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An Instrumental Electrode Configuration for 3D Ultrasound Modulated Electrical Impedance Tomography

Xizi Song,

Tianjin Key Laboratory of Process Measurement and Control, School of Electrical and Information Engineering, Tianjin University, Tianjin 300072, China

Yanbin Xu [Member, IEEE],

Tianjin Key Laboratory of Process Measurement and Control, School of Electrical and Information Engineering, Tianjin University, Tianjin 300072, China

Feng Dong [Senior Member, IEEE], and

Tianjin Key Laboratory of Process Measurement and Control, School of Electrical and Information Engineering, Tianjin University, Tianjin 300072, China

Russell S. Witte [Member, IEEE]

Department of Medical Imaging, University of Arizona, Tucson, AZ USA 85724

Abstract

Ultrasound modulated electrical impedance tomography (UMEIT) is a novel hybrid imaging technique, which utilizes coupling between electric and acoustic modalities. Based on the forward solver along different current directions, an instrumental electrode configuration is proposed for 3D UMEIT. The proposed electrode configuration can produce a similar longitudinal current, making the power density distribution on the x-y plane approximately consistent with the corresponding conductivity distribution. Then, this satisfying power density is adopted to reconstruct a higher-resolution conductivity distribution. Therefore, the proposed electrode configuration contributes to improving the image reconstruction quality of UMEIT. Also, to clearly demonstrate its meaning in theory, the forward solver results are analyzed from an electrical point of view. In addition, the nonlinear partial differential equation (PDE) relating the power density to the measured data is derived again with a more reasonable expression. Finally, simulation with realistic geometry model of human breast is done and feasibility verifying experiment is made. Both simulation and experimental results validate the feasibility of the proposed electrode configuration.

Index Terms

Electrode configuration; Electrical impedance tomography; Inverse problem; Image reconstruction; Ultrasound modulated electrical impedance tomography

I. Introduction

Electrical properties of biological tissues provide important functional information for characterizing tissue and detecting abnormalities. Consequently, sensing and imaging these properties noninvasively could play a role for diagnosing disease, for example cancer detection. Conventional electrical impedance tomography (EIT) reconstructs the conductivity distribution by injecting current into the imaging object and measuring the resulting voltage on its boundary [1–3]. EIT has merits for being safe, non-invasive, low-cost and portable. However, with limited measurement information, the inverse problem of EIT is ill-posed, and the reconstructed images are of low resolution [4].

Recently, hybrid imaging techniques have been investigated to obtain more effective measurement information and reduce the ill-posed nature of the inverse problem for conventional EIT [5–8]. The hybrid imaging described here refers to techniques involving interaction of physical processes, which are different from fusing images of different modalities. As a kind of hybrid imaging technique, ultrasound modulated electrical impedance tomography (UMEIT) combines the contrast advantage of EIT and resolution advantage of ultrasound imaging. Based on the acousto-electric effect, UMEIT can not only measure the boundary voltages response to the current injections, but also obtain additional measurements with position information: the boundary voltages response to the current injections with ultrasound beam focusing on the imaging object. Thus, compared with EIT, UMEIT can obtain more effective measurement information. Also, the intrinsic resolution of UMEIT depends on the size of the focal spot, a few millimeters, such that UMEIT can provide higher resolution compared to standard EIT. Therefore, UMEIT overcomes the shortcoming of conventional EIT, while retaining its merits.

In 2004, acousto-electrical tomography (AET) was proposed by Zhang and Wang [9], which is a basis for the generation and development of UMEIT. A four-electrode impedance-measuring system was used to detect the acousto-electric signal. The electrodes and the ultrasound transducer were raster scanned together in the x-y plane with a step size of 1.2 mm in both directions. Plotting the detected acousto-electric signals at different focal locations, AET directly forms images without resorting to inverse algorithms.

Then, the image reconstruction of UMEIT has been widely investigated mathematically. Ammari related the power density to the measured data with ultrasonic perturbation and reconstructed the conductivity distribution from the power density [10]. Capdeboscq introduced two objective functions from the optimization point of view and solved them with descent method and Gauss-Newton method respectively [11]. Bal investigated the Cauchy problem for UMEIT [12] and showed that the conductivity can be uniquely and stably reconstructed from knowledge of a sufficient large number of power densities [13]. Also, Levenberg–Marquardt iteration algorithm is implemented to reconstruct the conductivity [14] and some investigations about the anisotropic conductivity reconstruction from power densities are made by Monard and Bal [15] and Bal *et al.* [16]. Using synthetic focusing instead of perfect focusing of ultrasound perturbing the imaging object, Kuchment firstly synthesized the power density from the measured data and then proposed a linearized algorithm for the image reconstruction of UMEIT [17–18]. These works lay a good

foundation for the mathematical theory of UMEIT image reconstruction and prove that the feasibility of UMEIT image reconstruction. However, until now, the electrode configuration has not been investigated, which is critical for obtaining more measurement information and improving the image reconstruction quality.

In this paper, based on the forward solver along different current directions, an instrumental electrode configuration is proposed for 3D UMEIT. The forward solver results are analyzed from an electrical point of view, and the relationship between power density and conductivity distribution is also discussed. In addition, to improve the power density theory, the nonlinear PDE relating the power density to the measured data is derived again with a more reasonable expression. Then, utilizing the derived power density expression, the power density and conductivity reconstruction with the realistic geometry model of human breast is accomplished. Finally, a feasibility experiment is made to validate the effectiveness of the proposed electrode configuration.

II. Ultrasound Modulated Electrical Impedance Tomography

As illustrated in Fig. 1, a typical UMEIT system is composed of four main parts: ultrasound equipment and scanning device, electrode arrays, data acquisition system and image reconstruction system/host computer. Two major computational problems exist in UMEIT, the forward problem and the inverse problem.

A. Forward Problem

Calculations of the potential distribution u , power density distribution S of the imaging object without ultrasonic perturbation and the perturbed potential distribution u_ω of the imaging object with ultrasonic perturbation from the known conductivity distribution and boundary conditions are called the forward problem of UMEIT.

Without ultrasonic perturbation, the relationship between conductivity and potential distribution u is demonstrated by the following equation

$$\begin{cases} \nabla \cdot (\sigma \nabla u) = 0 & \text{in } \Omega \\ \sigma \frac{\partial u}{\partial n} = j & \text{on } \partial\Omega, \end{cases} \quad (1)$$

where σ is the conductivity distribution in Ω , j is the applied current density on Ω and Ω is the domain of imaging object. The boundary voltage in the absence of ultrasonic perturbation is denoted as $\phi = u|_{\Omega}$.

After obtaining the potential distribution u by solving the above equation, electric field and power density distribution S can be calculated according to the definitions

$$E = -\nabla u, \quad (2)$$

and

$$S = \sigma |E|^2, \quad (3)$$

respectively.

Based on acousto-electric effect [19–22] shown in Fig. 2, depicting that focused ultrasound changes the conductivity in the focal spot, when ultrasound focus in a region ω of the imaging object, the resulting conductivity distribution σ_ω equals to

$$\sigma_\omega = \sigma + \delta\sigma, \quad (4)$$

and

$$\delta\sigma = kP\sigma, \quad (5)$$

where $\delta\sigma$ is the change of conductivity, P is the applied ultrasonic pressure, and k is the medium dependent modulation coefficient, which is of the order of 10^{-9} Pa^{-1} in 0.9% NaCl solution [21–22].

In the presence of ultrasonic perturbation localized in the ω region, with the same current j injected, the relation between the perturbed conductivity σ_ω and perturbed potential u_ω satisfies

$$\begin{cases} \nabla \cdot (\sigma_\omega \nabla u_\omega) = 0 & \text{in } \Omega \\ \sigma_\omega \frac{\partial u_\omega}{\partial n} = j & \text{on } \partial\Omega. \end{cases} \quad (6)$$

In the presence of ultrasonic perturbation localized in the ω region, the corresponding boundary voltage is denoted as $\phi_\omega = u_\omega|_{\Omega}$. And the change of potential is $\delta u = u_\omega - u$, due to the small conductivity perturbation $\delta\sigma$.

B. Inverse Problem

The inverse problem for UMEIT is to determine the conductivity distribution of the imaging object using a set of given values of applied current density, the corresponding boundary voltage and reconstructed power density distribution.

Firstly, the power density distribution of imaging object is reconstructed using the boundary voltage with and without the ultrasonic perturbation. The nonlinear PDE relating the power density to the measured data is derived and presented in the Section IV. Then, the reconstructed power density distribution is used to implement the conductivity reconstruction with image reconstruction algorithm.

III. An Instrumental Electrode Configuration

In this section, an instrumental electrode configuration is proposed based on the forward solver along different current directions. Then, the forward solver results are analyzed from an electrical point of view, and the relationship between power density and conductivity distribution is also investigated.

A. The Proposed Instrumental Electrode Configuration

Electrode configuration is important for boundary voltage measurements and image reconstruction in UMEIT. Selecting proper electrode configuration can help to obtain more measurement information and improve the image reconstruction quality. Shown in Fig. 1, ultrasound goes through along z axis. As displayed in Fig. 3(a), the transverse current referred in this paper denotes the x direction current, while the longitudinal current indicates the current along z axis direction. The entire areas of two surfaces are simulated as electrodes to inject current. Forward problem simulation experiments are made using the tested model Fig. 3(a). 3D tested model of $6 \times 6 \times 12 \text{ cm}^3$ is built as the imaging object in this simulation study. The origin of the coordinate system is set at the center of the object. The model is a cube with three inclusions whose parameters are shown in Table 1. The conductivity distributions in the slices at $z = -3, 0$ and 3 cm , Fig. 3(b), are displayed in Fig. 3(c). Fig. 4 displays the 3D current density line and the power density distribution in the corresponding three slices, with transverse current and longitudinal current respectively.

Comparing the power density distributions with conductivity distributions Fig. 3(c), it's obvious that it is difficult to directly extract conductivity distribution information from the power density distribution with the transverse current pattern, while, with the longitudinal current pattern, the conductivity distribution can be almost inferred from the power density distribution. With the longitudinal current pattern, the power density distribution is approximately consistent with the conductivity distribution. Therefore, with same image reconstruct algorithm, a higher-resolution conductivity reconstruction result can be obtained with this satisfying power density distribution.

According to the forward solver results, an instrumental electrode configuration is proposed, shown in Fig. 5 (a). From the 3D current density lines shown in Fig. 5 (b), it can be seen that the proposed electrode configuration has similar current density distribution with the longitudinal current pattern. Also, the power density distributions in Fig. 5 (c) are consistent with the corresponding conductivity distributions.

B. Forward Solver Results Analysis

To clearly demonstrate the meaning of the proposed electrode configuration, the forward solver results are analyzed from an electrical point of view. This section presents the relationship between power density and conductivity distribution with different current directions and explains why, for the same conductivity distribution, different power density distributions are produced with different current directions. Firstly, the relationship between power density and conductivity with transverse current is demonstrated. Then, the relationship with longitudinal current is explained.

1) Relationship Between Power Density and Conductivity With Transverse

Current—For the tested mode shown in Fig. 3(a), forward problem simulation results with transverse current, including the equipotential line distribution and power density distribution in the slice at $z = 0$ cm, are displayed respectively in Fig. 6 (a) and (b).

Consider the discrete local field as uniform electric field, i.e.,

$$E = \frac{U}{d}, \quad (7)$$

where U is the potential of the local field and d is a distance along the direction of potential drop.

For the conductivity varying boundary n shown in Fig. 6, the conductivity distributions on both sides are approximately connected in parallel with the same potential value U . Thus, the power density equals to

$$S = \sigma E^2 = \sigma \left(\frac{U}{d} \right)^2. \quad (8)$$

Therefore, the change of conductivity distribution leads to an approximately consistent change for the corresponding power density distribution. As shown in Fig. 7 (a), the above relationship is further confirmed by the line profiles of conductivity and power density along the white dashed lines y marked in Fig. 6 (b) and Fig. 3 (c). When the conductivity has an increased or reduced change, there is a nearly synchronous consistent change, increased or reduced, for power density distribution.

For the conductivity varying boundary m shown in Fig. 6, the conductivity distributions on both sides are approximately connected in series circuit with the same current value I . According to Ohm's law, the potential is inversely proportional to the conductivity as

$$U = IR = I\rho \frac{l}{s} = I \frac{l}{\sigma s}, \quad (9)$$

where length l and cross-sectional area s are the parameters of the local field, and ρ is the resistivity.

Substituting (7) and (9) into (3), we have the following approximate relationship

$$S = \sigma E^2 = \frac{1}{\sigma} \left(I \frac{l}{sd} \right)^2. \quad (10)$$

Therefore, the change of conductivity distribution leads to an approximately reversed change for the corresponding power density distribution. Shown in Fig. 7 (b), the above relationship

is further confirmed by the line profiles of conductivity and power density along the white dashed lines x marked in Fig. 6 (b) and Fig. 3 (c). When the conductivity distribution has an increased or reduced change, there is a nearly synchronous reversed change, reduced or increased, for power density distribution.

2) Relationship Between Power Density and Conductivity With Longitudinal

Current—For the tested mode shown in Fig. 3(a), forward problem simulation results with longitudinal current pattern, including the 3D current density lines and 2D power density distribution in the slice at $z = 0$ cm, are respectively displayed in Fig. 8.

Based on the analysis about the relationship between power density and conductivity with transverse current, with longitudinal current, the conductivity distributions on both sides of all conductivity change interfaces are approximately in parallel. So, the power density distribution has a nearly synchronously consistent change with the conductivity distribution. As shown in Fig. 9 (a–b), the above relationship is further validated by the line profiles of conductivity and power density along the white dashed lines y and x marked in Fig. 8 and Fig. 3 (c) respectively. When the conductivity has an increased or reduced change, there is a synchronously consistent change, increased or reduced, for power density distribution. Therefore, with longitudinal current, power density distribution is approximately consistent with the corresponding conductivity distribution, and conductivity distribution can be even inferred from power density distribution.

This section investigates the relationship between power density and conductivity distribution, which presents that the change of conductivity distribution will lead to a corresponding change for power density distribution with different current directions and demonstrates the meaning of the proposed electrode configuration. However, strictly speaking, both conductivity and electric field influence the power density distribution, according to the definition of power density (3). Thus, it need to point out that the change of conductivity distribution must lead to a corresponding change of power density distribution, analyzed in this section, while the former is not the only reason for the latter.

IV. PDE Derived for Power Density Reconstruction

In 2008, Ammari related the point-wise values of the power density to the measured data for the first time [10]. The derivation is based on the method of asymptotic expansions of small volume inclusions, and the ultrasonic perturbation is assumed to play a part in the variation of the focal volume only, assuming the density of conductivity to be constant. However, the influence of acousto-electric effect cannot be reasonably taken into account. The formula of power density reconstruction appeared in [23] for the second time. However, it neglected the part of acousto-electric effect and only reserved the part of measured data. Even though the part of measured data plays a leading role for the power density reconstruction, the part of acousto-electric effect is important and indispensable for demonstrating the meaning of power density. Therefore, the nonlinear PDE relating the power density to the measured data is derived again with a clear formulation, which directly and reasonably presents the influence of acousto-electric effect.

Based on a linear approximation of (6), the relationship between $\delta\sigma$ and the linear change δu can be expressed by

$$\nabla \cdot (\delta\sigma \nabla u) = -\nabla \cdot (\sigma \nabla \delta u). \quad (11)$$

Multiplying (11) by u and doing integral operation, according to divergence theorem, we have the following formula

$$\int_{\partial\Omega} u \delta j + \int_{\Omega} \delta\sigma \nabla u \cdot \nabla u = - \int_{\Omega} \sigma \nabla \delta u \cdot \nabla u. \quad (12)$$

Due to the same current injected $\delta j = 0$, $\int_{\partial\Omega} u \delta j = 0$. Therefore, we have the following formula

$$\int_{\Omega} \delta\sigma \nabla u \cdot \nabla u = - \int_{\Omega} \sigma \nabla \delta u \cdot \nabla u. \quad (13)$$

A. Approximate the Right-Hand Side of (13)

Based on identical equation $\nabla \cdot (\delta u \nabla u) = \nabla \delta u \cdot \nabla u + \delta u \nabla^2 u$, the right-hand side of (13) equals to following formula

$$- \int_{\Omega} \sigma \nabla \delta u \cdot \nabla u = - \int_{\Omega} \sigma \nabla \cdot (\delta u \nabla u) + \int_{\Omega} \sigma \delta u \nabla^2 u. \quad (14)$$

Assuming the conductivity is uniform, based on divergence theorem, the first term of the right-hand side of (14) satisfies

$$- \int_{\Omega} \sigma \nabla \cdot (\delta u \cdot \nabla u) = - \int_{\partial\Omega} \sigma \delta u \nabla u \cdot d\vec{s} = - \int_{\partial\Omega} \delta u j ds. \quad (15)$$

And, according to equation (1), $\sigma \nabla^2 u = 0$, and the second term of the right-hand side of (14) satisfies

$$\int_{\Omega} \sigma \delta u \nabla^2 u = 0. \quad (16)$$

With $\delta u|_{\Omega} = u_{\omega}|_{\Omega} - u|_{\Omega} = \phi_{\omega} - \phi$, the right-hand side of (13) is

$$- \int_{\partial\Omega} (\phi_{\omega} - \phi) j ds. \quad (17)$$

B. Approximate the Left-Hand Side of (13)

Since only ω region is perturbed by focused ultrasound, the small conductivity perturbation $\delta\sigma$ arises only in the ω region. Therefore, the exact form of the left-hand side of (13) is

$$\int_{\omega} \delta \sigma \nabla u \cdot \nabla u. \quad (18)$$

Substituting (5) into (18), it has the following form

$$\int_{\omega} k p \sigma \nabla u \cdot \nabla u. \quad (19)$$

In the discrete numerical processing, each focal spot is a pixel element. So the conductivity, potential and power density value, S_{ω} , in the ω region are constants. According to the definition of power density, equation (19) satisfies

$$S_{\omega} A_{\omega} \int_{\omega} k p, \quad (20)$$

where A_{ω} is the area of the ω focal spot.

Combing the approximate right-hand and left-hand side of (13), equation (17) and (20), the nonlinear PDE relating the power density to the measured data is derived

$$S_{\omega} = - (A_{\omega} \int_{\omega} k p)^{-1} \int_{\partial \Omega} (\phi_{\omega} - \phi) j ds. \quad (21)$$

The first part of equation (21) directly and reasonably demonstrates the influence of acousto-electric effect. It presents that both the applied ultrasonic performance and the medium feature influence the reconstruction of power density.

Equation (21) shows that the power density value of the focal spot can be acquired by perturbing the corresponding region. After scanning the whole section of the imaging object, the power density distribution of the corresponding section can be imaged.

V. Simulation and Experimental Results

A. Simulation With Realistic Geometry Model of Human Breast

In order to evaluate the practical performance of the proposed electrode configuration, a realistic geometry model of human breast is tested. According to the realistic magnetic resonance imaging (MRI) image of human breast [24] displayed in Fig. 10, the human breast model with tumors is constructed and shown in Fig. 11. The breast model is composed of fat, gland area and tumors, and the conductivities of those components are shown in Table 2. The height of the breast model is 7 cm. The maximum diameter of the breast is 15 cm. With 6 cm height, the maximum diameter of the gland area is 10 cm. The larger tumor is 2 cm in side length, located at (2.2, 2.2, 0) cm. The smaller tumor is 1 cm in side length and 1.2 cm in height, located at (2.2, -2.3, 0) cm. 16 electrodes are attached on this breast model, with eight discrete electrodes in each layer. The current is injected from the discrete electrode, and then the boundary voltages are measured on these electrodes. Finite element method (FEM) is used to solve the conductivity problem with COMSOL software, which runs in an

Intel Core2 Duo CPU of 2.93 GHz. Using the measured boundary voltages without ultrasonic perturbation and with ultrasound perturbing the slice at $z = 2.2$ cm, the corresponding power density distribution is reconstructed according to derived equation (21). Applied ultrasonic pressure is 1.635 MPa, which is calculated using COMSOL. 10^{-9} Pa $^{-1}$ is used as the modulation coefficient, which has the same order in cardiac tissues [25–26]. What's more, using the J-substitution algorithm with homogeneous initial guess, the conductivity reconstruction is implemented. To conveniently compare, both the reconstructed and target power density and reconstructed conductivity distribution are normalized to the range from 0 to 1.

The power density reconstruction result is shown in Fig. 12 (d). It is obvious that the reconstructed power density distribution is of great consistency with the target one in Fig. 12 (c). Quantitatively, the correlation coefficient between the reconstructed power density distribution and the target one is 0.9809 and the relative image error is 0.1136. Also, along the black dashed lines x and y marked in Fig. 12 (c–d), the lines profiles of target and reconstructed power density distribution are displayed in Fig. 13. It can be seen that, compared with the target one, the power density distribution is precisely reconstructed. Besides, according to the target conductivity distribution Fig. 12 (b), the tumors in human breast can be almost identified from the reconstructed power density distribution. From the conductivity reconstruction result shown in Fig. 12 (e), it is obvious that, even with simple reconstruction algorithm, the reconstructed image can reflect the target conductivity distribution Fig. 12 (b) of the tested model. Besides, it also shows that the quality of the reconstructed conductivity distribution depends on the quality of the power density distribution. The improvement of power density reconstruction is the key to improving the image reconstruction quality for UMEIT.

B. Experimental Results

Feasibility verifying experiment is made to test the forward solver results analysis and further confirm the effectiveness of the proposed electrode configuration. The photography of experimental detail is displayed in Fig. 14. The chamber described in [26] is adopted, of which sample is placed inside the tunnel. Pork fat is used as sample and a small piece of pork muscle is put in the fat. A 1MHz single-element focused ultrasound transducer (A392S, Panametrics Inc., Waltham, MA) is excited by ultrasonic pulser/receiver (5077PR, Panametrics Inc., Waltham, MA) with a pulse repetition frequency (PRF) of 2 KHz. Along the z direction, the ultrasound goes across the acoustic window and focuses on the sample from below. In the focal spot, the beam size is 3.9 mm (lateral) and 2.2 mm (axial) and the peak pressure at the focal spot is 3.4 MPa. The sample is placed in the x-y plane. Sinusoidal current at 200 Hz passes through the sample along x direction, which is stimulated by a pair of platinum electrodes (S+ and S–) connected to function generator (33220A, Agilent Technologies Inc., Santa Clara, CA). Ultrasound is synchronized with the beginning of the injection current. An Ag/AgCl recording electrode (R) is used to detecting the resulting acousto-electric signal. Going through the high-pass filter (470 kHz cutoff frequency) and amplified with a total gain of 45 dB, the acousto-electric signal is captured by a data acquisition system (NI-PXI 5105, National Instruments Corp., Austin, TX) at 20 MHz. Controlled by a programmable stepper motor (Velmex Inc.), ultrasound transducer scans

along the black dashed line x and y with a step size of 0.5 mm and 0.12 mm respectively. For each focal position, the resulting acousto-electric signal is measured.

According to equation (21), the power density lines along black dashed line x and y in Fig. 14 are reconstructed using measured acousto-electric signals. Fig. 15 shows the power density along black dashed line y. It can be seen that at the range of -0.5 mm to 0.5 mm, power density is obvious larger than that at other zone. As current passes through the sample along x direction, line y vertical to the current direction. According to the analysis in section III-(B), it can be inferred that the conductivity at the range of -0.5 mm to 0.5 mm is larger than that at other zone. Shown in Fig.14, along y line, the muscle about 1 mm width is located in the middle of the fat. The muscle conductivity is higher than fat conductivity [27]. The experimental result is consistent with the target sample. The power density along x line is displayed in Fig. 16. Along x line, with the scanning of ultrasound transducer, the focal spot is away from the stimulating electrode and the current density at each focal spot decreases gradually. So the overall trend of power density is declining in Fig. 16. The perturbation of recording electrode leads to the irregular larger value around 5 mm. Near the positions -5 mm and 0 mm respectively, power density decrease after an increase. Considering that line x is parallel to the current direction, a larger conductivity distribution can be inferred at the range of -5 mm to 0 mm. This experimental result is also consistent with the target sample. Experiment, perfectly matching with simulation, cannot be made now and this simple feasibility verifying experiment is made instead. With the consistence between the experiment results and target sample, it validates that the forward solver analysis is feasibility and further confirms the potential and effectiveness of the proposed electrode configuration.

VI. Conclusion

An instrumental electrode configuration is proposed for 3D UMEIT. With the proposed electrode configuration, the power density distribution is approximately consistent with the corresponding conductivity distribution. Thus, a higher-resolution conductivity reconstruction result can be obtained with this satisfying power density distribution. Also, the relationship between power density and conductivity distribution is investigated from an electrical point of view, which demonstrates the reasonableness of proposed electrode configuration in theory. Besides, the nonlinear PDE relating the power density to the measured data is derived again with a clear formulation, and it directly and reasonably presents the influence of acousto-electric effect. Finally, both simulation and experiment are performed. Image reconstruction results with realistic geometry model of human breast demonstrate the potential of the proposed electrode configuration. Feasibility verifying experiment validates that the forward solver analysis is feasibility and further confirm the effectiveness of the proposed electrode configuration.

As a primary study for 3D UMEIT, an instrumental electrode configuration is proposed in this paper. Actually, based on this work, many needs to be further investigated in detail to improve the image quality of 3D UMEIT. For example, optimization of electrode number, way of electrode arrangement (aligned or offset for the two electrode layers), optimization of measurement strategy and so on.

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Biographies

Xizi Song received her B.S. degree in electronic information engineering from Hebei Normal University, Shijiazhuang, Hebei, China, 2012. She is currently working toward the Ph.D. degree at the School of Electrical and Information Engineering, Tianjin University, Tianjin. Her current research interests include electrical tomography, acoustoelectric tomography, modeling of acousto-electric effect, and other related hybrid imaging technique.

Yanbin Xu received the B.S., M.S., and Ph.D. degrees from Tianjin University, Tianjin, China, in 2001, 2004, and 2009, respectively, all in control science and engineering. She is currently an Associate Professor in School of Electrical and Information Engineering, Tianjin University. Her research interests include process tomography, biomedical imaging, inverse problem and hybrid imaging.

Feng Dong (M'03-SM'06) received the B.S., M.S., and Ph.D. degrees in control science and engineering from Tianjin University, Tianjin, China, in 1988, 1996, and 2002, respectively. He is a Professor with the School of Electrical and Information Engineering, Tianjin

University, and the Director of the Tianjin Key Laboratory of Process Measurement and Control. His research interests include process parameter detection and control system, industrial process tomography, multiphase flow measurement, and intelligent information processing.

Russell S. Witte graduated with Honors in Physics (BS, 1993) from University of Arizona and Bioengineering (PhD, 2002) from Arizona State University, where he used electrode arrays to study sensory coding and learning-induced plasticity in the brain. As a postdoctoral fellow at the University of Michigan, he helped develop state-of-the-art techniques to image the nervous and musculoskeletal systems. Dr. Witte now resides in his hometown of Tucson, where he is Associate Professor of Medical Imaging, Biomedical Engineering, and Optical Sciences at the University of Arizona. His Experimental Ultrasound and Neural Imaging Laboratory (EUNIL) devises hybrid imaging methods that integrate light, ultrasound, and microwaves for advanced imaging with novel contrast. These noninvasive techniques, such as acoustoelectric imaging, thermoacoustic imaging, and ultrasound elastography, quantify changes in the electrical, optical and/or mechanical properties of tissue at high spatial resolution. The ultimate goal of Dr. Witte's research is to improve patient care by providing tools that improve diagnostic accuracy and treatment-decision making for a variety of conditions ranging from epilepsy and arrhythmia to tendinopathy and cancer.

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Fig. 1.
Typical illustrative diagram of UMEIT system.

Fig. 2.
Sketch of acousto-electric effect.

Fig. 3.

Model for forward problem simulation experiments. (a) tested 3D model, I_x represents transverse current along x direction, and I_z indicates the longitudinal current along z direction, (b) slices at $z = -3, 0$ and 3 cm, (c) conductivity distributions in these three slices.

Fig. 4.

Forward problem simulation results of transverse current pattern and longitudinal current pattern respectively. (a) 3D current density lines and (b) the power density distributions in the slices at $z = -3, 0$ and 3 cm with transverse current pattern; (c) 3D current density lines and (d) the power density distributions in the slices at $z = -3, 0$ and 3 cm with longitudinal current pattern.

Fig. 5. Proposed electrode configuration. (a) electrode configuration, (b) 3D current density lines and (c) the power density distributions in the slices at $z = -3, 0$ and 3 cm.

Fig. 6. Relationship between power density and conductivity with transverse current. (a) the equipotential line distribution in the slice at $z = 0$ cm and (b) the corresponding power density distribution.

Fig. 7.

Line profiles of power density and conductivity along the white dashed lines y and x marked in Fig. 6 (b) and Fig. 3 (c). (a) along line y and (b) along line x.

Fig. 8. Relationship between power density and conductivity with longitudinal current, including the 3D current density lines and the 2D power density distribution in the slice at $z = 0$ cm.

Fig. 9.

Line profiles of power density and conductivity along the white dashed lines y and x marked in Fig. 8 and Fig. 3 (c). (a) along line y and (b) along line x.

Fig. 10.
Realistic MRI image of human breast.

Fig. 11.

Calculation model of realistic geometry human breast with electrodes. (a) top view of the model, (b) side view of the model.

Fig. 12.

Power density and conductivity reconstruction result. (a) slice at $z = 2.2$ cm for human breast model shown in Fig.11, (b) target conductivity distribution in the slices at $z = 2.2$ cm, (c) the corresponding calculated power density distribution based on forward solver and (d) the corresponding reconstructed power density distribution, (e) reconstructed conductivity distribution from the reconstructed power density distribution in (d).

Fig. 13.

Lines profiles of target and reconstructed power density distribution along the black dashed line x and y marked in Fig. 12 (c–d).

Fig. 14.
Photography of experimental detail.

Fig. 15.
Power density line along black dashed line y in Fig. 14.

Fig. 16.
Power density line along black dashed line x in Fig. 14.

TABLE I

Parameters of Model Shown as Fig. 3 (a)

Media	Center (cm)	Side length (cm)	Height (cm)	Conductivity (S/m)
medium 1	(0,0,0)	6	12	0.5
medium 2	(-1, 0, 1.5)	2	6	2
medium 3	(1.6, 0, -1.5)	1.2	5	2

TABLE II

Conductivity of Breast Model

Breast	Fat	Gland area	Tumor
Conductivity (S/m)	0.04	0.06	0.6