Innovative biomagnetic imaging sensors for breast cancer: A model-based study

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Abstract: Breast cancer is a serious potential health problem for all women and is the second leading cause of cancer deaths in the United States. The current screening procedures and imaging techniques, including x-ray mammography, clinical biopsy, ultrasound imaging, and magnetic resonance imaging, provide only 73% accuracy in detecting breast cancer. This gives the impetus to explore alternate techniques for imaging the breast and detecting early stage tumors. Among the complementary methods, microwave imaging has led to considerable motivation for developing complementary breast imaging methods. Among them, microwave breast imaging avoids breast compressions that the prevalent x-ray mammography suffers from are avoided. It therefore offers very high contrast because of the significant electromagnetic properties’ differences between the cancerous, benign, and normal breast tissues. In this paper, a hybrid and accurate modeling tool for biomagnetic breast imaging is developed, which couples the electromagnetic and ultrasonic energies, and initial validations between the model prediction and experimental findings are conducted.

I. INTRODUCTION

Breast cancer is the second leading cause of cancer deaths among women in the United States. The five-year survival rate for breast cancers diagnosed prior to metastasis has been reported as 97%. Thus, regular health examinations at an early stage could help detect cancer and increase the survival rate. The need for early-stage breast cancer detection with high levels of specificity (detect only cancerous tumors) and sensitivity (detect most tumors in the breast) has led to the development of several diagnosis and treatment methods.

Unfortunately, even in the case of prevalent x-ray mammography techniques, about up to 15% of breast cancer cases are improperly diagnosed, and biopsy outcome corroborating the findings of x-ray mammogram has been reported to range between 10-50%. It is also difficult to image the 25% of women who have dense breast. Lastly, there are health concerns related to exposure to ionizing radiation, and many women find breast compression in mammography uncomfortable or painful. Other medical imaging modalities have been investigated and applied to breast imaging, such as ultrasound (US) imaging and magnetic resonance imaging (MRI). However, both of them, especially the MRI, are relatively expensive as a screening tool. The limitations of those modalities have led to considerable motivation for developing complementary breast imaging methods. Among them, microwave breast imaging is very promising, because recent research and data\textsuperscript{1} suggest that the electrical properties of breast tissue offer a high contrast for depiction of malignancy over wide portions of the non-ionizing electromagnetic (EM) spectrum, in which the literature review results that demonstrated the high contrast between malignant and benign tissues are shown.\textsuperscript{1}

Moreover, microwave breast imaging avoids breast compressions, and the examination usually offers higher throughput than US and MRI due to the fast imaging speed.\textsuperscript{7}

Several research groups in the world are actively focusing on utilizing microwave imaging to detect breast cancer. The first near-field microwave imaging system used in clinical trials was developed at Dartmouth College,\textsuperscript{2,3} and their initial results were just published in Radiology in 2007; different ultra-wideband (UWB) microwave imaging systems were developed by researchers at Duke University\textsuperscript{4} and the University of Bristol, UK.\textsuperscript{5} Since the year 2009, different new biomagnetic sensors have been investigated at the author’s group, including eddy current imaging, microwave imaging, and innovative hybrid-sensing techniques, such as thermoacoustic imaging.

Microwave-induced thermoacoustic imaging is a noninvasive modality, which can provide unique information for dielectric materials, e.g., breast tissues characterization based on thermoelastic wave generation, by taking advantage of high microwave absorption coefficients’ contrast of biological tissues and retaining the superior spatial resolution of ultrasonic waves. Both microwave and ultrasonic imaging techniques are two common methods of assessing the internal conditions of biological tissues in medical fields or the structural integrity of materials in nondestructive testing (NDT). Although not widely accepted by clinicians yet, microwave imaging has developed into an important research imaging technique for materials evaluation and tumor detection, with excellent sensitivity of dielectric property variation and rapid inspection speed without using any couplant. However, there are inherent weaknesses of microwave imaging, including modest accuracy and large lesion detection size. On the other hand, ultrasonic imaging techniques do not suffer from these weaknesses. However, ultrasonic techniques also have inherent weaknesses as compared to microwave methods, such as

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limited penetration depth and poor selectivity as a result of severe attenuation and its moderate sensitivity to acoustic impedance difference. Intuitively, it would be beneficial for medical imaging of tumors detection if we can combine these two techniques into a hybrid technique to take advantage of their inherent advantages. Actually, this approach, which is referred to as microwave-induced thermoacoustic imaging, has been successfully applied in a lab environment, since it can provide much clearer and more affordable imaging as compared to other methods, such as pure ultrasound and microwave imaging. However, some basic imaging physics questions still need to be answered, so the experimental data can be better interpreted and understood, e.g., which material properties, acoustic differences, or dielectric differences dominate the thermoacoustic signals. That is challenging experimentally, since the difficulty lies in decoupling various physical parameters during data acquisition. A hybrid and accurate model is developed here to validate the experimental studies and help to understand the underlying physics better.

II. METHODS AND MODELS

To facilitate the biomagnetic sensors’ development, numerical modeling always plays a critical role by validating the experimental results and conducting efficient and low-cost simulation studies. The experimental setup of the thermoacoustic imaging system we modeled can be found in Mashal et al., and the simulation geometry is illustrated in Fig. 1. In this study, we choose the target as mixtures of ethylene glycol (EG), with micro-bubbles due to their echo-enhancing properties and low microwave absorption. The solution domains of both electromagnetic illumination and ultrasonic waves emission at diagnostic frequencies (MHz) overlapped in our hybrid model. To reduce the simulation time and computational efforts, the perfect matched layer (or absorbing boundary condition) was applied to limit both domains within 1.0 m². The microwave antenna is placed to the left of the dielectric target, with the ultrasound transducer/receiver to the right. Finite-difference time-domain (FDTD) formulations are adopted and different from previous microwave or ultrasonic simulations; the bio-heat effect is taken into consideration in our model and ultimately makes two types of energy coupled in our hybrid FDTD model.

Derived from the equations of thermal expansion and motion, assuming a homogeneous medium, the microwave-induced thermoacoustic imaging equation in its differential form is as follows:

\[ \nabla^2 p(r, t) - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} P(r, t) = -\beta_c \rho \frac{\partial^2}{\partial t^2} T(r, t), \tag{1} \]

where \( \Delta T = \frac{\Delta A R \cdot c^2}{\rho c_s} \), and \( \frac{\partial |E|^2}{\partial t} \) denotes the temperature change due to the microwave illumination and absorption. In our simulation, we simplify the source term on the right side of Eq. (1) further by the approximation

\[ -\beta_c \rho \frac{\partial^2}{\partial t^2} \left( \frac{1}{c_s^2} \frac{\partial |E|^2}{\partial t} \right) \approx -\beta_c \rho \frac{\partial^2}{\partial t^2} \sum_i |E_i|^2. \]

Here, \( C_p \) is the specific heat and SAR is the specific absorption rate; \( E \) is the electric field of interest, since we are simulating the transverse magnetic (TM) case with \( E_x = E_y = 0 \). \( p(r, t) \) and \( T(r, t) \) are the local acoustic pressure and temperature in the medium due to microwave absorption, and \( \beta_c \) is the volume expansion coefficient. \( c \) is the speed of ultrasound in the coupling media and biological tissues and \( \rho \) is the corresponding density of materials. We choose our microwave pulse length \( \tau \) to be 0.9 μs, so the ultrasound waves are in the MHz range. The coupling media for wave propagation is chosen to be safflower oil that has both low relative conductivity and relative permittivity.

III. RESULTS AND DISCUSSION

The microwave pulses kept impinging on the mixture target for a short period of time and depositing energy into it, causing temperature rising. After time \( \tau \), the total EM energy deposition can be calculated based on the approximation formula we derived above. By generating the ultrasonic waves at MHz, the axial resolution is consequently within the mm range; the lateral resolution mainly depends on the specification of the receiving transducers, e.g., the size or nominal element size, which is also at mm scale in our work. The same as the arbitrary unit (a.u.) applied in experimental data, we disregarded the units in our simulation data and conducted normalization in all of the following results. The integrated mesh for both microwave and ultrasonic FDTD model is discretized with \( \Delta x = \Delta y = 0.9468 \) mm.

Starting at about 30 μs, the ultrasound receivers for both experimental and simulation setup recorded one-dimensional (1D) acoustic signals, as shown in Figs. 2 and 3, respectively.
Be noted that, to obtain the clean experimental signals, an average of 200 waveforms have been performed. Also, due to the unavailability of the dielectric property values at the 100% weight concentration of micro-bubbles, the solution 6 result for simulation is not generated by our model. This is trivial, however, because, in this case, the acoustic signal is minimal, as demonstrated in the experimental results.

From both results, it is obvious that higher conductivity ($\sigma$) yields greater acoustic wave amplitude at 3 GHz microwave frequency because of more EM dissipation, and the thermoacoustic response diminishes with increasing concentrations of micro-bubbles. Furthermore, the change in the micro-bubble concentrations varies the speed of sound in the medium and surrounding oil environment. High concentration causes the reductions of both thermoacoustic signal amplitude and temporal width.

The model predictions agree with the Mashal et al. conclusion very well; furthermore, it can help to understand the imaging physics by easily decoupling the effects of dielectric and acoustic differences. Mashal et al. predicted that the different values of $\varepsilon_r$ and $\sigma$ of materials dominate the thermoacoustic data characteristics and, in spite of the temporal width reduction due to the varying acoustic velocity, the changes in amplitude are promising enough to warrant further investigation into the use of micro-bubbles as a potential contrast agent. Our model simulated two scenarios for dielectric differences only and acoustic differences only, shown in Figs. 4 and 5, respectively. From the features of the simulated curves, it is easily seen that the observed reduction and shape change in the first and second peaks of the response with increasing concentrations of micro-bubbles is mainly due to the reduced effective conductivity and relative permittivity, which can also be proved in analytic solutions, but is difficult to validate in experimental studies only. Another interesting finding that is hard to be revealed experimentally is, by integrating the $|E_z|^2$ over microwave pulses, we found that the power deposition on the homogeneous target is non-uniform, although most previous works assume constant distribution of energy absorption in thermoacoustic imaging research. Similar phenomena can be found in Peterson et al. for the 1D analytical solutions when a electromagnetic plane wave incidents on a 2D cylindrical object. Our hybrid modeling solutions show that the power deposition has a unique geometric signature and may affect the sensors development.

In this paper, an innovative biomagnetic sensing technique for breast cancer detection, microwave-induced thermoacoustic imaging, has been presented. An accurate and hybrid numerical model based on the FDTD method was developed and validated by the experimental results. The power and usefulness of the model study has been demonstrated by understanding the underlying physics of this new imaging method and may serve as a tool for future biomagnetic sensor development.