Two dimensional finite element method simulation to determine the brain capacitance based on ECVT measurement

S H Sirait\textsuperscript{1}, W P Taruno\textsuperscript{2}, S N Khotimah\textsuperscript{1} and F Haryanto\textsuperscript{1}

\textsuperscript{1}Physics Department, Faculty of Mathematics and Natural Sciences, Institut Teknologi Bandung, Jalan Ganesa 10 Bandung 40132, Indonesia

\textsuperscript{2}Center of Medical Physics and Cancer Research, CTECH Laboratories, Indonesia

E-mail: syarif.hussein.sirait@gmail.com

Abstract. A simulation to determine capacitance of brain’s electrical activity based on two electrodes ECVT was conducted in this study. This study began with construction of 2D coronal head geometry with five different layers and ECVT sensor design, and then both of these designs were merged. After that, boundary conditions were applied on two electrodes in the ECVT sensor. The first electrode was defined as a Dirichlet boundary condition with 20 V in potential and another electrode was defined as a Dirichlet boundary condition with 0 V in potential. Simulated Hodgkin-Huxley-based action potentials were applied as electrical activity of the brain and sequentially were put on 3 different cross-sectional positions. As the governing equation, the Poisson equation was implemented in the geometry. Poisson equation was solved by finite element method. The simulation showed that the simulated capacitance values were affected by action potentials and cross-sectional action potential positions.

1. Introduction
In the field of tomography, electrical capacitance volume tomography (ECVT) is a relatively new modality for direct 3D imaging permittivity distribution [1]. This modality was developed based on 2D permittivity imaging modality so called ECT which usually used in industry processes. ECVT utilize several capacitance sensors to collect capacitance data from its objects (forward problem) and reconstruct permittivity distribution image using appropriate reconstruction algorithms (inverse problem). ECVT has been used in multiphase flow systems include bubble columns, gas-solid fluidized beds and consider as potential imaging modality in industry [2].

Recently, ECVT has been developed for brain tumor detection [3] and study of the brain’s activity using ECVT has been proposed by Warsito et al. [4] [5]. They showed that ECVT was available to observe the activity of the brain during different kinds of simulation and motoric movement. It is possible that due to the depolarization in neuron the impedance will change [6] then the change in the impedance will possibly change its capacitance. However, it is still lack of confirmation on what specific parameters in neuron which affect the capacitance measurements.

In this simulation we used simulated action potential as electrical activity. Cross-sectional positions of action potential were varied on geometry. This paper aimed to study the effects of action potential on brain’s capacitance using finite element simulation based on 2 electrodes ECVT measurement,
but this simulation is still need to be verified using another experiment. However, the result can be used to improve ECVT’s data acquisition system for the measurement of brain activities.

2. Methodology

2.1. Head design
The head was formed from five different layers with different relative permittivity ($\varepsilon_r$) values and was assumed to be isotropic [7]. We used relative permittivity values at 2.5 MHz in corresponding to real ECVT measurement which applied 2.5 MHz in frequency. Those five layers were white matter, grey matter, CSF, skull, and skin with its permittivity values were 308, 604, 109, 93, and 799 [8], respectively, as shown in figure 1.

2.2. Sensor design
Two electrodes ECVT sensor were designed and followed the real 2 electrodes brain ECVT sensor. It consists of vessel, excitation electrode, detection electrode, axial screen, and grounded screen with its relative permittivity values are 3, 1, 1, 1, and 1, respectively as shown in Figure 1. The electrodes had 5cm in length and width. Vessel is usually used in ECVT as part of the sensor so the measurement system becomes non-invasive, and non-destructive. Axial screen and grounded screen were applied in ECVT so unwanted electrical field would not affect the capacitance measurement. Next, the head design and the sensor design were combined as shown in figure 1.

![Simulated 2D design of coronal head and ECVT sensor](image)

**Figure 1.** Simulated 2D design of coronal head and ECVT sensor.

2.3. Electrical activity
Simulated Hodgkin-Huxley action potentials were applied as brain’s electrical activity. One cycle of 6 ms action potential was used and had $1 \times 10^{-5}$s in sampling interval. We assumed that action potential was occurred at a point in the geometry. This action potential can be viewed in figure 2. Cross-sectional position was defined as distance from the center and in this case the center was point 1. Action potential subsequently was put on 3 different cross-sectional positions with point 1 on (0; 0.03), point 2 on (-0.03; 0.03), and point 3 on (0.03; 0.03). The positions of these points can be viewed in figure 1 above as pt1, pt2, and pt3.
2.4. Simulation setup

Poisson equation was implemented as the governing equation to estimate the physical phenomena in geometry like it was described in ECT [9] [10] [11] and ECVT [1] [2]. Excitation electrode was defined as a Dirichlet boundary condition with static 20 V in potential and detection electrode was defined as a Dirichlet boundary condition with 0 V in potential. Static potential was used rather than time-dependent potential to simplify the equation into electrostatic approximation. In future, time dependent potential with f=2.5 MHz could be applied but with different estimation. Axial screen and grounded screen were defined as ground. Relative permittivity in the head design and the sensor design were assumed to be isotropic. Simulated action potential was defined as a point potential and was put subsequently on point 1, point 2, and point 3 in geometry. Free charges were assumed that it did not exist in the simulation domain. Poisson equation and the boundary condition hold:

\[ \nabla \cdot \varepsilon \nabla \phi(x, y) = 0 \]
\[ \phi|_{\Gamma_i} = V : \phi|_{\Gamma_j} = 0 \]

where \( \phi(x, y) \) were potential distribution in geometry, with \( V = 20 \) volt. \( \Gamma_i \) and \( \Gamma_j \) were Dirichlet boundary condition for excitation electrode and detection electrode, respectively. Finite element method was used to solve Poisson equation for finding potential distribution. Finite element method worked and subsequentialy changed the Poisson equation into its weak formulation.

\[ - \int_{\Omega} \nabla \cdot D \, d\Omega = - \oint_{\Gamma} w D \cdot n \, dl \]
\[ D = \varepsilon \nabla \phi(x, y) \]

\( w \) as residual weight and \( D \) as electric displacement. After potential distributions had been found, the capacitance was calculated using this capacitance equation.

\[ C_{ij} = - \frac{1}{\Delta \phi_j} \oint_{A_i} \varepsilon \nabla \phi(x, y) \cdot n \, dA \]

3. Results and discussion

The entire domain was solved by finite element method. Every simulation was performed for 6 milliseconds long potential action. The simulation was run for every potential action of position in geometry. Head and sensor design were discretised using triangle element, as can be viewed in Figure 3. Meshing process were good and produced 24948 elements.

Figure 2. Simulated Hodgkin-Huxley action potential.
As can be viewed from figure 5, high potential was blocked and accumulated around the excitation electrode due to a high relative permittivity ($\varepsilon_r = 799$) value in skin layer. A potential of about 4.5 V from excitation electrode was successfully penetrated into the deepest layer and achieved the detection electrode. Hence, this potential was adequate to be used in excitation electrode. Axial screen and grounded screen were effective to block unwanted electrical field because there was no potential penetration.

Figure 5 shows that the pattern of capacitance values followed the pattern of action potential value which is shown in figure 2. Action potential from different cross-sectional position affected simulated brain’s capacitance value. Brain’s capacitance affected by action potential on point 1 had peak 0.258pF and valley 0.219pF, affected by point 2 had peak 0.286pF and valley 0.249pF, and affected by point 3 had peak 0.290pF and valley 0.250pF. All capacitance had the range of peak and valley for about 0.04pF. Capacitance that affected by action potential on point 1 had a difference for about 0.03pF with capacitance affected by action potential on point 2 and point 3 due to the difference in the cross-sectional position. Capacitance affected by action potential on point 2 had slightly difference with capacitance affected by action potential on point 3 due to the similarities in cross-sectional positions but in opposite direction.
4. Conclusions
We have studied the action potential effect to capacitance value in ECVT measurement by using finite element simulation. It showed that the capacitance values were changed simultaneously with the action potential. These simulation results a suggestion that the action potential possibly could be detected using ECVT due to its effect to the capacitance value. It also showed that the action potentials which were put on different cross-sectional positions made difference in simulated capacitance value. These differences in capacitance were happened due to the cross-sectional positions that showed a potential for ECVT as imaging modality for brain’s activity.

References
[1] Warsito W, Marashdeh Q and Fan L S 2007 IEEE Sensor Journal 7(4) pp 525-35
[2] Marashdeh Q, Fan L S and Warsito W 2008 Ind. Eng. Chem 47 pp 3708-37
[3] Taruno W P, Baidillah M R, Sulaiman R I, Ihsan M F, Yusuf A, Widada W and Aljohani M 2013 6th Annual International IEEE EMBS Conference on Neural Engineering pp 743-6
[4] Taruno W P, Baidillah R M, Sulaiman R I, Ihsan M F, Fatmi S E, Muhtadi A H, Haryanto F and Aljohani M 2013 IEEE 10th International Symposium on Biomedical Imaging pp 1006-9
[5] Taruno W P, Ihsan M F, Baidillah M R, Tandian T, Mahendra M and Aljohani M 2014 Middle East Conference on Biomedical Engineering pp 147-50
[6] Aristovich K Y, Packham B C, Koo H, Santos G S D, McEvoy A and Holder D S 2016 NeuroImage 124 pp 204-13
[7] Miranda C Pedro, Mekonnen A, Salvador R and Basser P J 2014 Phys. Med. Biol 59 pp 4137-47
[8] An internet resources for the calculations of dielectric properties of body tissues. http:niremf.ifac.cnr.it/tissprop. [Accessed February 2015]
[9] Alme K J and Mylvaganam S 2006 IEEE Sensor Journal 6(5) pp 1256-66
[10] Banasiak R, Wajman R and Soleimani M 2009 Insight 51 pp 36-9

Acknowledgment
The authors would like to thank CTech Labs in Tangerang, Indonesia for providing collaboration in ECVT research. This work was partially supported by RIK ITB 2016 (006p/I1.C01/PL/2016) and PUPT Ristekdikti 2016.