A hand-held probe for combined ultrasound and electrical impedance tomography

R. Kulkarni¹, T-J. Kao², G. Boverman³, G. J. Saulnier¹, D. Isaacson⁴, T. L. Szabo⁵, and J. C. Newell²

¹ Department of Electrical Engineering, Rensselaer Polytechnic Institute
² Department of Biomedical Engineering, Rensselaer Polytechnic Institute
³ USC, Information Sciences Institute
⁴ Department of Mathematics, Rensselaer Polytechnic Institute
⁵ Department of Biomedical Engineering, Boston University

E-mail: saulng@rpi.edu

Abstract. The admittivity differences observed between normal and malignant tissue make electrical impedance tomography (EIT) a candidate technique for breast cancer detection. One way to improve tumor detection and classification is to combine EIT with other imaging modalities like ultrasound. We present in this paper a combined ultrasound/EIT hand-held probe which can simultaneously collect data from each modality. We develop a 6 × 6 ultrasound-like hand-held probe geometry using the Fourier decomposition method to obtain the forward solution in the linearized EIT reconstruction algorithm. We use a saline-filled tank to collect experimental target data for increasing target depths away from the electrode array. We demonstrate the satisfactory performance of the array with electrode dimensions 7 mm square, with a gap of 2 mm between electrodes and an overall array size of 54 × 54 mm in detecting a 1 cm² target up to depths of 25 mm. We also show successful detection of an agar target having lesser contrast, at lesser depths.

1. Introduction

The forward problem in electrical impedance tomography is to determine the voltages/currents on the surface of the body, given the admittivity distribution inside the body and currents/voltages applied to the surface. The inverse problem is to reconstruct the admittivity distribution inside the body given the voltage/current applied and measured on the surface of the body [1]. At Rensselaer, EIT data is collected using the fourth generation Adaptive Current Tomograph (ACT 4) [2]. Reconstructed images are made using the Newton’s One Step Error Reconstructor (NOSER) algorithm for image reconstruction as described by Isaacson [3]. This algorithm uses one step of the Newton’s method with constant admittivity as an initial guess [4].

EIT can be used in combination with other imaging modalities like ultrasound to improve tumor detection. This paper presents a dual-mode probe that can be used to collect ultrasound and EIT data simultaneously and in register. This probe places a 6 × 6 planar array of electrodes in front of an ultrasound probe, with the central electrodes being sonolucent. We solve the forward problem for a 6 × 6 hand-held geometry using a Fourier decomposition approach and show its satisfactory performance in detecting a copper target immersed up to depths of 25 mm.
in a saline tank. We also show results for an insulating target in a saline tank at lesser depths of up to 7 mm.

2. Dual ultrasound/EIT hand-held probe array
Figure 1 is a photograph of the dual-mode EIT/ultrasound hand-held probe. The probe uses a $6 \times 6$ array of EIT electrodes. A standard ultrasound probe is inserted inside the housing, with the active end of the ultrasound probe coupled to the back of the sonolucent central two columns of the array using ultrasound gel. These sonolucent electrodes are constructed by depositing a thin layer of gold on Kapton. The outer columns of electrodes are constructed as printed circuit boards (PCB). The overall probe is placed in contact with the patient using ultrasound gel which provides the needed electrical and acoustic coupling. The electrode array is a square grid with 6 electrodes in the $x$ and $y$ direction. The dimensions of the electrodes are 7 mm square, with a gap of 2 mm between electrodes. The array size is $54 \times 54$ mm.

3. Fourier Forward Solution
The hand-held probe geometry can be modeled as an infinite half space, with the $x$ and $y$ co-ordinates going from $-\infty$ to $+\infty$ whereas the $z$ co-ordinates go from 0 to $+\infty$. We express the forward solution as a decomposition of its Fourier components as done previously in the mammography geometry [4], [5], [6]. We solve the problem using the method of separation of variables. The forward voltage obtained by decomposition using the eigenfunctions of the ave-gap model [7], can be expressed as:

\[
U(x, y, z) = \sum_{n=0}^{F} \sum_{m=0}^{F} u_{n,m} \cos \left( \frac{n\pi x}{h_x} \right) \cos \left( \frac{m\pi y}{h_y} \right) e^{-\lambda_{n,m} z} \tag{1}
\]

Here $U(x, y, z)$ is the electric potential, $F$ is the number of Fourier coefficients and $\lambda_{n,m} = \sqrt{\frac{n\pi^2}{h_x^2} + \frac{m\pi^2}{h_y^2}}$. We solve for the unknown coefficient $u_{n,m} = \frac{j_{n,m}}{\gamma_0 \lambda_{n,m}}$ where, $j$ is the current density and $\gamma_0$ is constant admittance from which the varying admittance $\gamma$ perturbs only slightly. This gives the forward solution in a homogeneous medium, with assumed constant admittance $\gamma_0$.

The reconstruction algorithm is a linearized algorithm that assumes an admittance distribution $\gamma(x, y, z)$ that differs only slightly from a constant value $\gamma_0$ for the homogeneous model [3].

4. $6 \times 6$ hand-held probe geometry
We built a PCB electrode array with the same dimensions as the $6 \times 6$ hand-held probe array for the purpose of experimentation. Figure 2 shows the geometry of the PCB electrode array. We test the implementation of our algorithm with an experimental tank with the $6 \times 6$ electrode array in one of the side walls. The tank dimensions are 41 cm, 58 cm, and 83.5 cm, in the $x$, $y$
and z directions, respectively. The tank was filled with saline solution with conductivity of 190 mS/m. Figure 3 shows the experimental tank set-up. We obtained the voltage data from this tank for the set of optimal current patterns for the 6 × 6 array geometry with a 1 cm³ copper target placed at different depths away from the electrode array. The reconstruction mesh used was a 576 voxel mesh, with 9 slices of 8 × 8 voxel grid each. Each slice was 5 mm thick except the first two slices which were 2 mm and 3 mm respectively. Reconstructions were obtained up to a depth of 40 mm. We do not display the first 2 mm slice adjacent to the electrode array in the reconstructions shown in Figure 4 due to its proximity to the electrode array which causes the reconstructed conductivity in this region to be considerably high in all voxels in the slice. We observe satisfactory depth resolution of the target for the reconstructions at all depths.

Next we explore the performance for a rod shaped insulating cylindrical object with diameter of 7 mm. The target is 7 mm from the array. Figure 5 shows the position in which the insulating target is held and reconstructions in the appropriate location. and as having lower conductivity than the medium.

5. Future work
In the future we would like to collect data with the hand-held probe in register with ultrasound data and analyze the results obtained from the two modalities. Of particular interest is the potential usefulness of the dual-mode data in the detection of breast cancer.

References
[1] Isaacson D and Edic P 1992 IEEE EMBC 14 1693
[2] Saulnier G J, Ning L, Tamma C, Xia H, Kao T, Newell J and Isaacson D 2007 29 th IEEE EMBS Annual International Conference (Lyon, France)
[3] Isaacson D, Cheney M, Newell J, Simske S and Goble J 1990 Imaging Systems and Technology 2 66–75
[4] Choi M, Kao T J, Isaacson D, Saulnier G and Newell J 2004 Engineering in Medicine and Biology Society 2 1310–1313
[5] Kulkarni R, Boverman G, Isaacson D, Saulnier G J, Kao T J and Newell J C 2009 Physiological Measurement 30 S19–S34
[6] Kulkarni R 2009 Analytical forward models for breast cancer detection using electrical impedance tomography Ph.D. thesis Troy, NY
[7] Mueller J, Isaacson D and Newell J 1999 IEEE trans. on Biomedical Eng 46 1379–1386
Figure 4. Reconstructions using $6 \times 6$ array with a target at 5 different depths as shown in the right-most column. The palette is the same across each row, but has less value as the target depth increases.

Figure 5. Difference reconstruction of an insulating target using the $6 \times 6$ array.