International Journal of Engineering & Technology, 7 (3.7) (2018) 601-604

SPC

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

Reconstruction of Fetal Imaging During Pregnancy with the Electrical Impedance Imaging Technique

Sravan Kumar Konki[1], Anil Kumar Khambampati[2], You Jung Han[1],Sung Yob Kim[3], Kyung Youn Kim[4*]

[1]*Faculty of Applied Energy System, Major of Electronic Engineering, Jeju National University*
[2]*BK21+ Clean Energy Convergence and Integration Center for Human Resources Training and Education, Jeju National University*
[3]*Obstetrics and Gynecology, Jeju National University Hospital*
[4]*Department of Electronic Engineering, Jeju National University*
[*]*Corresponding author: kyungyk@jejunu.ac.kr*

Abstract

Intelligent fetal imaging techniques are required to monitor the development of fetal growth and fetal condition during pregnancy period. Conventional fetal imaging techniques such as fetal ultrasound and Cardiotocogram (CTG) are expensive and uncomfortable to the patient. In this study, we developed an electrical impedance tomography (EIT) imaging method to reconstruct fetal images. EIT is a non-invasive and low cost medical imaging technique that reconstructs the internal resistivity distribution of fetus by injecting electrical currents and measure the resulting voltages through the electrodes which are placed on the boundary of pregnant abdomen. Finite element method (FEM) used as an EIT forward solver and inverse solver based on Newton-Raphson method with Tikhonov regularization is used to estimate the electrical resistivity distribution of the fetus inside the pregnant abdomen. To investigate the performance of proposed EIT fetal imaging method, we performed numerical simulations with different locations of fetus in the pregnant abdomen shaped mesh. Numerical simulation results are shown that the EIT imaging with Newton-Raphson method (mNR) could be applied to the fetal imaging during pregnancy period.

Keywords: *Fetal imaging; Electrical impedance tomography; FEM; Newton-Rapson method; pregnant abdomen; Tikhonov regularization*.

1. Introduction

Fetal imaging is an essential clinical tool to monitor the condition of fetus, development of fetal growth and fetal anomaly detection. Better quality fetal imaging techniques are needed to identify health issues of fetus during pregnancy. Fetal Ultrasound images are important for the fetal biometric measurements and prenatal diagnosis. Wu, Lingyun, et al developed a FUIQA method to improve the fetal Ultra Sound acquisition outcomes [1]. Cardiotocogram (CTG) have been analyzed fetal diagnosis parameters. In the real time monitoring, data acquisition system proceeds continuously and provides an up-to-date display of the uterine contraction signals and fetal heart rate (FHR) during pregnancy [2]. Another research work presented in [3] Fetal Electrocardiogram has a potential to record signal obtained from the pregnant abdomen for monitoring fetal heart rate. According to the research work presented by Wasimuddin et al [4] designed a Least Mean Square (LMS) adaptive filter to remove the maternal heartbeat signal from the electrocardiogram fetal signal for accurate fetus diagnosis. Despite of their performance, accuracy and image quality, these fetal imaging methods have limitations. To overcome these limitations, here we have introduced an electrical impedance imaging method to reconstruct images of the fetus during pregnancy.
Electrical impedance tomography (EIT) is a non-invasive imaging technique that reconstructs the internal resistivity distribution of the object. This technique is based on the fact that the organs or targets inside domain have different electrical resistivity. In fact, the quantity to be imaged in EIT is the impedivity, but since EIT often assumes that the resistive part of the impedivity dominates, it estimates the resistivity distribution EIT has been developed as an alternative to the medical imaging techniques such as computer tomography (CT), magnetic resonance imaging (MRI), ultrasonic imaging that are expensive and/or even cause adverse health effects [5]. EIT has been applied to several medical applications that include lung imaging (Brown 2001, Mueller et al. 2001), head imaging (Holder 1992), and breast imaging (Osterman et al. 2000, Cherepenin et al. 2002, Kerner et al. 2002).
The purpose of proposed work is to introduce an electrical impedance imaging method to reconstruct images of the fetus during pregnancy. Finite element method used as an EIT forward solver and inverse problem is solved by Newton-Raphson method with Tikhonov regulation to estimate the resistivity distribution of fetus in the pregnant abdomen. We carried out numerical simulations to illustrate the reconstruction performance of fetal EIT imaging method.

2. Mathematical Modeling of EIT

In order to reconstruct fetal image during pregnancy, surface electrodes e_l ($l = 1,2,\cdots,L,$) have to be placed around the abdominal boundary $\partial\Omega$ of the pregnant women. Time varyingc electrial currents I^l ($l = 1,2,\cdots,L$) are injecting through the electrodes placed on the pregnant abdomen and fetus having the electrical resistivity distribution $\rho(x, y)$ within in the abdominal boundary, then the resulting electrical potential $u(x, y)$ on the Ω is computed by using the governing equation, which can be derived through the Maxwell equations [5].

$$\nabla \cdot (\sigma \nabla u) = \nabla \cdot (\frac{1}{\rho} \nabla u) = 0, \quad \text{in } \Omega \tag{1}$$

To solve the governing equation, the complete electrode model with boundary conditions based on are used and are defined by

$$u + z_l \sigma \frac{\partial u}{\partial \mathbf{n}} = U^l, \quad (x, y) \in e_l, \; l = 1, 2, \cdots, L, \tag{2}$$

$$\int_{e_l} \sigma \frac{\partial u}{\partial \mathbf{n}} dS = I^l, \quad (x, y) \in e_l, \; l = 1, 2, \cdots, L \tag{3}$$

$$\frac{1}{\rho} \frac{\partial u}{\partial \mathbf{n}} = 0, \quad (x, y) \in \partial\Omega \setminus \bigcup_{l=1}^{L} e_l \tag{4}$$

Where L is the number of electrodes on the pregnant abdomen boundary, z_l is the effective contact impedance between l th electrode and surface of the abdomen, U^l is the measured electrical potentials, and I^l is the applied alternating current. In addition to electrode model, following Kirchhoff's rules on the measured potentials and the injected currents should guarantee the existence and uniqueness of the solution.

$$\sum_{l=1}^{L} I^l = 0, \quad \sum_{l=1}^{L} U^l = 0 \tag{5}$$

3. Forward Solver: Finite Element Method

In FEM forward solver, the object (pregnant abdomen domain) Ω is discretized into small elements as shown in figure 1 (a) -(b). The vertices of the triangle elements are called the nodes. The point elements are corresponding to the point electrodes attached to the circumference of the abdomen. If N_n is the number of nodes of the FEM abdominal shaped mesh, the electric potentials u within the abdomen are approximated as u^h, and it is represented as

$$u \equiv u(x, y) \approx u^h(x, y) = \sum_{i=1}^{N_n} \alpha_i \phi_i(x, y), \tag{6}$$

And the electrical voltages U on the electrodes are estimated as

$$U \approx U^h = \sum_{j=1}^{L-1} \beta_j \mathbf{m}_j, \tag{7}$$

Where ϕ_i is the first-order basis function, α_i and β_j are the unknown coefficients.

The matrix $\mathbf{m}_j$ ensures that the constraint (5) is fulfilled. The finite element formulation is represented as $\mathbf{Ab} = \mathbf{f}$, as the above equation can be expressed in a matrix form where each component is defined as

$$\mathbf{A} = \begin{pmatrix} \mathbf{B} & \mathbf{C} \\ \mathbf{C}^T & \mathbf{D} \end{pmatrix}, \mathbf{b} = \begin{pmatrix} \boldsymbol{\alpha} \\ \boldsymbol{\beta} \end{pmatrix}, \mathbf{f} = \begin{pmatrix} \mathbf{0} \\ \mathbf{M}^T I \end{pmatrix} \tag{8}$$

Where

$$\mathbf{B}(i, j) = \int_\Omega \rho^{-1} \nabla\phi_i \cdot \nabla\phi_j d\Omega + \sum_{l=1}^{L} \frac{1}{z_l} \int_{e_l} \phi_i \phi_j dS \tag{9}$$

$$\mathbf{C}(i, j) = -\left(\frac{1}{z_1} \int_{e_1} \phi_i dS - \frac{1}{z_{j+1}} \int_{e_{j+1}} \phi_i dS \right), \tag{10}$$

$i = 1, 2, \cdots, N_n$ and $j = 1, 2, \cdots, L-1$

$$\mathbf{D}(i, j) = \sum_{l=1}^{L} \frac{1}{z_l} \int_{e_l} \mathbf{m}_i \mathbf{m}_j dS \tag{11}$$

Therefore, the approximate solutions u^h and U^h for the forward problem are obtained by solving $\mathbf{b} = \mathbf{A}^{-1}\mathbf{f}$. That is, the last $L-1$ coefficients in $\mathbf{b}$ give the referenced electrical voltages on the point electrodes.

4. Inverse Solver: Gauss-Newton Algorithm

The relation for the electrical voltages on boundary electrodes U and resistivity distribution ρ within the abdomen is a nonlinear function. The general EIT inverse problem approach for estimating the internal resistivity distribution is represented as a least squares problem. In the least squares problem, the estimated resistivity distribution $\hat{\rho}$ that minimizes the l2-norm of the residual errors is selected as an optimal choice for the internal resistivity distribution ρ. The objective function to find the optimal estimates $\hat{\rho}$ are given by

$$\Phi = \Phi(\hat{\rho}) = \frac{1}{2} \left[\tilde{U} - U(\hat{\rho}) \right]^T \left[\tilde{U} - U(\hat{\rho}) \right]. \tag{12}$$

Where $\tilde{U}$ is the measured voltage vector and $U(\hat{\rho})$ is the vector of computed boundary voltage. $\hat{\rho} = \rho_c + \Delta\rho$, where ρ_c is the estimated current resistivity distribution which can converge to least squares estimates and $\Delta\rho$ is sufficiently small value. Linearizing $U(\hat{\rho})$ at ρ_c using a first-order Taylor series expansion,

$$U(\hat{\rho}) \approx U(\rho_c) + H\Delta\rho, \tag{13}$$

Where $H \equiv H(\rho_c) \equiv \dfrac{\partial U(\rho_c)}{\partial \rho_c} \in \mathbb{R}^{N_m \times N_e}$ is the Jacobian matrix.

The above objective function can be written as

$$\Phi(\hat{\rho}) \approx \Phi(\Delta\rho) = \frac{1}{2}\left[\Delta U_c - H\Delta\rho\right]^T \left[\Delta U_c - H\Delta\rho\right]. \tag{14}$$

To find the global minimum of the quadratic function of equation (14), the differentiation of the equation (14) is set to zero as

$$\nabla_{\Delta\rho}\Phi \equiv \Phi'(\Delta\rho) = H^T H\Delta\rho - H^T \Delta U_c = 0. \tag{15}$$

From the above equation, we have the following equation

$$H^T H\Delta\rho = H^T \Delta U_c. \tag{16}$$

If the $H^T H$ called Hessian matrix is positive definite, then $H^T H$ can be inverted to obtain the solution for the optimal estimate as

$$\Delta\rho = (H^T H)^{-1} H^T \Delta U_c. \tag{17}$$

Using $\hat{\rho} = \rho_c + \Delta\rho$ and $\Delta U_c \equiv \tilde{U} - U(\rho_c)$, Gauss-Newton algorithm can be obtained as

$$\hat{\rho} = \rho_c + (H^T H)^{-1} H^T (\tilde{U} - U(\rho_c)). \tag{18}$$

Also, using iterative index i, the above equation can be rewritten as

$$\hat{\rho}_{i+1} = \hat{\rho}_i + (H_i^T H_i)^{-1} H_i^T (\tilde{U} - U(\hat{\rho}_i)). \tag{19}$$

The Hessian matrix ($H_i^T H_i$) in (19) is highly ill-posed. So, in order to have stability of inverse solution and the meaningful solution, the regularization method as a penalty or prior information has to be used in the equation (19).

5. Numerical simulation results and discussion:

To perform the numerical simulations, pregnant abdomen shaped domain with 16 electrodes is used. A pregnant abdomen shaped FEM mesh is designed and two different meshes used to mitigate the inverse problem as shown in (figure 1 (a) and 1 (b)). In order to measure the true voltages, we have used abdomen shaped forward mesh of 1201 nodes (N) and 2304 triangular elements (E) shown in (figure 1 (a)). In order to obtain the voltages and resistivity distribution of fetus, we used abdomen shaped inverse mesh of 313 nodes (N) and 573 triangular elements (E) shown in (figure 1 (b)). The pregnant abdomen is considered to be filled with body fluids having resistivity of (588 ohm cm) and fetus shaped target having resistivity of (154 ohm cm) is placed inside the pregnant abdomen.

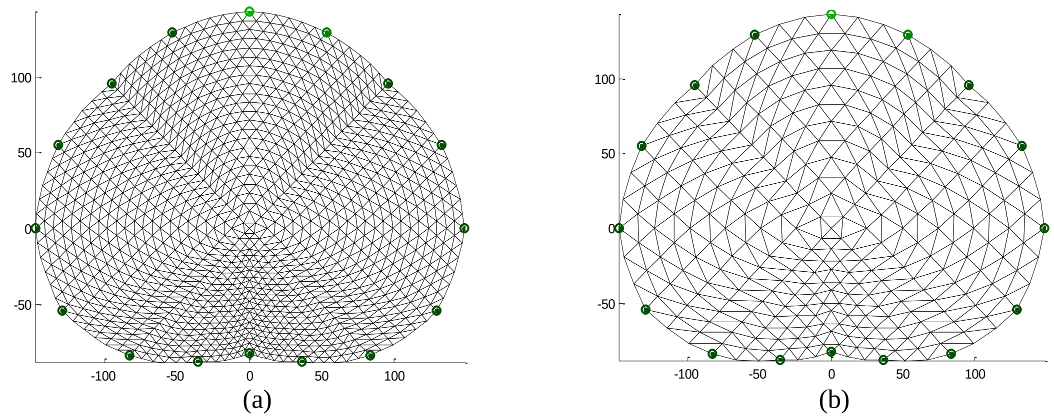


Figure 1: Meshes are designed by Finite element method for fetal imaging (a) forward mesh with 2304 triangular elements (b) inverse mesh with 573 triangular elements.

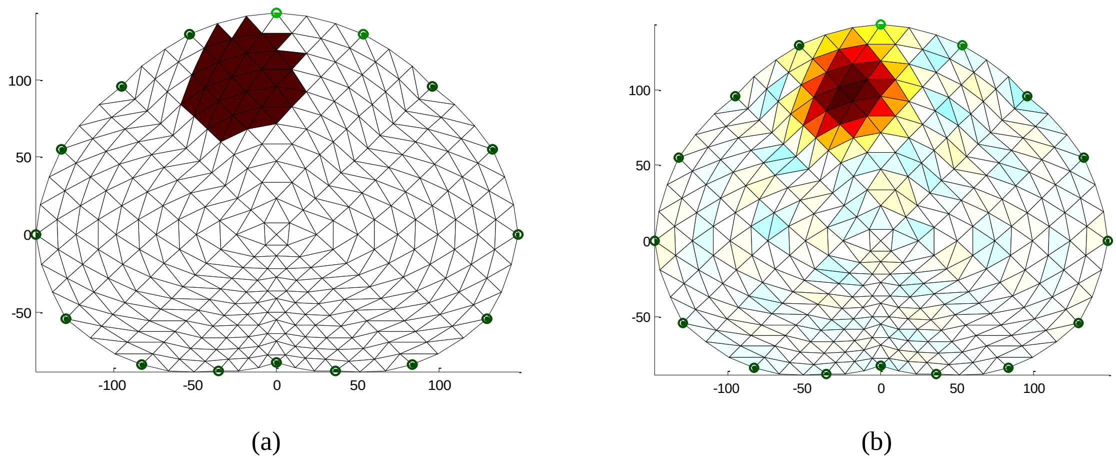
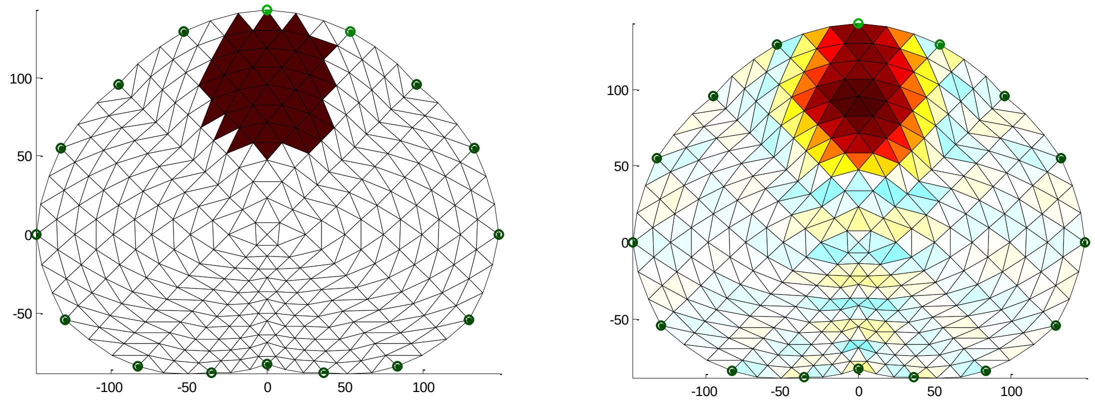
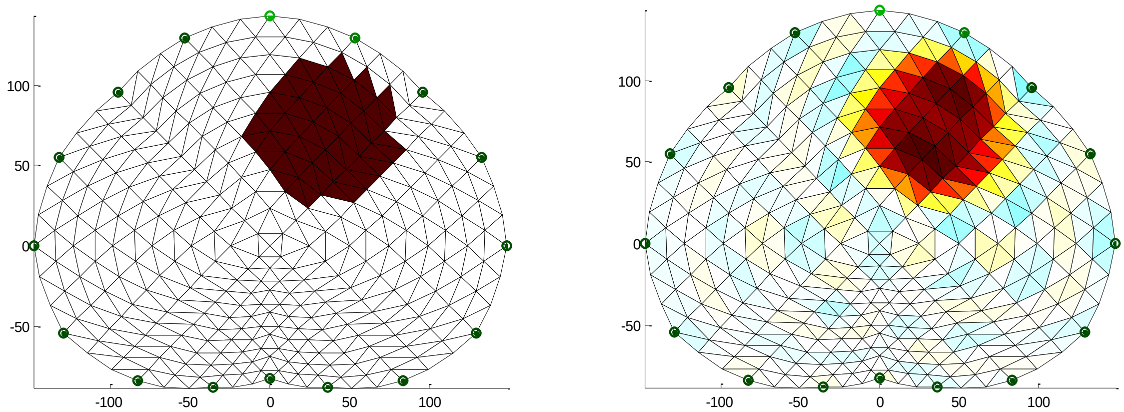


Figure 2: Numerical simulations of fetal imaging: (a) True images of a fetus shaped target is placed in upper left part of the pregnant abdomen. (b) fetal image reconstructed by mNR.



(a) (b)

Figure 3: Numerical simulations of fetal imaging: (a) True images of a fetus shaped target is placed in the top middle part of the pregnant abdomen. (b) Fetal image reconstructed by mNR.



(a) (b)

Figure 4: Numerical simulations of fetal imaging: (a) True images of a fetus shaped target is placed in an upper right part of the pregnant abdomen. (b) Fetal image reconstructed by mNR.

Three static cases of the fetus shaped target is placed in an upper part of the abdomen is considered. In the 1st case a fetus shaped target (resistivity of 154 ohm cm) is placed in upper left part of the pregnant abdomen (resistivity of 588 ohm cm), in the 2nd case a fetus shaped target is placed in top middle part of the pregnant abdomen and 3rd case a fetus shaped target is placed in an upper right part of the pregnant abdomen. Figure 2, 3 and 4 shows true fetal images and reconstructed images for each three static cases. Figure 2(a), 3(a)&4 (a) shows true fetal images. The reconstructed images of all 3 cases shown in Figure 2(b), 3(b) &4(b). The all 3 cases are examined to verify the reconstruction performance by Newton Raphson method with Tikhonov regularization.

6. Conclusion:

In this report, we have introduced an EIT imaging technique to estimate a resistivity distribution of fetus during pregnancy. Finite element method is used as an EIT forward solver and inverse solver based on Newton-Raphson method with Tikhonov regularization is used to estimate the resistivity distribution of the fetus in the pregnant abdomen. We conducted 3 cases of numerical simulations with different locations of the fetus in the pregnant abdomen shaped structure.

Numerical simulation results illustrate the Newton Raphson method with Tikhonov regularization can estimate the resistivity distribution of the fetus. Therefore, it can be expected that the proposed method is suitable for fetal imaging during pregnancy period.

Acknowledgement

This work was supported by the research grant from Jeju National University Hospital development fund in 2016.

References

[1] Wu, Lingyun, et al. "FUIQA: Fetal ultrasound image quality assessment with deep convolutional networks." IEEE transactions on cybernetics 47.5 (2017): 1336-1349.

[2] Jeiewski, et al. "Fetal monitoring with automated analysis of cardiotocogram: the KOMPOR system." Engineering in Medicine and Biology Society, 1993. Proceedings of the 15th Annual International Conference of the IEEE. IEEE, 1993.

[3] Kainz, Bernhard, et al. "Adaptive scan strategies for fetal MRI imaging using slice to volume techniques." Biomedical Imaging (ISBI), 2015 IEEE 12th International Symposium on. IEEE, 2015.

[4] Wasimuddin,et al. "Design and implementation of Least Mean Square adaptive filter on fetal electrocardiography." American Society for Engineering Education (ASEE Zone 1), 2014 Zone 1 Conference of the. IEEE, 2014.

[5] Sarwan, et al. "Development of a non-invasive point of care diagnostic tool for fetal monitoring using electrical impedance based approach." Point-of-Care Healthcare Technologies (PHT), 2013 IEEE. IEEE, 2013.