Estimation of dynamic conductivity distribution of conductive fabric using ERT for fetus monitoring

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Abstract

Monitoring fetal movements regularly helps us know about the wellbeing of fetus. With the rapid development in sensor technology, it is possible to have the status checked in a nonclinical setting before visiting or consulting a doctor. Electrical resistance tomography applied with conductive fabric can be used as a sensing tool to detect the fetal changes nondestructively. This paper considers estimating time varying conductivity distribution across the fabric surface due to the fetal movement. Fetal movements can be random therefore it is assumed that the change in the conductivity of the fabric at the pressure point is dynamically varying and the time varying conductivity distribution across fabric is estimated using Kalman filter. The proposed method is evaluated with numerical experiments and the results show that the proposed method is successful in identifying the fetal changes on the fabric surface

1. Introduction

Fetal movements, also referred to as fetal kicks, denote the motions carried out by a developing fetus within the uterus during pregnancy. These movements serve as indicators of fetal well-being and development and are usually sensed by the pregnant individual beginning around the second trimester [1]. However, their perception may vary, occurring earlier or later, influenced by factors like the placental position and the individual's body size. The fetal movements manifest as kicks, punches, rolls, or hiccups and as pregnancy advances, the fetal movements typically become more synchronized and robust. The differences in intensity, frequency, and manner characterize variations in fetal movements.

Careful monitoring of fetal movement's constitutes a critical component of prenatal care. As the expected mothers are encouraged to note the patterns in baby's movement and notify their healthcare provider of any noteworthy variations, such as reduced activity. Reduced fetal movements may signify potential concerns regarding fetal health, such as distress or restricted growth, necessitating further assessment. During regular periodic checkups, it is usual practice to have discussions on fetal movement and the doctors use several methods to assess the fetal health such as ultrasound imaging [2], electronic fetal monitoring, Doppler imaging [3], cardiotocography [4] and fetal movement tracking.

The above methods are expensive and also need to be done inside a clinical environment under the supervision of expert health practitioner [5]. Fetal movement sensors when integrated with wearable devices can be used as an alternative method for monitoring fetal health in nonclinical environment thus are suitable for home use, allowing expectant mothers to track their baby's fetal movements regularly. Thus, avoiding the need for frequent visits to hospital thereby reducing anxiety and promoting peace of mind during pregnancy. In this regard, accelerometers and motion sensors have been developed for fetus monitoring [5]. Nonetheless, few drawbacks are observed that include the stability and accuracy.

Conductive fabrics also known as e-textiles are the fabrics woven or integrated with conductive filling that are used extensively for smart clothing with unique properties and has applications ranging in fitness tracking, health monitoring, heating, flexible electronics, energy harvesting, human machine interface device applications such as touch sensitive panels, gesture recognition systems [6]. Electrical resistive tomography (ERT) that involve placing electrodes around region of interest is used for process monitoring. ERT is a nondestructive method that is applied in medical imaging for instance in lung imaging to diagnose respiratory conditions like COPD, detecting breast cancer, identifying brain abnormalities such as tumors and strokes, evaluating muscle function and joint mobility in musculoskeletal imaging, monitoring wound healing progress, and fetus imaging. In fetus monitoring with ERT, laboratory tests are performed with papaya as phantom and different fruits are considered as targets inside [7]. In another work, Kumar et al. [8] conducted studies on ERT's application in monitoring pregnancies, utilizing papaya and a solution comprising salt, sugar, and water as a phantom.

ERT coupled with the conductive fabric can be developed as continuous noninvasive fetus monitoring tool for home use. Conductive fabric when placed on the mother's abdomen absorbs the localized pressure due to fetal movement and undergoes mechanical deformation which changes conductivity. By placing electrodes around the conductive fabric and applying ERT techniques, it is possible to visualize the conductive distribution across the fabric surface online. Conductive fabric is a very high conductive material therefore with ERT, the voltages measured on the attached electrodes are very low. Due to the ill-posed nature of ERT inverse problem, the reconstructions are greatly influenced by the noise.

In this study, we propose a dynamic imaging method for ERT based fetus monitoring using conductive fabric. The fetal movements cause a mechanical deformation of fabric thereby changing the conductivity at that region of impact. The fetal movements can be random and transient in nature. The conductivity distribution across the fabric is considered as time varying and it is assumed that distribution can change within the time to acquire one frame of data. The time varying conductivity is considered as state variable and is estimated using Kalman filter. Numerical experiments for fetus monitoring are carried out and the results show that the proposed method is successful in estimating time varying conductivity distribution across the fabric.

2. Conductive Fabric

Electronic skin and conductive fabric represent cutting-edge materials utilized across diverse domains, including wearable technology, biomedical engineering, and smart textiles. Electronic skin, often referred to as e-skin or artificial skin, replicates the sensory functions of human skin, enabling the detection of touch, pressure, temperature, and various stimuli. This technology finds applications in prosthetics, robotics, and human-machine interfaces, enhancing tactile feedback and interaction with the surroundings [9-10]. Conversely, conductive fabric integrates conductive elements like metal fibers or coatings, facilitating electrical conduction. Widely deployed in electronic textiles, wearable sensors, and flexible electronics, conductive fabric enables the creation of circuits, antennas, and electrodes [11-13]. Both electronic skin and conductive fabric play pivotal roles in the advancement of wearable devices, healthcare monitoring systems, and interactive textiles, reshaping human-technology interaction and the landscape of innovation [14-16].

Conductive fabrics utilizing electrical resistance tomography (ERT) offers a novel approach to fetus monitoring. ERT-based fabric sensor incorporates arrays of conductive electrodes detect changes in electrical resistance caused by mechanical deformation of abdomen. By mapping electrical resistance changes across the abdomen, ERT-based fabric sensor enables high-temporal resolution of conductivity. This technology is low cost, suitable for continuous monitoring and enabling it to be used in nonclinical settings (Fig .1).

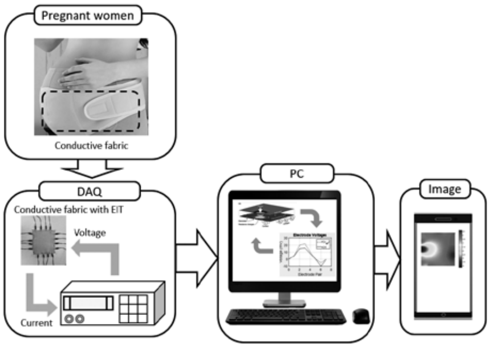


Fig. 1. ERT with conductive fabric for fetus monitoring

3. Electrical resistance tomography with conductive fabric for fetus monitoring

Along the boundary of the conductive fabric $\partial\Omega$, an array of L electrodes are placed equidistantly. Currents I_l are passed through the electrodes into the fabric domain Ω that has conductivity distribution $\sigma(p), p \in (x, y)$ and the resulting excited voltages $\bar{U}_l$ are measured. The image reconstruction with ERT is realized by solving the forward and inverse solution iteratively.

A. ERT Mathematical Model: The forward solver

The potential distribution u inside the domain Ω and the conductivity of fabric σ are related through governing equation derived from the Maxwell's equations is of the form [17]

$$\nabla.(\sigma(p)\nabla u(p)) = 0, in\ \Omega, p \in (x, y) \quad (1)$$

The forward solution of computing the boundary voltages from the given conductivity distribution is obtained from solving the above governing equation with suitable boundary conditions. The typical boundary conditions of ERT are defined in terms of the current density which are described below

$$\int_{e_l} \sigma\frac{\partial u}{\partial n} dS = I_l, (x, y) \in e_l, l = 1,2,\cdots, L \quad (2)$$

$$\sigma\frac{\partial u}{\partial n} = 0, (x, y) \in \partial\Omega \setminus \cup_{l=1}^{L} e_l \quad (3)$$

The potential distribution u inside the domain Ω and the boundary voltages $\bar{U}_l$ are described using complete electrode model given by

$$u + z_l\sigma\frac{\partial u}{\partial n} = \bar{U}_l\ on\ e_l, l = 1,2,\cdots, L \quad (4)$$

To achieve unique solution for conductivity additional constraints on injected currents and voltages are imposed which are of the form

$$\textstyle\sum_{l=1}^{L} I_l = 0 \quad (5)$$

$$\textstyle\sum_{l=1}^{L} \bar{U}_l = 0 \quad (6)$$

Finite element method is used to obtain numerical solution for the forward problem using boundary and constraint conditions (2-6). Finite element formulation of ERT problem results in set of algebraic equations represented in a matrix form as follows

$$\mathbf{Ab} = \tilde{\mathbf{I}} \quad (7)$$

where $\mathbf{A}$ is the system matrix, $\mathbf{b}$ is the unknown vector comprising of nodal and boundary voltages, $\tilde{\mathbf{I}}$ is the data vector. For full description of forward solution using FEM see [18].

4. Dynamic conductivity estimation of fabric using extended Kalman filter

The time varying conductivity distribution of the fabric due to fetal movement is unknown to be estimated using extended Kalman filter (EKF). If the fetal movements are random and conductivity distribution changes before acquiring complete data set of voltages, then conventional methods that use full frame of voltage data set to reconstruct a single image may not be good. Dynamic methods that can reconstruct even with part of the data are useful. In dealing with dynamic ERT, the unknown conductivity is treated as the state variables and the inverse problem here is converted to a state estimation problem.

In the state estimation problem, we have the state equation, i.e., the temporal evolution of the state and the measurement or observation equation, i.e., the relationship between the state and boundary voltages. The state equation for conductivity is assumed to be of linear represented as [19-20]

$$\sigma_t = \mathrm{F}_{t-1}\sigma_{t-1} + \omega_{t-1} \tag{8}$$

The linearized measurement equation for boundary voltages is of the form

$$\bar{U}_t = \mathrm{J}_t\sigma_t + \nu_t \tag{9}$$

where subscript t represents state index, $\mathrm{F}_t \in \mathcal{R}^{NxN}$ is the state transition matrix, N is the number of unknown state variables, J_t is the Jacobian matrix, $\omega_t \in \mathcal{R}^{Nx1}$, $\nu_t \in \mathcal{R}^{Nx1}$ denote the process and measurement noise, respectively. They are assumed zero mean Gaussian noise and with covariance $\mathbf{Q} = E[\omega_t\omega_t^{\mathrm{T}}]$, $\mathbf{R} = E[\nu_t\nu_t^{\mathrm{T}}]$ respectively. Also in (9), $J_t\sigma_t$ represents the calculated FEM forward solution. With the above Gaussian assumption we define the cost function for the extended Kalman filter EKF which is of the form [20]

$$\Phi(\sigma_t) = \frac{1}{2}\left\|\sigma_t - \sigma_{t|t-1}\right\|_{\Gamma^{-1}_{t|t-1}} \tag{10}$$

where, $\Gamma_{t|t-1} = E[(\sigma_t - \sigma_{t|t-1})(\sigma_t - \sigma_{t|t-1})^T]$. Minimizing the above cost functional (10) and then solving for covariances matrices we have the expressions for EKF with time and measurement updates given below [21-22]

- Time updating (prediction)

$$P_{t|t-1} = \mathrm{F}_{t-1}P_{t-1|t-1}\mathrm{F}_{t-1}^T + \mathbf{Q}_{t-1} \tag{11}$$

$$\hat{\sigma}_{t|t-1} = \mathrm{F}_{t-1}\hat{\sigma}_{t-1|t-1} \tag{12}$$

- Measurement updating (filtering)

$$K_t = P_{t|t-1}\, J_t^T\left[\mathrm{J}_t P_{t|t-1}\, \mathrm{J}_{t-1}^T + R_t\right]^{-1} \tag{13}$$

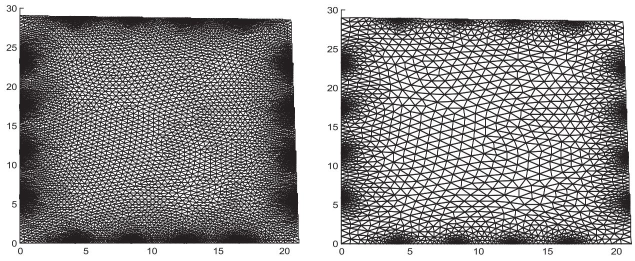
$$P_{t|t-1} = (I_N - K_t\, J_t)\, P_{t|t-1} \tag{14}$$

$$\hat{\sigma}_{t|t} = \hat{\sigma}_{t|t-1} + K_t\left(\bar{U}_t - J_t\,\hat{\sigma}_{t|t-1}\right) \tag{15}$$

where $P_{t|t-1}$ denotes state-error covariance matrix and K_t is Kalman gain matrix. Therefore, with time and measurement update we can find the time varying conductivity state vector $\hat{\sigma}_{t|t}$ for true vector σ_t .

5. Results

In this section, we present the numerical results for fetus monitoring using ERT. For simulation studies, a very high conductive fabric of rectangular shape with size 21.1 cm x 29 cm with thickness of is considered. Conductive fabric has a surface resistivity of 1 Ω /sq . Along the circumference of the fabric, 16 electrodes are placed equidistantly with four electrodes on each side. As a current injection protocol, adjacent method with neighboring electrodes used as source and sink is used while boundary voltages are measured across all the electrodes. There are 16 current patterns corresponding to different pairs of electrodes used as source and sink. One frame data contains total of 120 voltage measurements, i.e. (16x15/2). The fabric is very highly conductive therefore to have reasonable voltage data for reconstruction; large magnitude of current is used. Current of magnitude of 100 mA is injected through the electrodes and low contact impedance of 1E-9 Ω x cm^2 is used. Finite element mesh are constructed using NETGEN with fabric dimensions. A fine mesh with 16620 triangle elements is used for forward solution to generate voltage data while coarse mesh with 4155 elements is used for conductivity estimation. Two different meshes are used to avoid the inverse crime (Fig. 2). The true conductivity of fabric without application of pressure is considered as 10 mS/cm and when pressure is applied at a certain position it is assumed that the conductivity is increased about 10 times. As an initial guess for conductivity, best homogeneous conductivity is computed using least squares solution.



(a) (b)

Fig 2. Finite element mesh constructed considering fabric dimensions for numerical experiments
(a) fine mesh (b) coarse mesh

For numerical experiments, a total of four test cases is considered in fetal movements. Different situations are considered for fetus monitoring, and the conductivity distribution is estimated using extended Kalman filter. To evaluate the performance of proposed method as a performance metric root mean square error of conductivity and voltages are used and they are defined as follows

$$RMSE(\sigma) = \frac{\|\sigma_{estimated} - \sigma_{true}\|}{\|\sigma_{true}\|} \quad (16)$$

$$RMSE(U) = \frac{\|U_{estimated} - U_{\mathrm{true}}\|}{\|U_{true}\|} \quad (17)$$

Three different cases were studied, and the performance is evaluated in numerical simulations. In case 1, it is assumed that there is no fetal movement, i.e. conductivity distribution across the fabric is homogeneous (Fig 3(a)). The conductivity reconstructions for case 1 are shown in Fig 3(b). It is seen that the proposed Kalman filter could estimate homogeneous conductivity with good accuracy. Fig. 3(c-d) shows the RMSE for estimated conductivity and voltages. RMSE values are computed, and it is noticed that it has very low value of order 1E-6 which tells the accuracy of estimated conductivity. In Fig 4, conductivity estimation for case 1 in the pressure of noise is shown. Measurement noise of 1 % is added to the generated true voltages. From the reconstructed conductivity plots (Figs 4(b)), it is seen that even in the presence of noise proposed Kalman filter-based estimation has estimated the fabric conductivity with good accuracy. Qualitative performance of case 1 with noisy data is shown in Fig (4(c-d)). As compared to the case of no noise the RMSE values for conductivity and voltage are computed slightly higher values. However, they are still in the order of 1E-4 which tells the estimation accuracy.

In case 2, it is considered that conductivity of fabric is found to change within the time to collect one frame, i.e., 16 current patterns. It is seen from the true distribution (Fig 5(a)) during the time to collect 8 patterns there is no fetal movement. From 9th current pattern it is seen there is fetal movement that cause the mechanical deformation of fabric, giving rise to increase of conductivity at that place (10 times). The reconstructed conductivity for case 2 without noise is shown in Fig 5(b). It is seen that conductivity distribution that conductivity change is found to be noticed after 9th current pattern which is same as true distribution (Fig 5 (a)). Although initially there are few patterns where the location is not identified correctly. But, as with more voltage data, it is seen the location of pressure and increase of conductivity matches true distribution. The performance metrics for case 2 without noise are shown in Fig 5(c-d). RMSE values are found to be higher after current pattern 8 due to fetal movement and the values decrease after that. Fig 6 has the result for case 2 in the presence of noisy data. Conductivity estimation with noisy data is found to be reasonable and the noise has not affected the conductivity both qualitatively and quantitatively (Fig 6(c-d)).

In case 3, more dynamic case is considered for fetal movement. It is considered the fetal movement is continuous across the abdomen. Variation of true conductivity due to fetal movement can be seen from Fig 7(a). The reconstructed results for the more dynamic evolution of conductivity is shown in Fig 7(b). It is seen that even in case of continuous fetal movement situation with limited data the proposed method could estimate the time varying conductivity with good accuracy. Although the size is not estimated accurately. It shows higher conductivity distribution whenever there is fetal movement. The performance metrics in case 3 without noise is shown Fig 7(c-d). Higher RMSE values are observed as compared to case 1 and case 2. Fig 8 shows the reconstruction result for case 3 in the presence of measurement noise. It is seen that when compared to no-noise case the reconstructed conductivity has slightly higher RMSE values for conductivity and voltages.

From the simulation studies with three test cases in the presence of noise and no noise conditions it is seen the proposed Kalman filter for conductivity estimation was successful in locating and identifying the changes in the conductivity corresponding to fetal movement.

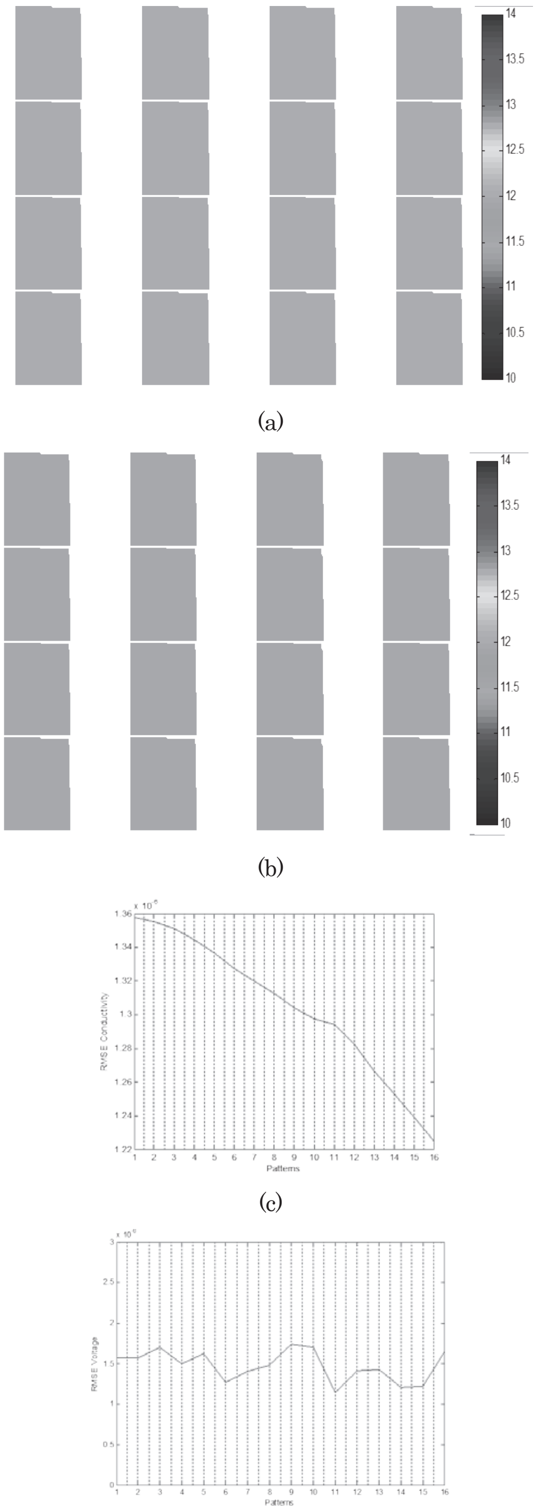


Fig. 3. Numerical simulations for fetus monitoring in case 1 and no noise (a) True conductivity distribution (b) estimated conductivity using EKF (c) RMSE conductivity (d) RMSE voltage.

(a)

(b)

(c)

(d)

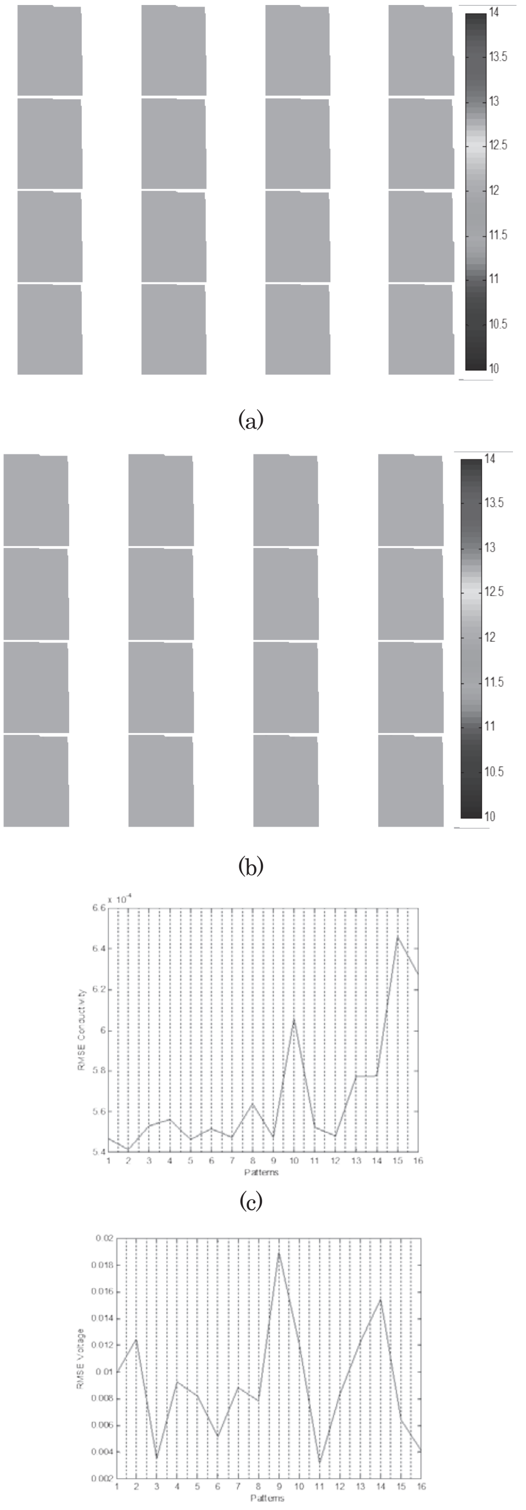


Fig. 4. Numerical simulations for fetus monitoring in case 1 with 1% noise
(a) True conductivity distribution
(b) estimated conductivity using EKF
(c) RMSE conductivity (d) RMSE voltage

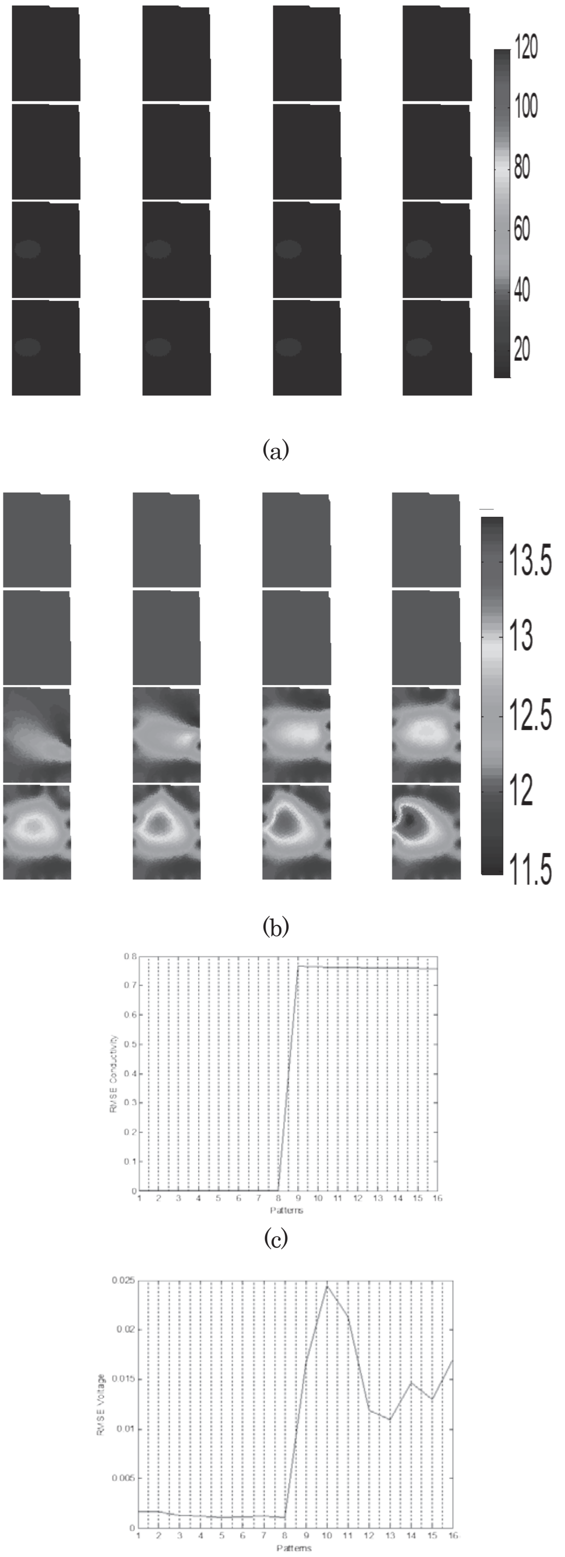
(a)

(b)

(c)

(d)

Fig. 5. Numerical simulations for fetus monitoring in case 2 and no noise (a) True conductivity distribution (b) estimated conductivity using EKF (c) RMSE conductivity (d) RMSE voltage



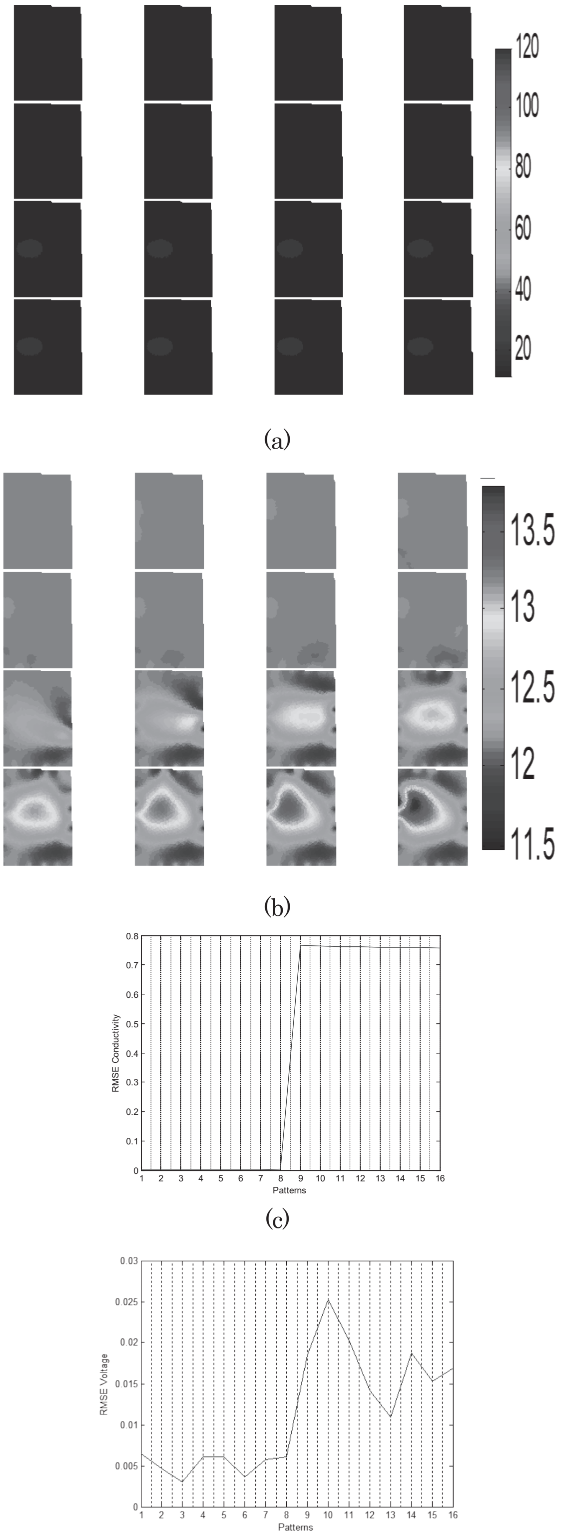
(a)

(b)

(c)

(d)

Fig. 6. Numerical simulations for fetus monitoring in case 2 and 1% noise (a) True conductivity distribution (b) estimated conductivity using EKF (c) RMSE voltage (d) RMSE conductivity



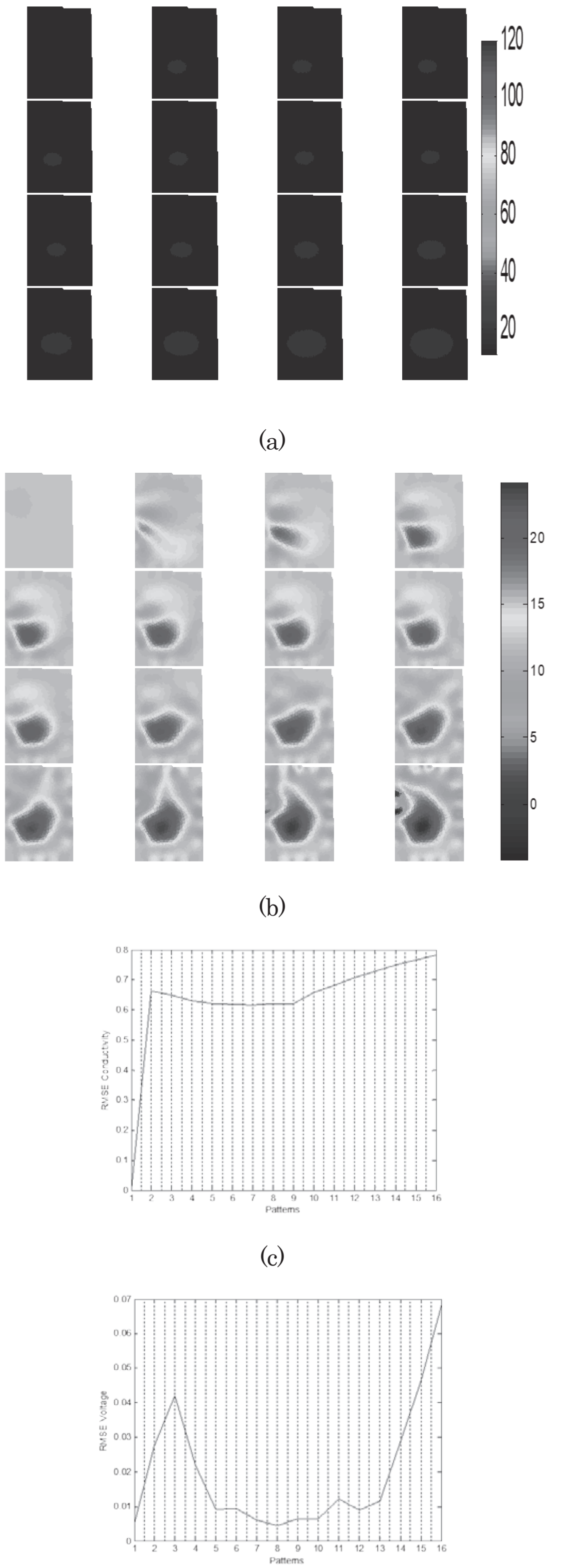
(a)

(b)

(c)

(d)

Fig. 7. Numerical simulations for fetus monitoring in case 3 and no noise (a) True conductivity distribution (b) estimated conductivity using EKF (c) RMSE voltage (d) RMSE conductivity.



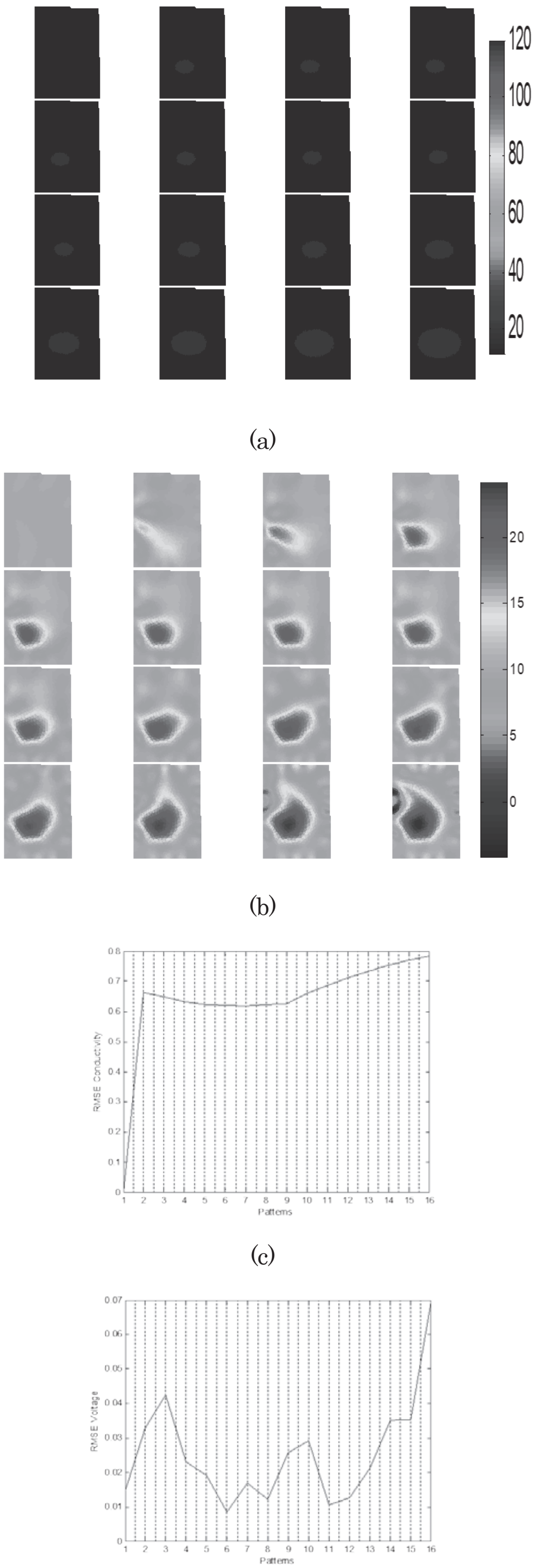
(a)

(b)

(c)

(d)

Fig. 8. Numerical simulations for fetus monitoring in case 3 and 1% noise (a) True conductivity distribution (b) estimated conductivity using EKF (c) RMSE voltage (d) RMSE conductivity



(a)

(b)

(c)

(d)

6. Conclusions

There is a need for low-cost fetal monitoring methods that can be done at non-clinical setting in situations when it is difficult to visit a doctor on regular basis. This study presents a fetus monitoring system using conductive fabric with electrical resistance tomography. The baby movement makes a localized force at the boundary and this pressure is absorbed by the stretchable conductive fabric which in turn change the conductivity distribution. The time varying conductivity distribution is estimated using Kalman filter. Numerical experiments involving scenarios where the conductivity distribution is temporally varied and the proposed Kalman filter is applied for the conductivity estimation across the fabric surface. The results presented reveal that the proposed method can identify the dynamic changes in conductivity with good accuracy.

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