIT system.

3.4. Data Processing
From iteration result, processing of the current density data is performed to obtain the sensitivity distribution of the EIT system. The sensitivity \( S \) for current injection \( I \) can be calculated using [4]:

\[
S = \frac{J_1 \cdot J_2 + J_{y1} \cdot J_{y2} + J_{z1} \cdot J_{z2}}{I^2}
\]

where \( J_1 \) and \( J_2 \) are the current density associated with the current injection or transmitter and receiver.
4. Results
The comparison of simulation results based on the dimension of the electrode for the homogeneous and inhomogeneous medium are presented separately.

4.1. Homogeneous Medium
Figure 3 shows the comparison of sensitivity distribution of the first stimulation port in X-axis for the elliptic cylinder phantom of homogeneous from simulation and data processing. In figure 3a, the red color shows high sensitivity and the blue color shows low sensitivity. The sensitivity is equal to current density, and the current density is also equal to electric current flow. The red regions are on an electrode injected by the current and the regions close to the electrode. In figure 3b, the horizontal axis is the X-axis which shows some measurement and the vertical axis represents a mean sensitivity value at the region. The peak of the sensitivity distribution graph shows a high sensitivity which is on a current source. From references, at a high sensitivity, an object can be detected as very well in the region [3].

![Figure 3](image)

Figure 3. Sensitivity distribution of X-axis of the first stimulation port for the elliptic cylinder measurement in a homogeneous medium from (a) simulation and (b) data processing.

The combination of sensitivity distribution for all stimulation ports is shown in the form of different lines as shown in figure 4. Figure 4 also shows the comparison of sensitivity distribution with the electrode’s dimension of $2 \times 2 \text{ cm}^2$ and $4 \times 4 \text{ cm}^2$.

![Figure 4](image)

Figure 4. Sensitivity distribution of X-axis of all stimulation port with varying different electrode’s dimension of (a) $2 \times 2 \text{ cm}^2$ and (b) $4 \times 4 \text{ cm}^2$.

The sensitivity distribution shows many localized areas of the high sensitivity value between the transmitter and the receiver and the low sensitivity value between the receivers of the electrode pair. The sensitivity value of each line on a plane had been found to decrease exponentially with the distance of transmitter. The change of sensitivity distribution with the change electrode dimensions had also been
The peak of sensitivity distribution at a small dimension is higher than at a large dimension even though the sensitivity distribution pattern of the large electrode’s dimension is more tightly and more organized than the small electrode’s dimensions. It is in accordance with ohm law that the cross-sectional area is inversely proportional to the current density, and the sensitivity is equal to the current density. From Shuvo’s research using the tetrapolar EIT system, sensitivity changes linearly against the change of electrode dimensions (radius) inhomogeneous medium [4]. So, the result of this study the same as a result of previous research. We get that the performance of the EIT system with the small electrode’s dimension can detect an object as very well with high sensitivity distribution at the various positions.

4.2. Inhomogeneous Medium

The sensitivity distribution of the inhomogeneous medium shows different results than those of homogeneous medium. Figure 5a shows the sensitivity distribution of the X-axis for the inhomogeneous medium from simulation and Figure 5b shows the mean sensitivity graph from data processing.

From the simulation result analysis, we know that electrical properties of tissue can also influence the sensitivity distribution. It is indicated by the color degradation in the muscle layer which has high electrical conductivity and the blue color in the other layers which have low electrical conductivity. The simulation result of this study is similar to a study conducted by Shuvo. From his research that uses different conductivity values in the five cylindrical layers, a high sensitivity distribution is only in the muscle layer with high electrical conductivity while the distribution color in other layers is blue which states a low sensitivity [4]. Based on Ohm’s law, we know that electrical conductivity inversely proportional to current density.

The combination of sensitivity distribution for all stimulation ports is shown in the form of different lines as shown in figure 6. Figure 6 also shows the comparison of sensitivity distribution with the electrode’s dimension of $2 \times 2$ cm$^2$ and $4 \times 4$ cm$^2$. The sensitivity distribution pattern of the inhomogeneous medium is very non-uniformly than the homogeneous medium even though the sensitivity value of the medium is more highly than the sensitivity value of the homogeneous medium. It is due to the different conductivity of each tissue layers. The different conductivity of the tissue layers can affect the performance of the EIT system in the detecting an object in the phantom. In the thorax imaging, an EIT system that can detect an object well is necessary. As explained by Shuvo in his research for human upper arm analyze using tetrapolar EIT system, the adjustment of sensitivity distribution with tissue layers is necessary to get the best performance of EIT system in the imaging [4].
The change of sensitivity distribution with the change of electrode’s dimension is not significant in an inhomogeneous medium. It fact tend a similar result which is analyzed by Shuvo using a relation graph between integrated sensitivity and drive-receive separation (a distance between electrodes) [4]. In the graph, be found that the integrated sensitivities between two adjacent distance point are almost the same. In the study, we know that a distance between the electrodes of the system with small electrode dimension is larger than a system with a large electrode dimension, but the comparison of both is not significant.

5. Conclusion
The performance of systems was assessed by analysis of the change of sensitivity with the change of electrode dimensions in the homogeneous and inhomogeneous medium. The sensitivity distribution of the EIT system with the large electrode’s dimension can detect an object at the various positions inhomogeneous medium and the sensitivity distribution in an inhomogeneous medium is influenced by the different conductivity of tissue layers. The adjustment of sensitivity distribution with tissue layers of the human thorax is necessary to get the best performance of the EIT system in the thorax imaging.

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