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Review Article

Microwave Imaging: Potential for Early Breast Cancer Detection

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Abstract: Early breast cancer detection can save the women infected by malignant tumors. Microwave imaging has recently been proposed for detecting small malignant breast tumors at early stages. This type of cancer is the top-most cause of death among women due to malignant tumors. The detection of early-stage tumors in the breast by microwave imaging is challenged by both the moderate endogenous dielectric contrast between healthy and malignant glandular tissues and the spatial resolution available from illumination at microwave frequencies. The high endogenous dielectric contrast between adipose and fibroglandular tissue structures increases the difficulty of tumor detection due to the high dynamic range of the contrast function to be imaged and the low level of signal scattered from a tumor relative to the clutter scattered by normal tissue structures. Microwave inverse scattering techniques, used to estimate the complete spatial profile of the dielectric properties within the breast, have the potential to reconstruct both normal and cancerous tissue structures. However, the ill-posedness of the associated inverse problem often limits the frequency of microwave illumination to the ultra high frequency (UHF) band within which early-stage cancers have sub-wavelength dimensions. This review presents the research status of microwave imaging for malignant tumor detection. Many methods have been used, i.e., active, passive, and hybrid. However, it is important to remember that, in addition to microwave imaging, several alternative breast cancer detection modalities are actively being pursued, including optical imaging methods.

Keywords: Breast cancer detection, microwave imaging, inverse scattering

1. INTRODUCTION

Detecting breast cancer in its earliest stages is looked upon as the best hope for successful treatment of the disease [2]. The limitations of conventional X-ray mammograms are well-recognized [2, 3] and, in response to these limitations, several complementary modalities for breast cancer are under investigation. Currently, X-ray mammography represents the gold standard method of breast imaging. Other methods, including magnetic resonance imaging (MRI) and ultrasound approaches are as yet either less effective or too expensive for mass-screening purposes. X-ray mammography is based on the fact that tumor tissue exhibits micro calcifications, which affect mammogram formation. Mammogram is 2-D map that represents the intensity of X-ray radiation passed through the previously compressed breast (in order to reduce image blurring and to reach uniformity of tissue). However, relatively small contrast between affected and normal tissues for X-rays leads to sufficiently high false negative (4–34%) and false-positive (70%) rates [4]. Besides this, very early stage tumors do not necessarily exhibit micro-classifications. Also, ionizing radiation is accumulated over repeated scans.

As a supplement to X-ray mammography, microwave imaging is a new and promising technique for breast cancer detection. It has a lot of advantages, including real time monitoring, non-invasive and can function over wide ranges of time and size scales involved in biomedical processes. As is well known, microwave imaging is a technique aimed at sensing a given scene by means of interrogating microwaves. This active technique

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was considered for a long time as an emerging technique. Microwave imaging has recently proven capable of providing excellent diagnostic capabilities in several areas, including civil and industrial engineering, geophysical prospecting and biomedical engineering. To date, the primary motivation for developing microwave systems has been the need for improved detection of malignant breast tumors [1].

Microwave imaging approaches to early breast cancer detection offer an attractive alternative to conventional mammography. The attraction is motivated by dielectric property contrast between normal and malignant breast tissue at microwave frequencies (between 2:1 and 10:1) [5, 6]. Endogenous contrast and spatial resolution are two important considerations in the detection and location of tumors by microwave imaging techniques. Recent studies of the histopathology and microwave-frequency dielectric properties of excised breast tissues suggested a much lower contrast between healthy and cancerous tissues than was previously understood [16]. The ex vivo microwave dielectric properties of malignant glandular tissues were observed to be about ten times those of adipose tissue, but only one-tenth higher than the properties of normal glandular tissues. Furthermore, the electrical dimensions of early- stage cancers are at or below the nominal half-wavelength resolution limit of the UHF-band frequencies (0.3–3.0 GHz) typically employed in frequency-domain microwave inverse scattering. Although super-resolution has been observed and attributed to evanescent waves in near-field measurements or in multiple-scattering environments [17, 18], microwave detection of early-stage malignancies is nevertheless challenged by the moderate endogenous dielectric contrast, the small scattering area of these malignancies, and the heterogeneous scattering environment of healthy glandular tissue in which tumors often form.

Ultra-wideband (UWB) radar technique was introduced by S.C. Hagness in 1998 [5–13]. The technique, based on the ideas of ground penetrating radar, estimates the energy reflected from any point chosen inside the breast, without reconstruction of the breast's dielectric-properties profile. The key point of the technique is time shifting and summing (synthetic focusing) of scattered waveforms. Later, Hagness and colleagues presented further development of UWB radar approach which improved the process of scattered energy estimation, namely Microwave Imaging via Space Time (MIST) Beam Forming method in both time and frequency domains [14, 15]. In contrast to the image recovery goal of tomography, the proposed UWB radar approach solves a simpler computational problem by seeking only to identify the presence and location of significant scatterers such as malignant breast tumors. In the UWB radar approach, high bandwidths and large antenna apertures are used to improve spatial resolution at microwave frequencies.

Another class of numerical technique in radar terminology is inverse scattering method. The object profile is reconstructed by solving the inverse scattering problem using iterative methods. In addition to obtaining the shape of the object, a quantitative description of the dielectric constant profile is also obtainable, which is extremely valuable diagnostic information.

2. TUMOR DETECTION AND IDENTIFICATION SCHEMES

Currently, three directions in microwave breast imaging can be distinguished: hybrid microwave-induced acoustic imaging [7–8], microwave tomography [9–10], and UWB radar technique [5–11]. In the first direction, microwaves are used to heat (and, thus, expand) tumors; the pressure waves so generated are then detected by ultrasound transducers. Microwave tomography relies on recovering the dielectric-properties profile on the basis of measurements of narrow-band microwave signals transmitted through the breast. This type requires solving both forward scattering problem and nonlinear ill-conditioned inverse scattering problem iteratively; until the computed and the measured data are close enough [12–10]. From the basic concepts of each approach, researchers have investigated different techniques to achieve a suitable system for breast cancer detection; the investigated techniques are illustrated in Fig.1.

Currently, tomographic and radar are the two major approaches [19]. Both passive and active

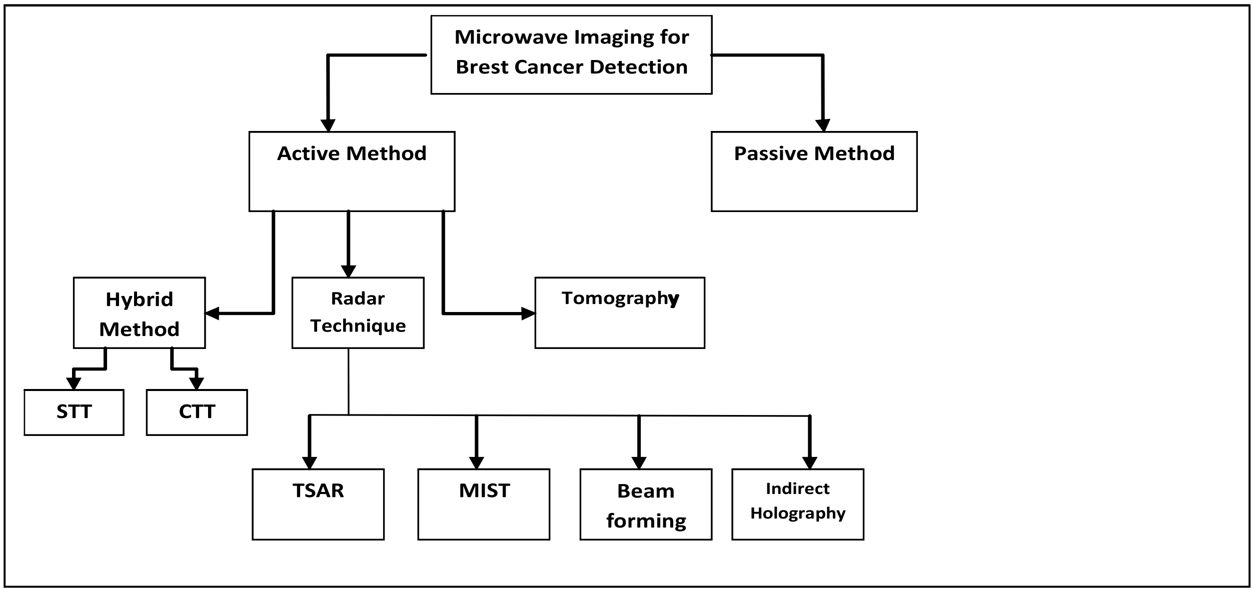

Fig.1. Schematic diagram of microwave imaging.

microwave imaging methods are being researched for breast cancer detection [30].

2.1. Passive Method

Passive microwave radiometry [31, 32] exploits temperature differences between malignant and normal breast tissue due to elevated metabolism in fast-growing malignant tumors.

The principle of operation refers to measurement of temperature of the breast by radiometric techniques and comparison of the formed thermical map "images" of the suspicious area with corresponding healthy breast area obtained at the microwave frequencies. The malignant indication are made by recognizing the temperature difference in the asymmetry between two images [33, 34]. Microwave radiometry (also called thermography) has been explored for many years especially as adjuvant to mammography.

2.2. Active Methods

Three types of active microwave breast imaging techniques have been proposed: hybrid-induced acoustic imaging, microwave tomography, ultra wideband microwave radar techniques.

In general, active microwave imaging falls under the broad category of inverse problems. The objective of MWI is to reconstruct the unknown distribution of the complex permittivity inside the mammary tissue given a set of data measured along the perimeter of the volume. There are several groups currently performing research in active microwave imaging [25]. While these systems take varying approaches to the specifics of data acquisition and image reconstruction, they share the common potential advantages that microwave imaging offers over traditional mammography. First, active microwave imaging systems do not require the use of ionizing radiation. In addition, MWI systems would eliminate the need for uncomfortable breast compression. Furthermore, microwave imaging systems are expected to be less expensive than x-ray systems and much less costly than MRI. All of these characteristics would allow for earlier and more frequent examinations. Finally, microwave imaging has the potential for a much higher sensitivity in detecting tumors, as well as higher specificity in differentiating malignant and benign tumors. This is because the electrical contrast is likely to be much higher than the density contrast, particularly for malignant lesions. Active methods can be divided into further two groups, i.e., tomography and radar-based.

2.3. Hybrid Method

Hybrid methods could include, for example, two-step procedures in which fast qualitative algorithms are combined with quantitative methods in order to first derive the supports of the unknown scatterers and successively retrieve the distributions of their dielectric parameters. The principle of operation is to illuminate the breast by using microwave frequency and measure the signal by the ultrasound transducer, since more energy is deposited in tumors due to its higher conductivity, as a result the tumor expanding and generates pressure waves, which are detected by the ultrasound transducer.

Two approaches of hybrid microwave acoustic imaging system has been proposed, namely, computed thermo-acoustic tomography (CTT) and scanning thermo-acoustic tomography (STT).

2.3.1. Computed Thermo-acoustic Tomography (CTT)

The breast is placed in a water-bath and illuminated with 0.5 μs pluses of 434 MHz signals using waveguide; 0.5 μs waves are used to generate ultrasound waves in the medical region [20, 21]. Ultrasound transducers are arranged on a hemisphere, and data are recorded as the transducers configuration is rotated through 360 degrees to collect sufficient data.

Filtered back projection algorithms adapted from X-ray computed tomography has been used to form the images. The clinical results have been obtained with this method to demonstrate images, which show internal tissues structure in the breast.

2.3.2. Scanning Thermo-acoustic Tomography (STT)

L. Wang and his colleagues developed the Scanning Thermo-acoustic Tomography *(*STT) technique; good experimental results were obtained with various properties and thickness phantoms containing block of fat and muscles [21, 22]. Numerous improvements on imaging algorithms for the STT approach were derived for planner and cylindrical systems [23, 24]. For the spherical coordinate system, modified back projection was proposed [23]. The resolution of the obtained images was approximately 0.5 mm, which shows a good detection capability.

Although research groups have taken a variety of approaches to microwave imaging, these approaches can be divided into two main categories: tomographic methods that utilize traditional inverse scattering approach both sequential 2D slice methods and full 3D methods and methods that use beamsteering approaches confocal imaging, MIST, TSAR (including UWB). The fundamental difference between these two methods is the way in which a voxel of material data is localized. In the case of inverse scattering approaches, the electrical properties of all locations in the volume are determined simultaneously using an inversion algorithm that operates on the aggregate of the measured data. Alternatively, beamsteering approaches isolate a particular location in the volume to be measured, and data is taken for each individual voxel. Statistical methods are then employed to determine a given voxel's electrical properties.

2.4. Tomographic Imaging Systems

In tomographic microwave imaging systems, a set of measurement data is collected using antennas on the surface of a chamber, and the unknown complex permittivity distribution of the material inside can then be found using one of a variety of methods that have been developed to address this ill-posed inverse problem. These systems can generally be categorized into two main types based on whether the inverse problem is solved for a series of two-dimensional slices using data collected from a planar array of antennas (2D imaging) or for the entire volume using data collected from antennas positioned throughout the perimeter of the chamber (3D imaging).

2.4.1. Sequential 2D Slice Approach

In the case of the 2D slice approach, the volume to be scanned is surrounded by the 2D array of antennas, typically arranged in a ring, and sequential 2D images are generated by translating the entire array vertically through a series of positions. There are several advantages to using such an approach. First, a relatively small number of simple antennas can be used to illuminate the breast, significantly reducing the complexity of the system to be modeled in the reconstruction algorithm. Furthermore, the 2D nature of the problem itself further simplifies the inversion process. In addition, a translating 2D array reduces the complexity of the hardware system design and data-acquisition process. Difficulties associated with packing a dense number of antennas in a full 3D configuration are eliminated, and isolating sensitive electronics from the necessary matching fluid is also much easier to accomplish. Finally, the positioning of the antennas is potentially more flexible since their locations are determined by the CNC motor. This approach is not without its disadvantages, however. Due to the nature of the motorized translation system, data-acquisition time will be much slower than an electronically switched 3D imaging system. This prolonged acquisition time, combined with the motion united with the translating antenna array, will likely lead to increased noise. Furthermore, a 2D approach to data collection reduces the number of possible antenna combinations and does not have the ability to utilize data from out of plane antenna combinations. Finally, such a 2D approach is likely to result in reduced resolution and errors since the translation in the transverse direction is on the order of a wavelength. For a further discussion of the trade offs associated with 2D imaging, the reader is referred to [26].

2.4.2. Full 3D Inversion Approach

The full 3D inverse scattering approach offers many potential advantages over the other two approaches detailed in this paper, often at the cost of added complexity. First, a full 3D array of densely packed antennas that are switched electronically offers effcient data collection and highly precise antenna positioning. A complete 3D array also provides the maximum combination of transmit and receive antennas, and enables the collection of out-of-plane transmission data. Finally, a fully 3D system is able to take advantage of the optimizations and advances in 3D inversion techniques that have recently been made. All of these contribute to the potential of 3D inversion methods to offer greater resolution, increased SNR, and more rapid data collection [27, 28, 29].

2.5. Beam Steering Approaches

Beamforming systems have their roots in optics, confocal microscopy, and RADAR. The general approach in such systems is to focus an illuminating microwave signal at a particular point in the scanning volume and then to refocus the scattered signal back to the point of illumination. By systematically scanning the focal point within a set of preselected voxels throughout the breast volume, a 3D image can be constructed. The ability of these systems to detect tumors relies on the increased backscatter caused by malignant tissue. The primary advantages of this approach are two-fold: there is no need for complex inversion techniques and simple time-gating methods can be used to reduce clutter and multiple scattering effects.

2.5.1. Confocal Imaging: Simple Delay-and-sum Beamforming

In a typical confocal breast imaging system, ultra wideband (UWB) pulses are generated by an antenna located on or near the surface of the breast. The backscattered waveform at that particular antenna location is then collected and stored in a computer.

Using both electronic switching and mechanical scanning, this procedure is repeated for each antenna element in an N element antenna array. The set of N backscattered signals are then time-shifted to achieve coherent addition for a specific for a specific focal point within the breast. The focal point is then scanned throughout the breast by adjusting the relative amount of time-shift applied to each backscattered signal. Statistical analysis is then used to predict the absence or presence of a tumor at each scanned voxel. Finally, all of the statistical decisions for each voxel are aggregated to form an image. It should be noted that this method does not seek to generate a map of the dielectric properties of the breast. Instead, it only seeks to identify and locate the presence of strong scatterers within the breast [5].

2.5.2. Microwave Imaging via Space-time Beamforming (MIST)

At the University of Wisconsin, Hagnees and colleagues have proposed a planar system termed Microwave Imaging via Space-time (MIST) system [36], the patient to be scanned lies in a supine position. Either one antenna or an array is placed on the flattened breast surface [4, 37, and38] and scanned to multiple locations. Special liquid has been used to approximate the dielectric properties of the medium to those of the object.

The first work was reported two dimensional studies [5], with using a simple monopole antenna and planer breast phantom, data simulated using the finite-difference-time-domain (FDTD). Reflections were obtained at 17 antenna locations and spherical tumor with 5 mm diameter was located 3 cm beneath the array was detected successfully. Resistively loaded bowtie antenna, 8 cm long was used as a sensor to perform -D study [12], spherical tumor 1.76 cm diameter located 5 cm below the antenna was detected.

Successful detection was performed of small tumor artificially introduced at a depth of 3.1 cm below the surface of the 2 cm thick skin layer in a complex phantom with planer system and more realistic MR based 2-D models [37]. Multi-static approaches were introduced [38], and initial results using data from a realistic FDTD model demonstrated successful detection of a small tumor 2mm in lossy, inhomogeneous human breast.

2.6. Tissue Sensing Adaptive Radar (TSAR)

As an alternative to MIST, Fear and Sill developed a similar system that has been termed Tissue Sensing Adaptive Radar. Like MIST, it seeks to address the shortcomings of the simple confocal system; however, there are a few fundamental difference between the two. For example, in the Tissue Sensing Adaptive Radar (TSAR) system, the patient lies prone and the pendulous breast is scanned from surrounding locations. Additionally, the TSAR system uses less complicated clutter reduction methods than MIST.

Simple time shifting and adding algorithm were used to reconstruct images in TSAR system, the steps of this algorithm were:

i) First, tissue sensing carried out to locate the breast in the tank; second, the skin reflections were estimated and subtracted. Finally, the signals without skin reflections were formed into an image.

ii) The results of this technique showed the ability for detecting image, for detecting and localizing tumors of greater than 4 mm diameter [36].

iii) The feasibility of the new technique, maximum-a-posteriori (MAP), for estimating the tumor response contained in the late time scattered field data was investigated and good results were obtained [39].

2.7. Indirect Holographic Method

Many of the radar methods are based on direct microwave holographic method to diagnose tumors. The obtained results of this method were encouraging. However, this method uses vector analyzer to measure the complex field of antenna over selected aperture in near field to reconstruct images, therefore is slow and expensive [43]. Another method which uses Indirect Holographic method as an alternative to detect tumors was also investigated [44].

Indirect holographic method uses the application of Fourier transform, frequency domain filtering and direct back transformation onto the measured interference pattern, the use of continuous wave signal for imaging avoids the problems associated with pulsed systems.

This method comprises of two stages. Stage-one is the recording of a holographic intensity pattern, by combing the signal scattered from the object, with a phase coherent reference plane wave signal. The second stage is the image reconstruction from the 2D holographic intensity pattern produced [45].

3. NUMERICAL METHODS FOR DETECTION

As time-domain microwave breast imaging algorithms are usually based on numerical simulations with the Finite-difference Time-domain (FDTD) method [40], accurately modeling all the different aspects of the problem is very important for the evaluation of these systems. Biological tissue in general is quite dispersive in the microwave frequency range. Modeling of the frequency dependence for the various types of tissue is an important challenge for time-domain analysis of microwave breast cancer detection systems. FDTD is a useful method for the simultaneous acquisition of multi frequency vector field data over the full bandwidth of interest. The sample spacing of the forward solution grid must be dense enough to limit the numerical dispersion in the FDTD simulation, but sparse enough to limit the computational cost of

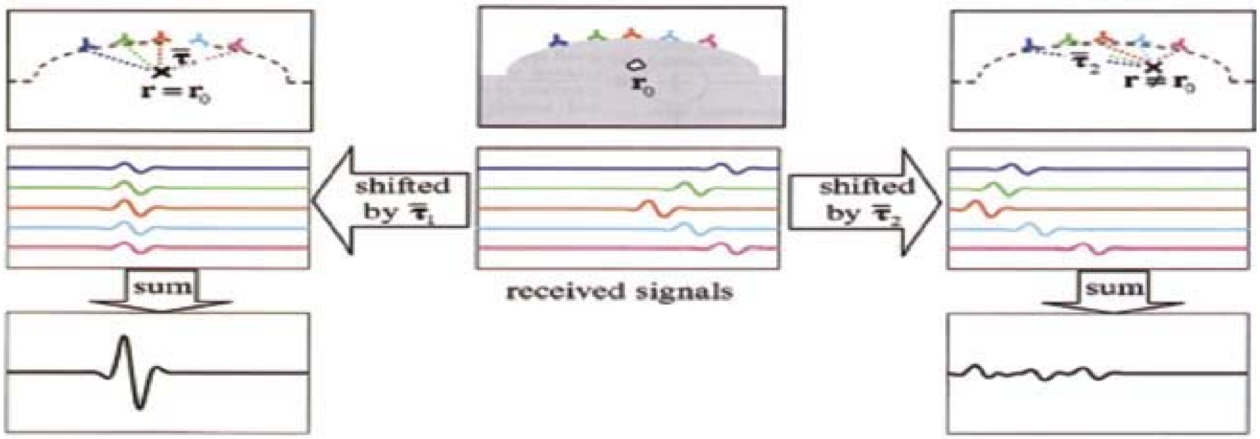

Fig. 2. Simple delay and sum beam former [35].

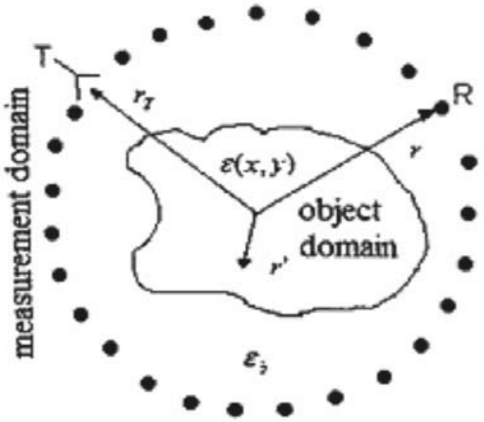

Fig. 3. Inverse scattering measurement configuration.

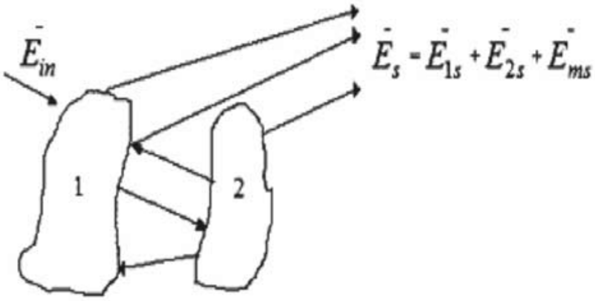

Fig. 4. Multiple scattering effects inside the object.

the simulations. The choice of the FDTD method is motivated by the fact that it has a distinct advantage of handling field sample interactions in the time domain. An understanding of these interactions becomes of significant importance, as microwave imaging is moving towards the search of better signal to noise ratio (SNR) and image resolution.

A uniform 2.0 mm sample spacing was selected for the forward FDTD solutions to balance this trade off. Since multiple FDTD simulations of the numerical phantoms are still computationally costly on a 2.0 mm grid, the simulations on a GPU based hardware accelerator were run to achieve a feasible imaging time. Alternative numerical techniques for reducing the computation time of the forward solution have been presented elsewhere [41, 28, 42]. For further explanation, consult Jocob et al [46].

4. CONCEPT OF INVERSE SCATTERING IN MICROWAVE IMAGING FOR TUMOR DETECTION

In inverse scattering the profile of the scattering object is inferred from the measurement data collected at a distance from the scatterer. In addition to obtaining the shape of the object, a quantitative description of profile of dielectric constant is also obtainable from the inverse scattering experiment.

The inverse scattering depends on the multiple scattering effects that take place within the object.

These effects cause the scattered fields to non-linearly relate to the object function; which is a function that describes the velocity, relative permittivity and conductivity distribution of the object. A solution to the inverse scattering is sought from the field perturbation, or the scattered field induced by object. The inverse scattering measurement configuration is shown in Fig. 2.

A solution to the inverse problem is non-unique, due to the generation of evanescent waves by high spatial frequency portions of the object. These waves are exponentially small at the receiver locations and in practice not measurable unless the receivers are very close to the object. This gives rise to the concept of near field imaging in microwave tomography.

The relationship between the scattered field and the scattering object is a non-linear one. This non-linearity arises from the multiple scattering effects within the object as shown in Fig. 4.

When only scatterer 1 is present, the scattered field is Eff_{1s} and when only scatterer 2 is present the scattered field is Eff_{2s}. However when both the scatterers are simultaneously present, the scattered field is $\mathrm{Eff}_{1s} + \mathrm{Eff}_{2s} + \mathrm{Eff}_{ms}$ where Eff_{ms} is a result of multiple scattering between the scatterers.

5. CONCLUSIONS

Motivated by the clinical desire, microwave breast imaging has been an active research area over the past two decades. Most of the works reported were simulations, and a few were tested experimentally on phantoms. Reconstruction of 2-D tomographic images from experimentally collected scattered fields on breast tissues (normal tissue with cancerous inclusion) in the presence of a matching coupling medium was not tried. The analyses for distorted Born iterative method to solve the inverse scattering problem using experimentally collected scattered data on breast tissues and on breast phantoms. This method was adopted as it is simple, easy to implement and could develop images with reasonable accuracy, for strong detection of malignant tumor by microwave technology.

Though these efforts have generated an expectation for something close to an ideal breast cancer detection system, a number of fundamental and contemporary issues deserve further research consideration about this microwave modality. Also, it is important to remember that in addition to microwave imaging, several other alternative breast cancer detection modalities are actively being pursued, including optical imaging methods.

6. ACKNOWLEDGMENTS

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7. REFERENCES

1. Harvey, J. A. & V. E. Bovbjerg. Quantitative assessment of mammographic breast density: Relationship with breast cancer risk. *Radiology* 230: 29–41 (2004).
2. Nass, S. J., I. Craig Henderson & Joyce C. Lashof (Eds). *Mammography and Beyond: Developing Technologies for the Early Detection of Breast Cancer*. The National Academies Press, Washington, DC (2001).
3. Huynh, P. T., A. M. Jarolimek & S. Daye. The false-negative mammogram. *Radiography* 18 (5): 1137–1154 (1998).
4. Fear, E.C., X. Li, S. C. Hagness, & M. Stuchly. Confocal microwave imaging for breast cancer detection: localizations of tumors in three dimensions. *IEEE Transactions on Biomedical Engineering* 49(8): 812–822 (2002).
5. Hagness, S.C., A. Taflove & J. E. Bridges. Two-dimensional FDTD analysis of a pulsed microwave confocal system for breast cancer detection: fixed-focus and antenna-array sensors. *IEEE Transactions on Biomedical Engineering* 45(12): 1470–1479 (1998).
6. Fear, E., P. Meaney & M. Stuchly. Microwaves for breast cancer detection? *IEEE Potentials* 22(1): 12–18 (2003).
7. Wang, L. V., X. Zho, H. Sun & G. Ku, Microwave-induced acoustic imaging of biological tissues. *Rev. Sci. Instrum.* 70: 3744–3748 (1999).
8. Kruger, R. A., K. D. Miller, H. E. Reynolds, W. L. Kiser Jr., D. R. Reinecke & G. A. Kruger. Breast cancer in vivo: Contrast enhancement with thermoacoustic CT at 434 MHz feasibility study. *Radiography* 211: 279—283 (2000).
9. Meaney, P. M. & K. D. Paulsen. Nonactive antenna compensation for xed-array microwave imaging: Part IIImaging results. *IEEE Transactions on Medical Imaging* 18 (6): 508–518 (1999).
10. Zhang, Z. Q., Q. Liu, C. Xiao, E. Ward, G. Ybarra

& W. T. Joines. Microwave breast imaging: 3-D forward scattering simulation *IEEE Transactions on Biomedical Engineering* 50 (10): 1180–1189 (2003).

11. Li, X., S. K. Davis, S. C. Hagness, D. W. van der Weide & B. D. Van Veen. Microwave imaging via space-time beamforming: Experimental investigation of tumor detection in multilayer breast phantoms, IEEE Trans. *Microwave Theory Tech.* 52(8): 1856–1865 (2004).
12. Bulyshev, A.E., S. Y., Semenov, A. E. Souvorov, R. H. Svenson, A. G. Nazarov, Y. E. Sizov & G. P. Tatsis. Computational modeling of three-dimensional microwave tomography of breast cancer. *IEEE Transactions on Biomedical Engineering* 48 (9): 1053–1056 (2001).
13. Hagness, S.C., A. Taflove, & J. E. Bridges. Two-dimensional FDTD analysis of a pulsed microwave confocal system for breast cancer detection: design of an antenna-array element. *IEEE Transactions on Antennas and Propagation* 47 (5): 783–791 (1999).
14. Bond, E.J., X. Li, S.C. Hagness & B. D. V. Veen. Microwave imaging via space–time beamforming for early detection of breast cancer. *IEEE Transactions on Antennas and Propagation* 51 (8): 1690–1705 (2003).
15. Davis, S., E. Bond, X. Li, S. Hagness & B. V. Veen. Microwave imaging via space–time beamforming for early detection of breast cancer: beamformer design in the frequency domain. *Journal of Electromagnetic Waves and Applications* 17 (2): 357–381 (2003).
16. Lazebnik, M. et al. A large-scale study of the ultrawideband microwave dielectric properties of normal, benign, and malignant breast tissues obtained from cancer surgeries. *Phys. Med. Biol.* 52: 6093–6115 (2007).
17. Chen, F. & W. C. Chew. Experimental verication of super resolution in nonlinear inverse scattering. *Appl.Phys. Lett.* 72: 3080–3082 (1998).
18. Kuhl, C. K. MRI of breast tumors. *Eur. Radiol.* 10: 46–58 (2000).
19. Gunnarsson, T. *Microwave Imaging of Biological Tissues: Applied toward breast tumor detection*. MS thesis, Department of Computer Science and Electronics, Malardaien University, Västerås, Sweden (2007).
20. Kruger, R. A., K.K. Kopecky, A.M. Aisen, P.R. Reinecke, G.A. Kurger, & W.L. Kiser, Jr. Thermoacoustic CT with radio waves: A medical imaging paradigm. *Radiology* 211: 275–278 (1999).
21. Krunger, R. A., W.L. Kiser, Jr., D.R. Reinecke, G.A. Kruger & R.L. Eisenhart. Thermoacoustic Computed Tomography of The breast at 434 MHz. In: *IEEE MTT-S Int. Microwave Symp. Dig., Vol. 2.*, p. 591-594 (1999).
22. Ku, G. & L. V. Wang. Scanning thermoacoustic tomography in biological tissue. *Med. Phys*. 27: 1195–1202 (2000).
23. Xu, Y., M. H. Xu & L. V. Wang. Exact Frequency-domain Reconstruction for Thermoacuostic Tomography. I. Planar Geometry. *IEEE Trans. Med. Image* 21: 832–828 (2002).
24. Xu, Y., M. H. Xu & L. V. Wang. Exact Frequency-domain Reconstruction for Thermoacuostic Tomography. II Cylindrical Geometry. *IEEE Trans. Med. Image* 21: 829–833 (2002).
25. Yu, C., M. Yuan, J. Stang, E. Bresslour, R. T. George, G. A. Ybarra, W. T. Joines & Q. H. Liu. Active microwave imaging ii: 3-d system prototype and image reconstruction from experimental data. *IEEE Trans. Microwave Theory Tech*. 56: 991–1000 (2008).
26. Meaney, P., K. Paulsen, S. Geimer, S. Haider, & M. Fanning. Quantification of 3-d field effects during 2-d microwave imaging. *IEEE Trans. Biomed. Eng.* 49: 708–720 (2002).
27. Zhang, Z. Q. & Q. H. Liu. Two nonlinear inverse methods for electromagnetic induction measurements. *IEEE Transactions on Geoscience and Remote Sensing* 39: 1331–1339 (2001).
28. Zhang, Z. Q., Q. H. Liu, C. Xiao, E. Ward, G. Ybarra, & W. Joines. Microwave breast imaging: 3-d forward scattering simulation. *IEEE Trans. Biomed. Eng.* 50: 1180–1189 (2003).
29. Zhang Z. Q. & Q. H. Liu. Three-dimensional nonlinear image reconstruction for microwave biomedical imaging. *IEEE Trans. Biomed. Eng.* 51: 544–548 (2004).
30. Fear, E.C., S.C. Hagness, P.M. Meaney, M. Okoniewski, & M.A. Stuchly. Enhancing breast tumor detection with near field imaging. *IEEE Microwave Magazine* 3: 8-56 (2002).
31. Carr, K. L. Microwave radiometry: its important to the detection of cancer. *IEEE Trans. Microwave Theory Tech.* 37: 1862-1869 (1989).
32. Bocquet, B., J. C. Van de Velde, A. Mamouni, Y. Leroy, G. Giaux, J. Delannoy & D. D. Valee. Microwave radiometry Imaging at 3GHz for the exploration of breast tumors. *IEEE Trans. Microwave Theory Tech*. 38: 791–793 (1990).
33. Mouty, S., B. Bocquet, R. Ringot, N. Rocourt, 7 P. Devos. Microwave radiometric imaging for the characterization of breast tumor. *Eur. Phys. J. Appl. Phys.* 10: 73-78 (2000).
34. Carr, K. L., P. Cevasco, P. Dunlea & J. Shaeffer. Radiometric sensing: An Adjuvant to Mammography to determine Breast Biopsy. *IEEE International Microwave Symposium Digest* 2: 929-932 (2000).
35. Li, X., E. Bond, B. Van Veen & S. Hagness. An overview of ultra-wideband microwave imaging

via space-time beamforming for early-stage breast cancer detection. *IEEE Antennas and Propagation Magazine* 47: 19–34 (2005).

36. Fear, E. C. Microwave Imaging of the Breast. *Tech. in Cancer Research & Treatment* 4 (1): 69–82 (2005).
37. Li X. & S. C. Hagness. A confocal microwave imaging algorithm for breast cancer detection. *IEEE Microwave Wireless Comp. Lett.* 11: 130–132 (2001).
38. Fear, E. C., J. Sill & M. A. Stuchly. Experimental Feasibility Study of Confocal Microwave Imaging for Breast Tumor Detection. *IEEE Transactions on Microwave Theory and Techniques*, MTT-51, March 2003, p. 887–892 (2003).
39. Doughlas, J., E.C. Fear & D. T. Westwick. Tumor Estimation in Tissue Sensing Adaption Radar (TSAR). In: *Signals Canadian Conference on Electrical and Computer Engineering*, p. 860–863 (2007).
40. Taflove A. & S. C. Hagness. *Computational Electrodynamics: The Finite-Difference Time-Domain Method.* Artech House, Boston, MA (2000).
41. Meaney, P. M., K. D. Paulsen & T. P. Ryan. Two-dimensional hybrid element image reconstruction for TM illumination. *IEEE Trans. Antennas Propag.* 43: 239–247 (1995).
42. Bulyshev, A. E., A. E. Souvorov, S. Y. Semenov, V. G. Posukh & Y. E. Sizov. Three-dimensional vector microwave tomography: Theory and computational experiments. *Inverse Probl.* 20: 1239–1259 (2004).
43. Jayanthy, M., N. Selvanathan & M. Abuon. *Microwave Holographic Imaging Technique for Tumor Detection.* Springer, Berlin, p. 275-277 (2000).
44. Elsdon, M., D. Smith, M. Leach & S.J. Foti. Experimental investigation of breast cancer tumor imaging using indirect microwave holography. *Microwave and Optical Technology Letters* 48: 480-482 (2006).
45. Smith, D., M. Leach & A.J. Sambell. Microwave indirect Holographic Imaging using an Adaptation of Optical Techniques. *IEEE Microwaves and Wireless Components Letters* 13: 379-381 (2003).
46. Jacob, D., Shea, Panagiotis Kosmas, Susan C. Hagness & Barry D.Van Veen. Three-dimensional microwave imaging of realistic numerical breast phantoms via a multiple-frequency inverse scattering technique. *Medical Physics* 37 (8): doi.org/10.1118/1.3443569 (2010).