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A method for analyzing electrical impedance spectroscopy data from breast cancer patients

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Introduction:

Electrical Impedance Tomography (EIT) is an imaging modality that estimates and reconstructs the electrical properties in a body from voltage and current measurements made at electrodes on its surface.

Research on freshly-excised breast tissues and in an *in vitro* impedance cell has shown found that breast tumors have different conductivity and permittivity from normal or non-malignant anomalies. Therefore, the contrast in the electric properties between normal and malignant tissues may provide a basis for breast cancer detection using EIT.

In this presentation, we describe a procedure for collecting electrical impedance spectroscopy data simultaneously and in register with Tomosynthesis data from patients at Massachusetts General Hospital. We next describe the methods used to analyze the data in order to determine if the electrodes are making contact with the breast of the patient. We describe the canonical voltage patterns applied and how these patterns can be used to synthesize the data that would have resulted from constant voltage patterns applied to each of the two parallel mammography plates. A type of Cole-Cole plot is generated and displayed from each of the currents measured on each of the electrodes for each of the frequencies (5k, 10k, 30k, 100k, 300k and 1 MHz) of applied voltages. We illustrate the potential usefulness of these displays in distinguishing breast cancer from benign lesions with the Cole-Cole plots for 2 patients - one having cancer and one having a benign lesion - by comparing these graphs with electrical impedance spectra previously found by Jossinet in tissue samples taken from a variety of patients.

ACT 4 System: [1, 2]

The ACT 4 system is the new electrical impedance imaging system being developed at Rensselaer. It is a high-speed, high-precision, multi-frequency, multi-channel instrument.

The ACT 4 system supports 64 channels and electrodes. Each electrode is driven by a high precision voltage source, and has a circuit for measuring the resulting electrode current. These circuits are digitally controlled to produce and measure signals at 5k, 10k, 30k, 100k, 300k and 1MHz. The magnitude and phase of each source are controlled independently.

ACT 4 has a distributed digital system, including a personal computer, digital signal processors (DSP) and field-programmable gate arrays (FPGA). We use FPGAs mainly for signal generation, voltage and current measurement, and analog circuit control.

Experimental Setup and Method:



The ACT 4 and Tomosynthesis Systems

- Breasts are compressed between mammography plates that have radiolucent electrode arrays attached.
- 60 Electrodes in two 5x6 arrays
- 60 voltage sources, controlled to 16 bits precision
- 60 current measurements on the same electrodes
- Each source, and each voltage and current measurement, is calibrated to a common standard reference
- 0.5 volts peak at all frequencies: 5 kHz – 1 MHz
- Currents per electrode range up to 0.4 mA peak at 5 kHz and up to 4.9 mA at 1 MHz in 10 mmx10 mm electrodes
- Total applied currents are below 3.5 mA at 5 kHz and below 55 mA at 1 MHz
- 59 ortho-normal excitation patterns are used to maximize distinguishability
- Real component → Conductivity Imaginary component → Permittivity

Method to Analyze the Data:

The ACT 4 system has voltage sources which are used to apply orthogonal sets of voltage patterns. After applying these patterns into the body, ACT 4 measures both the voltages and the currents. The measured voltage patterns are generally not orthogonal because the sources are not ideal. In order to use these measured voltage and current patterns in the data analysis, some pre-processing is needed.

➤ Step 1: Compute the synthesized current patterns \vec{T}_k that would be produced by \vec{U}_k .

$$\vec{V}_k \in \mathbb{C}^{L \times 1}, \vec{I}_k \in \mathbb{C}^{L \times 1} : \text{complex measured voltage and current patterns from experimental data}$$

$$\vec{U}_k \in \mathbb{R}^{L \times 1} : \text{real orthogonal voltage patterns (given)}$$

where L : number of electrodes

Using the orthogonal patterns \vec{U}_k , for any vector \vec{V}_k , the following equation should be satisfied

$$\vec{V}_k = \sum_{i=1}^{L-1} \langle \vec{U}_i, \vec{V}_k \rangle \vec{U}_i = \sum_{i=1}^{L-1} Q_{i,k} \vec{U}_i \quad \text{where } Q_{i,k} \equiv \langle \vec{U}_i, \vec{V}_k \rangle$$

And current patterns \vec{I}_k should be also satisfied as

$$\vec{I}_k = \sum_{i=1}^{L-1} Q_{i,k} \vec{T}_i$$

Using the inverse matrix of \mathbf{Q} , therefore, we have the following synthesized current patterns \vec{T}_k .

$$\vec{T}_k = \sum_{i=1}^{L-1} F_{i,k} \vec{I}_i \quad \text{where } \mathbf{F} \equiv \mathbf{Q}^{-1}$$

➤ Step 2: Compute the synthesized current vector \vec{J} that would be produced by \vec{W} .

$$\vec{W} \in \mathbb{R}^{L \times 1} : \text{real constant voltage vector (given)}$$

$$\vec{J} = \sum_{i=1}^{L-1} \langle \vec{U}_i, \vec{W} \rangle \vec{T}_i$$

where M : magnitude

For any vector \vec{W} , the following equation should be satisfied

And therefore, current vector \vec{J} should be also satisfied as

➤ Step 3: Compute and display admittance \vec{Y} .

$$Y_\ell = \frac{J_\ell}{W_\ell} \quad \ell = 1, 2, \dots, L$$

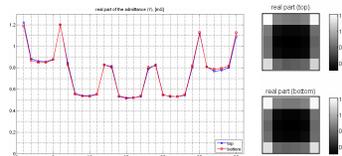
➤ Step 4: Using real part of admittance (\vec{Y}), determine if the electrodes are making contact with the breast skin of the patient.

➤ Step 5: Using admittance (\vec{Y}), a type of Cole-Cole plot is generated and displayed for each of the frequencies (5k, 10k, 30k, 100k, 300k and 1MHz).

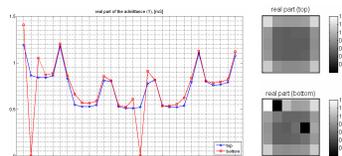
Experimental Results:

➤ Touching-electrode Test – Saline Tank Data

✓ All of the electrodes are making contact with the saline.

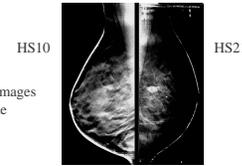


✓ The electrodes 2 and 17 at the bottom plane are taped in order to make non-touching-electrode with the saline.



➤ Tomosynthesis Images – Patient Data

✓ Which one has cancer?

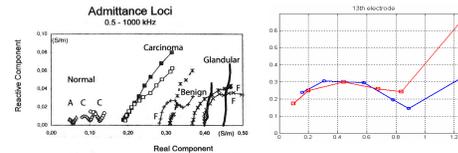


Here are Tomosynthesis images of the 2 subjects before the spectral data.

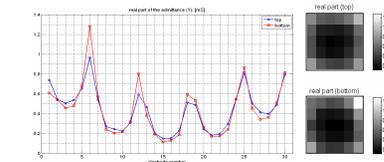
➤ Admittance Loci (Cole-Cole Plot)

Admittance Loci from *in vitro* tests provided by Jossinet & Schmitt [6]

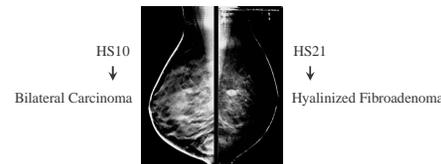
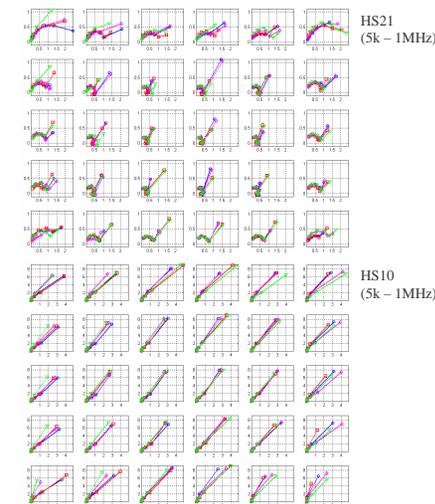
Admittance Loci from a pair of opposite electrodes on a normal breast



✓ Touching-electrode test

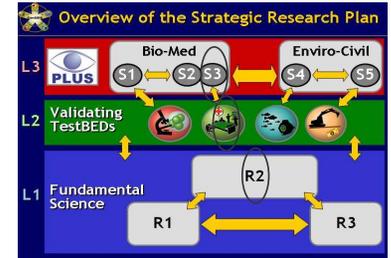


✓ Admittance Locus of all 30 pairs of electrodes – both breasts



Importance of the work and technology transfer:

The EIT clinical data and analysis in mammogram geometry will provide a foundation to assess the value of EIT as an adjunct to mammography for breast cancer screening and diagnosis. This is expected to be of significant commercial interest if a pathognomonic signature can be identified transcutananeously.



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Future Plans:

The ACT 4 system is collecting patient data from normal and breast cancer patients at Massachusetts General Hospital. This study will establish the ability of EIT to detect cancer by directly comparing EIT results with pathology findings. The main focus of the present work is to improve the reconstruction algorithms with the planar electrode geometry for the irregular boundary presented by the compressed breast.

Left Breast: blue-top red-bottom
 Right Breast: magenta-top green-bottom

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Publications Acknowledging NSF Support:

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Others:

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