Electrical Capacitance Tomography (ECT) Electrode Size Simulation Study for Cultured Cell

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Abstract. Cell sensing and monitoring using capacitive sensors are widely used in cell monitoring because of the flexible and uncomplicated design and fabrication. Previous work from many different fields of applications has integrated capacitive sensing technique with tomography to produce cross-sectional images of the internal dielectric distribution. This paper carried an investigation on the capabilities of four 16-channel sensor electrodes with different electrode sizes to detect the change in the dielectric distribution of the cultured cells. All three 16-channel sensor electrodes are designed and simulate on COMSOL 6.3a Multiphysics. The pre-processing results obtained from three finite element models (FEM) of ECT sensor configurations in detecting the cell phantom shows that bigger electrodes size are more sensitive to permittivity distribution.

1. Introduction

Electrical capacitance tomography (ECT) is mostly used in oil and gas industries to monitor and image the multiphase flow in the pipelines [1][2]. Ever since the application of electrical tomography using impedance measurements to image the cell culture, research interest in ECT has spiked to investigate the feasibility of ECT in the same area of application. Its feasibility has been proved elsewhere [3-5] where the behaviour of the cells is monitored via microscopy technique and quantitatively studied using capacitance measurements. Studying the cell’s behaviour has a significant contribution to drug screening
and development and understanding human diseases. The conventional method in studying the cell behaviour is through microscopic techniques, which mostly invasive and destructive because of its preparation procedures and the employed radiation light [5, 6]. These drawbacks bring an opportunity for investigating a new imaging technique that is competent to non-invasively and non-destructively image the cells in its culture medium. Such imaging technique is electrical capacitance tomography (ECT) where the sensors, in the aspect of sensor design, are uncomplicated and flexible, with relatively low-cost fabrication. However, ECT suffers from the soft-field effect which results in poor image spatial resolution. Thus, the recent development of ECT is focusing on developing a sensor that will give a high spatial resolution of the reconstructed image of the dielectric distribution.

One of the key factors influencing the performance of ECT is the design of the sensor configuration. The design of the sensor configuration encompasses the position of the electrodes either inside or outside of the wall or embedded between the inner wall and outer wall which depend on the dielectric material that is to be monitored [7]. For example, the sensor electrode is designed outside of the wall to prevent short circuit cases due to high conductivity material is in contact with the sensor electrodes. By increasing the number of electrodes in the sensing region will increase the spatial distribution of the electrical field from the excitation electrode to the receiving electrode. The electrical field caused a change in the internal distribution of the dielectric material while receiving electrode measuring the changes in capacitance. Therefore, full coverage of the electrical field on the dielectric material will increase the spatial resolution of the reconstructed image. The physical properties of the electrode such as the geometry and surface area of the electrode also contribute to the spatial distribution of the electrical field. Increasing the axial length of the electrode will bring the electrodes close to the adjacent electrodes which also limits the number of electrodes that can be used. Therefore, this paper aims in studying four FEM designs of 16-channel electrodes with different sizes on COMSOL 6.3a.

2. Electrical Capacitance Tomography (ECT)

Electrical capacitance tomography (ECT) made up of capacitive electrodes circularly arrange either inside or outside of the vessel wall containing the dielectric material. Figure 1 illustrates the proposed ECT system for monitoring the growth of yeast cells in a culture medium. This sensing technique has an advantage because of its cheap fabrication which contributes to a light weighted device. The sensor unit is made up of 16 electrodes where each electrode will take a turn to serve as an excitation plate. In the first cycle, one electrode serves as an excitation plate or transmitter while the remaining will serve as a receiver. After one cycle is complete, the next electrode will serve as the transmitter while the other electrodes serve as the receiver. This process will carry on until the full circle is complete which indicates that the process of measuring the capacitance of the dielectric distribution inside the container is done. The data acquisition system (DAQ) not only collects the measured capacitance value from the sensor unit but also responsible as a multiplexer to send the excitation signal to the electrode. DAQ will also convert these analog capacitance values to digital values. The cable connecting the computer and DAQ channel this digital data to the computer and process using an image reconstruction algorithm. The computer will serve as a visual real-time monitoring system for the growth of the cultured cell.

![Figure 1. Basic component of an ECT system](image-url)
2.1. Sensing Principle of Electrical Capacitance Tomography (ECT)

The sensing principle of electrical capacitance tomography (ECT) lies in the physical structure of the electrodes, where the basic structure of a capacitor is composed of dielectric material between two conductive plates. When an alternating voltage is applied to one of the plates, the capacitor will begin to charge and store electrical charge. The other plate will behave as a receiving plate if it is set to the ground (0 V). While one plate is supplied with an alternating voltage and the other is grounded, the plates will start to measure the value of the capacitance of the dielectric material between these plates. Many different application has developed a sensing technique based on the working principle of capacitor. Some application using the capacitive sensor only monitoring the behaviour of the cell through graphical presentation. Integrating the capacitive sensor with imaging modality such as tomography will allow real-time monitoring of the internal distribution of dielectric material through visualization on a computer screen. Research in ECT from the different field has proposed different capacitive sensor configuration. Capacitive sensor configuration varies because of the flexibility to design the sensor configuration based on the parameters depicted in equation (1) [8].

\[ C = f (d, A, \varepsilon_r) \]  

where,
\[ C \] = capacitance of the capacitive sensor
\[ d \] = distance of two electrodes
\[ A \] = surface area of electrode
\[ \varepsilon_r \] = relative permittivity of plate material

3. Methodology

Sensor configuration hugely impacts the image spatial resolution. Finite Element Method (FEM) analysis allows researchers to evaluate the performance of the sensor design with the control variables in a non-erroneous environment. This FEM study was conducted on COMSOL Multiphysics 6.3a to investigate the feasibility of three different sizes of electrodes in three different electrode configurations to detect the cell phantom in the sensing region. The permittivity (\(\varepsilon\)) and conductivity (\(\sigma\)) of the air, cell phantoms, and culture medium are tabulated in Table 1.

| Material          | Relative permittivity | Electrical conductivity (S/m) |
|-------------------|-----------------------|-----------------------------|
| Air               | 1.0                   | 0                           |
| Cell phantoms     | 50.6                  | 0.5                         |
| Culture medium    | 78.4                  | 1.7                         |

Table 2 and Figure 2 depicted the simulation parameters and sensor design for the three sensor configurations. This simulation study uses the sensor configuration from [9] and applied it to sensor configuration I. The purpose of the implementation of the impedance sensing principle in [9] is to investigate the sensor’s parameter feasibility for the capacitive sensing principle. Meanwhile, sensor configuration II and III is the result of an adjustment on the width and length of the electrode in sensor configuration I to explore various performance for 16 electrode sensor configuration for sensing region with a diameter of 17 mm.
Table 2. Simulation parameters for three sensor configurations

| Sensor configurations | I         | II        | III        |
|-----------------------|-----------|-----------|------------|
| Dimension (width x height) | 1.2 x 0.6mm | 1.2 x 1.8mm | 1.35 x 1.8mm |
| Material of electrodes | Copper    | Copper    | Copper     |
| Diameter of sensing area | 17 mm     | 17 mm     | 17 mm      |

Figure 2. 16-channel electrode configuration with electrode size of (a) 1.2mmx0.6mm, (b) 1.2mmx1.8mm and (c) 1.35mm x 1.8mm

4. Results and Discussions
The objective of this study is to evaluate how different sizes of electrodes impact the performance in detecting the permittivity of the cell phantom. This study compared the electrode size used in [9] and the maximum axial of electrodes that can be employed within the sensing region with a diameter of 17mm. It is important to note that increasing the axial of the electrode need to consider the space between the adjacent electrodes and the stray capacitance that may be induced. Figure 3 shows the streamlines of the electrical field projected between the excitation electrode and the receiving electrodes. Comparing the projected streamlines for all three electrode configurations, Figure 3 (b) shows denser streamlines compared to Figures 3 (a) and (c), which should result in better coverage of the sensing area. Full coverage of the sensing area will give a better visualization of the dielectric distribution of the materials in the reconstructed image.

Figure 3 demonstrates the electrical field distribution for the three sensor configurations when E1 is transmitting while the remaining electrodes (E2-E16) are receiving. The sensor measurements for all paired electrodes are tabulated and plotted in a graph, as depicted in Table 3 and Figure 4, respectively.
It is shown that increasing the size of the electrodes will increase the sensor capability to detect the capacitance of the dielectric material. Figure 4 also shows that the electrode pair of $E_1-E_2$ and $E_1-E_{16}$ for every sensor configuration measured the highest capacitance of the permittivity distribution. This is because of the location of the receiving electrode, $E_2$ and $E_{16}$ are closer to the excitation electrode, $E_1$. The plotted graph shows the declining pattern for the remaining receiving electrodes $E_3$ to $E_{15}$ due to the greater distance between the receiving electrodes to the excitation electrode [11]. Increasing the size of the electrode will bring the electrodes closer to the excitation electrode, hence higher value of capacitance is measured in sensor configuration II and III than in sensor configuration I. Referring to Figure 3, the cell phantom is located in between $E_6$ and $E_7$, where the electrical field distribution is denser compared to other regions. This phenomenon along with the parameters of the sensor configuration II contributes to its capability to detect the location of the cell phantoms through the highest capacitance value plotted at $E_1,8$. Based on the result of this simulation, for a sensing region of 17 mm in diameter, sensor configuration II achieved the optimum performance due to its capability to detect yeast phantom.

| Table 3. Inter-capacitance measurement for paired electrodes for sensor configuration (SC) I, II, and III |
|---------------------------------------------------------------|
| SC | $E_{1,2}$ | $E_{1,3}$ | $E_{1,4}$ | $E_{1,5}$ | $E_{1,6}$ | $E_{1,7}$ | $E_{1,8}$ | $E_{1,9}$ | $E_{1,10}$ | $E_{1,11}$ | $E_{1,12}$ | $E_{1,13}$ | $E_{1,14}$ | $E_{1,15}$ | $E_{1,16}$ |
|----|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| I  | 11.4     | 7.76     | 6.5      | 5.87     | 5.51     | 5.3      | 5.2      | 5.1      | 5.3      | 5.5      | 5.9      | 6.5      | 7.8      | 11.4     |
| II | 22.7     | 12.6     | 9.86     | 8.59     | 7.90     | 7.5      | 7.9      | 7.2      | 7.2      | 7.5      | 7.9      | 8.6      | 9.8      | 1.3      | 22.7     |
| III| 23.7     | 13.1     | 10.2     | 8.86     | 8.14     | 7.7      | 7.5      | 7.4      | 7.5      | 7.7      | 8.1      | 8.8      | 1.0      | 1.3      | 23.7     |

**Figure 4.** Inter-capacitance measurements of three 16-channel electrodes configurations

5. Conclusions
This study tested the established relationship of the capacitance and one of the varying parameters in sensor design, which is the surface area of the electrode. This study evaluated and discussed the capabilities of the 16-channel electrodes with increasing surface area. The simulation results are discussed and concluded that increasing surface area increases the capacitance measurements for each paired electrode. The performance of the sensor configuration in measuring higher capacitance value along with the capability to detect different permittivity distribution in the sensing region will significantly contribute to the performance of the image processing. This simulation study discovered that sensor configuration II is capable of detecting the location of the cell phantom in the sensing region through the measured abnormal capacitance value. Hence, the result of the image reconstruction where the cell phantom is clearly distinguished from its environment can be expected.
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