3D Microwave Breast Imaging Based on Multistatic Radar Concept System

Nikolai Simonov · Soon-Ik Jeon · Seong-Ho Son · Jong-Moon Lee · Hyuk-Je Kim

Abstract

Microwave imaging (MI) is one of the most promising and attractive new techniques for earlier breast cancer detection. Microwave tomography (MT) realizes configuration of a multistatic multiple-input multiple-output system and reconstructs dielectric properties of the breast by solving a nonlinear inversion scattering problem. In this paper, we describe ETRI 3D MT system with 3D MI reconstruction program and demonstrate its robustness through some examples of the image reconstruction.

Key words: Microwave Tomography, Cancer Detection, Electromagnetic Scattering Inverse Problem, Image Reconstruction, Microwave Imaging.

1. Introduction

The number of breast cancer patients has been increasing continuously during the last decades, especially in North America and some westernized countries [1]. Although X-ray mammography is the standard method for breast cancer detection, it uses harmful radiation, demonstrates a relatively high false negative rate, and is uncomfortable for patients due to the required breast compression. Some other conventional methods have been developed for the detection of breast cancer and produce improved quality of images, such as CT, MRI, and PET; however, these are more expensive.

Microwave imaging (MI) is a challenging alternative for cancer diagnostics. The main promising advantage is its higher sensitivity for breast cancer detection, which is based on the fact that breast tumors have considerably higher contrast at the microwave frequencies than at X-ray frequencies [2]~[9]. In addition, MI is safe, non-invasive, sensitive, and a potentially inexpensive method [2]~[9].

MI systems can apply monostatic, bistatic, or multistatic data acquisition methods. The multistatic method provides more information about the testing object, so it can also ensure better resolution and smaller reconstruction noise than other methods.

Two different active MI methods are available for breast cancer detection: microwave tomography (MT) [2]~[6] and UWB radar techniques [7]~[9]. The goal of the UWB MI radar systems is to reconstruct the im-

age of scatterer distribution only. Therefore, these types of systems apply relatively simple, approximate, and computational inexpensive algorithms, like confocal microwave imaging (CMI) that provides synthetic focusing of scattered signals [9].

In contrast to UWB MI radar, microwave tomography systems reconstruct an actual profile of dielectric properties inside the breast. Hence, MT provides more informative images than do UWB MI radars. This fact shows advantage of MT for cancer diagnostics, because the dielectric property of breast granularity can better identify cancer than can the image of scatterers. Because the MT system extracts more information about an object's inner dielectric structure, more extensive measured data of the multistatic multiple-input multiple-output (MIMO) scattering matrix must necessarily be processed.

At present, MI systems are challenging subjects of investigation and several groups around the world are researching and developing different types of MT systems. Some of these groups, like the one from the University of Wisconsin, USA, provide intensive theoretical and computer assisted investigations of MI using realistic numerical phantoms of the human breasts and numerical experiments of the image reconstruction [10]~[12].

Several experimental MI systems have been created in a number of different countries. Some of these have been applied in clinical trials, while others have been exploited for laboratory research. Most use a bath with a coupling liquid for better matching of antennas with the imaging object (human breast or other parts of bo-

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dies).

One of the first systems for early breast cancer detection was the MT system developed in Dartmouth College, USA [2], [3], [6], [13]~[15]. This system is currently being investigated in many clinical trials with real patients. It applies a circular array of 16 transmitting-receiving (Tx/Rx) monopoles that are arranged inside a bath filled with the coupling liquid. The system operates in the 0.5~3 GHz frequency band and can use 2D or 3D reconstruction algorithms [13]~[15].

The 2D MT system, which was created at the University of Keele, UK [5], [16], [17] applies a circular array of 24 Tx/Rx ceramic filled waveguides with opened ends. This array is attached to a metallic bath with the coupling liquid. The system operates in the 1.0~2.3 GHz frequency band and has been used to investigate imaging in soft animals tissues, like pig's extremities [16], [17].

The multistatic UWB radar from the University of Bristol, UK [18]~[20] provides 3D microwave imaging for early breast cancer detection. This group created and investigated systems with two spherical arrays that consist of 31 and 60 UWB antennas operating in 4~8 GHz frequency band [20]. Instead of the coupling liquid, the system exploits matching ceramic inserts, which are placed between the antennas and the breast. These systems have also been applied in some clinical trials.

The 2D MT system from the University of Manitoba, Canada [21]~[23] has a circular array of doubled layers Vivaldy antennas and operates in the 3~6 GHz frequency band. Test experiments did not use any matching material and investigated MI of different dielectric objects in an air environment.

Another 2D MT system was designed at the Chalmers University of Technology, Sweden [24]. This system contains a circular array with 20 short monopoles embedded in a metallic bath containing the coupling liquid. MI investigations were provided in the 0.5~4.5 GHz frequency band.

Although MI exhibits limited spatial resolution, it can be improved by using the following approaches:

- Increasing maximal operating frequency, using multi-frequency and UWB methods of reconstruction [6], [9], [12], [19], [21], [22];
- Acquisition of near-field components of signals from scattering objects [22].

The last factor is the reason for the super-resolution effect [22]. This indicates the case when the size of the spatial resolution is smaller than a media half-wavelength Rayleigh limit. An evident example of the super-resolution demonstrates impedance tomography, operating at very low frequencies [25]. However, some publications have reported MT image resolution of $\lambda/4$, $\lambda/6$ and smaller as well [22], [26]~[28].

rating at very low frequencies [25]. However, some publications have reported MT image resolution of $\lambda/4$, $\lambda/6$ and smaller as well [22], [26]~[28].

The present paper introduces an ETRI preclinical prototype of a microwave tomography system for early-stage breast cancer detection. The system provides microwave imaging of breast and tumor based on measured scattered waves in the 500~3,000 MHz frequency band.

II. Description of the ETRI 3D Microwave Tomography Breast Imaging System

2-1 ETRI 3D MT System Components

Key components of the system are the antenna array, transmitting-receiving device, and signal processing part. This system includes patient interface hardware as well as software for 3D image reconstruction and image interpretation programs. The ETRI 3D MT system operates at microwaves, from 500 MHz to 3 GHz. Fig. 1 shows a photo of this system and of its components, including the circular antenna array arranged inside the bath, which is filled with breast coupling liquid. The breast under examination is introduced into the middle part of the array, in the imaging zone (Fig. 2).

2-2 Application of the Multistatic Radar Concept for Microwave Imaging

The ETRI MT system exploits a multistatic MIMO radar concept for measured data acquisition, according to the arguments offered in the Introduction. This system has a circular array with 16 monopole antennas (Fig. 2) that are arranged inside the plastic bath, which is filled with the coupling liquid.

Fig. 1. Fabricated ETRI microwave 3D imaging system and components.

Fig. 2. Schematic plot of the antenna array of ETRI microwave imaging.

Each of the 16 antennas can transmit signals by turns, and then the other 15 receive the signals, which include components scattered by the testing object. Therefore, the total amount of collected data is 240 coherent measurements at each frequency for each imaging plane [29]. We also use data from similar measurements of the empty bath for calibration of the system. In contradiction to “classical” radars, the examined breast is situated in the near-field zone of the system antenna array.

The last version of the ETRI MT system with a 3D reconstruction algorithm also has the ability to move all of the antennas independently in a vertical direction. The maximal displacement of the antennas in the vertical direction is 150 mm and each step is 10 mm, which permits both in-plane and cross-plane data acquisition. The maximum number of measured scattered signals is 160×160 at each of 13 frequencies in the 500~3,000 MHz frequency band.

2-3 Electronic Part

The electronic part of the MT system consists of a transmitter-receiver device (TRx) and a switch (SW) matrix. The SW matrix realizes sequence connections of

Fig. 3. Control GUI of the transmitting-receiving (TRx) device and the microwave switch (SW) matrix.

the antennas to transmitting (Tx) or receiving (Rx) channels of TRx to provide the multistatic data acquisition. The control GUI of the TRx device and the microwave switch matrix is shown in Fig. 3.

The electronic part has the following technical parameters: input noise level -115 dBm, SW matrix isolation -110 dB. The transmitting power is 10 dBm, and the time for in-plane one layer data acquisition at all frequencies is 3.9 sec.

III. Reconstruction Algorithm

3-1 Method of Reconstruction

The reconstruction algorithm of the ETRI MT system evaluates the solution of the nonlinear three-dimensional inverse EM scattering problem for reconstructing the distribution of dielectric parameters inside the breast. We use a modified iterative Gauss-Newton method to solve this inverse problem. The forward solver is a 3D finite-difference time-domain (FDTD) algorithm, which utilizes a commercial library and uses acceleration by two GPU processors. Fig. 4 shows the GUI of the ETRI 3D MI reconstruction program.

The ETRI 3D MI reconstruction algorithm exploits an original method of breast parameter mapping that provides smooth imaging without additional regularization and spatial filtering. Note that the last two techniques are mandatory attributes of most reconstruction algorithms [2]~[3].

3-2 Flow Chart of MI

Fig. 4. GUI for the ETRI 3D image reconstruction program.

Fig. 5. Flow chart of the ETRI 3D reconstruction algorithm.

Fig. 5 demonstrates a flow chart of the iterative reconstruction algorithm. After starting, the program sets initial reconstructed parameters (permittivity and conductivity) equal to those of the bath material. The next step is calculation of the mesh for the forward solver and for the reconstruction algorithm. The feature of our imaging method is an application of matrix, which contains a set of basis functions with specific smooth profiles; this type of a basis matrix is calculated at the next step of the flow chart. Next, the algorithm produces the forward solution with help of an accelerated FDTD EM solver.

After that, the program updates the reconstructed parameters and starts a new iteration, if it is necessary. The reconstruction process can be stopped if the misfit error between the measured and calculated signals becomes less than an established minimum value or if a defined maximal iteration number occurs.

IV. Some Results of Image Reconstruction

In this section, we demonstrate results of reconstruction the images of simple numerical phantoms.

4-1 Spherical Phantom Inside the Bath Liquid

Results of reconstruction of a spherical phantom inside the bath of coupling liquid are demonstrated in Fig. 6. It is only necessary to mention that section plots in this figure have negative directions for both the x - and

Fig. 6. Reconstructed images of a sphere inside the bath liquid: top images are permittivity and bottom images are conductivity.

z -axes.

The diameter of the sphere is 40 mm and the position of the sphere center is: $x=20$ mm, $y=0$ mm, $z=30$ mm. The reconstruction provides 20 iterations at a frequency of 1,100 MHz. The coupling liquid material has permittivity of 20.0 and conductivity of 1.3 S/m; the sphere material has permittivity of 40.0 and conductivity of 0.2 S/m.

4-2 Two Spherical Phantoms inside the Bath Liquid

Sections of reconstructed images corresponding to depths $z=6, 18, 26, 34, 50$ and 75 mm are presented in Fig. 7.

The first sphere has a diameter of 20 mm and a center position $x=-37$ mm, $y=0$ mm, and $z=14$ mm. The second sphere has a diameter of 30 mm and a center position $x=37$ mm, $y=0$ mm, and $z=20$ mm. The reconstruction provides 20 iterations at a frequency of 1,100 MHz. The coupling liquid material: permittivity 20.0, conductivity 1.3 S/m. The sphere material: permittivity

Fig. 7. Horizontal sections of reconstructed images of two spherical phantoms inside the bath liquid. For each section, the top images are permittivity and the bottom images are conductivity.

40.0, conductivity 0.2 S/m.

4-3 Two Thin Cylindrical Phantoms inside the Bath Liquid

Fig. 8 demonstrates reconstructed images for two thin cylindrical phantoms, 2 and 5 mm in diameter, which play the role of tumor phantoms. The breast phantom, 100 mm in diameter, is a hollow cylinder with a bottom and negligibly thin walls. For the case of (a) and (c), the breast phantom contains a material the same as bath material, but for the case of (b) and (d) both materials are different. More specifically, the bath material has a permittivity of 9.8 and conductivity of 1.6 S/m; the breast material has a permittivity of 6.5 and conductivity of 0.8 S/m; and the tumor material has a permittivity of 11.3 and conductivity of 1.8 S/m. The reconstruction frequency is 2,900 MHz. We used 20 iterations for the reconstruction in each case.

Images presented in Fig. 8 show a comparison of two cases: A: breast and bath materials are the same (perfect matching) and B: different materials (mismatch). Plots (a) and (c) correspond to the perfect matching between breast and bath material but the other plots (b) and (d) relate to the case of the mismatch between breast and

bath materials. Note that the reconstructed images of the tumor look much clearer for plots (a) and (c) than for plots (b) and (d) of Fig. 8. The reason for this fact is the influence of error in calculated signals, scattered by the breast phantom, on the reconstructed image of the tumor.

V. Conclusion

Microwave imaging is an important direction of modern research. The paper describes an ETRI 3D MT system, which relates to one of the most promising applications of MI - for early breast concern detection. This system is a new 3D generation of ETRI preclinical prototypes [10]. The reconstruction algorithm is based on a 3D FDTD forward solver accelerated with two GPUs. Some results of the image reconstruction demonstrate the reliability and precision of the ETRI 3D reconstruction algorithm. However, the duration of the forward solution is still too long for an existing MI program so it is not convenient for practical application. Therefore, one of the main aims of the next research is to develop an advanced EM algorithm for the forward solver, that will be faster than the FDTD algorithm. Another important direction of our research is to create a MI system with better spatial resolution.

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Fig. 8. Horizontal sections of images of two thin cylindrical phantoms with diameters of 5 mm: (a), (b) and 2 mm: (c), (d). For each section, top images are permittivity and bottom images are conductivity.

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