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Microwave Breast Imaging Techniques and Measurement Systems

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Abstract

Electromagnetic waves at microwave frequencies allow penetration into many optically non-transparent mediums such as biological tissues. Over the past 30 years, researchers have extensively investigated microwave imaging (MI) approaches including imaging algorithms, measurement systems and applications in biomedical fields, such as breast tumor detection, brain stroke detection, heart imaging and bone imaging. Successful clinical trials of MI for breast imaging brought worldwide excitement, and this achievement further confirmed that the MI has potential to become a low-risk and cost-effective alternative to existing medical imaging tools such as X-ray mammography for early breast cancer detection. This chapter offers comprehensive descriptions of the most important MI approaches for early breast cancer detection, including reconstruction procedures and measurement systems as well as apparatus.

Keywords: microwave imaging, breast imaging, breast cancer detection, dielectric properties

1. Introduction

Medical imaging approaches, such as X-ray mammography, ultrasound and magnetic resonance imaging (MRI), play an important role in breast cancer detection [1]. X-ray mammography is the gold-standard method for breast cancer detection, but it has some limitations [2, 3], including harmful radiation, relatively high false-negative rates particularly with patients with dense breast tissue. Ultrasound presents good soft tissue contrast but fails in the presence of bone and air, and the image quality highly depends on operator [4]. MRI allows physicians to evaluate various parts of human body and determine the presence of certain diseases [5], but it is too expensive [6]. Therefore, it is important and necessary to develop a new imaging technique for early breast cancer detection.

In the late 1970s, Larsen et al. obtained the first microwave image of canine kidney [7]. Since then, MI has been intensively studied by many research groups [8–18], and the research objectives have been moved from imaging of organs to application-specific imaging for various tissues such as breast, joint tissues, blood and soft tissues. MI has been recommended as a safe, low-cost and low health risk alternative to existing medical imaging techniques including X-ray mammography and ultrasound. In the past many years, people paid too much attention to the MI algorithms. Several algorithms have been developed and validated numerically and in laboratory environments but they have not extensively validated in clinical environments. Recent clinical trial results demonstrated that more attention should be paid to the hardware implementation system, especially microwave sensors and sensor arrays, in clinical environments rather than laboratory environments.

This chapter presents the basic ideas of MI including currently available breast imaging methods which have been considered as important approaches for early breast cancer detection. The starting point for the development of MI methods is the formulation of the electromagnetic inverse scattering problem. Inverse scattering-based procedures address the data inversion in several different ways, depending on the target itself or on the imaging configuration and operation conditions. In this chapter, electrical properties of biological tissues, MI approaches and biomedical applications and several proof-of-concept apparatuses, including advantages, challenges and possible solutions, as well as future research directions are addressed.

2. Dielectric properties of biological tissues

The dielectric properties (DPs, relative permittivity ϵ_r and conductivity σ) of malignant tissues at the microwave spectrum change significantly compared to the normal tissue and the dielectric contrast can be detected and imaged by applying MI approaches [19]. The DPs of different types of biological tissues are very different due to water content difference, which are strongly nonlinear functions with frequency [20]. Choosing suitable operating frequencies for the MI system is a critical task, and the attenuation of RF signals increases with frequency due to increase in the conductivity, resulting in a lower penetration depth. Several computer models have been developed to investigate biological tissues. Debye and Cole-Cole models are the most commonly used models. The Debye model simulates the frequency dependence of DPs of tissues sufficiently [21]:

$$\epsilon_r = \epsilon_\infty + \frac{\epsilon_s + \epsilon_\infty}{1 + j\omega\tau} - j \frac{\sigma}{\omega\epsilon_0} \quad (1)$$

where ϵ_∞ means the permittivity value of the tissue, ϵ_s is the static permittivity of the tissue, and τ is characteristic relaxation time of the medium.

Cole-Cole model is defined as [22]:

$$\epsilon^*(\omega) = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 + (j\omega\tau)^{1-\alpha}} \quad (2)$$

where ϵ^* is the complex dielectric constant, ϵ_s and ϵ_∞ are static and infinite frequency dielectric constants, ω is the angular frequency and τ is a time constant. The exponent parameter α , which takes a value between 0 and 1, describes different spectral shapes. When $\alpha = 0$, the Cole-Cole model becomes to the Debye model.

Many research groups have investigated DPs of various biological tissues, including breast, heart, skin, liver, bone and lymph nodes [23–31]. Some factors that make effects on DPs of tissues include water content [20], change in the dielectric relaxation time [30], charging of the cell membrane [31], sodium content [31] and necrosis and inflammation causing breakdown of cell membrane [32].

3. Microwave imaging techniques

MI approaches can be classified as passive and active. Passive MI approaches use radiometric to measure temperature differences between normal and malignant tissues and identify the lesions based on the measurement differences. Active MI approaches span the high-MHz to low-GHz regime and appear to offer excellent opportunities to supplement the arsenal of screening tools to the radiologist, despite the fact that MI has yet to reach any demonstrated level of clinical feasibility [33]. This chapter focuses on active MI including tomography and radar-based techniques.

3.1. Microwave tomographic (MWT)

Microwave tomographic (MWT) provides quantitative information of DPs of the imaged object, which makes it possible to identify tissues and materials. One of the major limitations is heavy computation work. Based on the operating frequency of the measurement system, MMT can be grouped as single-frequency and multi-frequency approaches.

Larsen et al. [17] developed the first MWT system to produce a microwave canine kidney image at a frequency of 3.5GHz. The system consisted of one transmitting antenna and one receiving antenna, and antennas and the imaged object were immersed in coupling medium that made of water. During data collection, antennas moved to different positions. Such design was not convenient for practical implantation of MI theory, and long data acquisition time was required. To solve this problem, Hawley et al. [34] developed a new MWT system to measure blood content changes. This system consisted of a circular array of 64 waveguide antennas at an operating frequency of 2.45GHz, each waveguide antenna worked as transmitter and receiver, and mechanical movement was not required in the data collection.

A multi-frequency MWT system for breast cancer detection was developed by Meaney et al. (see **Figure 1**) [35]. The system was made of a cylindrical array of 16 monopole antennas that were placed around a breast phantom. The space between breast phantom and antennas was filled of matching medium that was made from glycerin and water mixture. This system was validated on various numerical breast models and phantoms, and simulation results showed that a small tumor (2 mm in diameter) can be imaged. A good agreement between simulation

Figure 1. (a) Multi-frequency MWT system for breast cancer detection and (b) microwave (top row, permittivity, and bottom row, conductivity, at 1100 MHz) images in the same anatomically coronal view for the left breast of a woman with fatty to scattered radiographic density. P1–P7 indicates microwave tomograms spaced 1 cm apart beginning near the chest wall.

and experimental results was observed. The same research group also conducted a three-dimensional MWT system for clinical trial, and results showed that breast tumor as small as 1 cm in diameter could be detected [11]. Although clinical results did not achieve a good agreement with experimental results [35], their studies confirmed that it is possible to use MI for breast cancer detection.

3.2. Radar-based microwave imaging

Radar-based MI approaches can be classified into five groups: confocal microwave imaging (CMI), tissue sensing adaptive radar (TSAR), microwave imaging via space time (MIST), multi-static adaptive (MSA) MI, and holographic microwave imaging technique (HMI). This section presents various radar-based MI approaches for breast cancer detection.

A CMI system was developed by Hagness et al. [13, 14]. In their numerical studies, an array of 17 monopole transceivers was placed along the surface of breast model, and all antennas were equally spaced and spanning 8 cm. Results showed that a small tumor (2 mm in diameter) can be detected by using the 2D system [13], and a tumor with size of 6 mm in diameter can be detected by using the 3D system [14]. The CMI provides necessary imaging resolution and adequate penetration depth in the breast. It does not compensate for frequency-dependent propagation effects but has limited ability to discriminate against artefacts and noise. To overcome these challenges, they applied delay multiply-and-sum signal processing with CMI, where the scattered signals were time-shifted, multiplied in pair and the products

were summed to form a synthetic focal point [15]. This method has an ability to produce higher resolution image and high interference rejection capability [16].

A TSAR prototype system as shown in **Figure 2(a)** was developed by Fear et al. [18]. During data acquisition, a patient was lying in prone position on the examination table with her breast extending through the breast hole and the antennas was scanned around the breast. In order to reduce the noise, the breast image was formed from the reflection signals without skin reflections. Clinical results (see **Figure 2(b)**) showed that the TSAR has an ability to detect and localize lesions with size greater than 4 mm in diameter. The major limitations of TSAR include the large reflections caused from the skin and expensive electronics for real-time imaging. To solve these problems, a Bayesian estimator was applied to enhance the reconstructed image [36].

A MIST beam-forming was developed by Bond et al. [16, 37–38]. A planar array of 16 horn antennas was placed close to the surface of the breast model, and a UWB signal was transmitted sequentially from each antenna. Numerical results demonstrated that a small tumor (2 mm in diameter) embedded in the heterogeneous breast tissue were successfully detected even with denser breast tissue. MIST offers significant improvement in performance over UWB MI approaches based on simpler focusing schemes. However, the system caused skin-breast artefacts in the image prior. The research team upgraded the imaging system (see **Figure 3(a)**) to overcome the challenges of detecting, localizing and resolving multiple or multifocal lesions [39]. The experimental results demonstrated that tumors with size of 4 mm in diameter could be imaged (see **Figure 3(b)**).

Recently, Smith et al. [40–43] proposed a near-field indirect HMI method, which involves recording the holographic intensity pattern and reconstructing the image by using Fourier transformation from the recorded intensity pattern. Compared to TSAR, indirect HMI has the ability to produce real-time image at a significantly low cost. However, more validation works are required on the theory and proof-of-concept for medical applications.

More recently, the authors proposed a far-field HMI method for imaging of biological objects [44–46]. Different from IHM, the 3D HMI uses physical displacement (scan of the distance)

Figure 2. (a) TSAR prototype system and (b) TSAR images for patient.

Figure 3. (a) MIST experimental system setup; reconstructed images with a 4-mm-diameter tumor; (b) yz-plane at $x = 0.1$ cm; (c) xz-plane at $y = 0.1$ cm and (d) xy-plane at $z = 2.3$ cm [39].

between the sensor array plane and the imaged object over a specified range (vertical) to obtain the depth information from sequenced 2D images. Both simulation and experimental results demonstrated that the HMI has several advantages in data collection, including that no matching medium was required and that the complex permittivity of the object was not required to calculate to generate an image that reduced the imaging reconstruction time.

3.3. Imaging systems

Most of existing active MI measurement systems involve hardware and software parts. The hardware system generally includes a microwave source generator, transmitting antenna(s) to send microwave signals toward the target object, receiving antennas(s) to measure the scattered electric field from the target object, a signal measurement controller to control antennas and antenna array plane, and a host computer that contains a matched software system to analyze the measured data using image processing algorithm to display the reconstructed image on a screen displaying unit. The transmitter and receiver can use the same sensor. The requirements for the hardware systems and the computational power are different due to the image algorithm differences. **Table 1** presents various developed MI systems.

3.3.1. Microwave sensor

To design an efficient and robust MI system, it is necessary to develop a sensor to match specific requirements including operating frequency, bandwidth, directivity, sensitivity, accuracy of the detection and many other factors such as compact size and low cost. Sensors should be designed specifically for lower frequencies to enhance electric field intensities inside biological tissues, due to more penetration inside the tissue when the frequency is relatively low; thus, more useful information of the object can be obtained. Various sensors have been developed for imaging of breast, including open-ended coaxial probe [47–57], tapered slot antenna (TSA) [59–63], bow-tie antenna [64–70], monopole antenna [71–78], dipole antenna [79, 80], waveguide antenna [81–84], patch antenna and Vivaldi antenna.

	Dartmouth College (USA)	Keele University (UK)	University of Bristol (UK)	University of Manitoba (Canada)	Auckland University of Technology (NZ)
Antenna	Circular array of 16 monopoles	Circular array of 24 ceramic-filled open-ended waveguides	Two spherical arrays consist of 31 and 60 ultra-wideband antennas	Circular array of doubled layers Vivaldi antennas	Spiral array of 16 open-ended waveguide antennas
Frequency	0.5–3 GHz	1.0–2.3 GHz	4–8 GHz	3–6 GHz	12 GHz
Test phantom	Real patients	Soft animal tissues	Real breasts	Various dielectric objects	Various dielectric objects
Immersion medium	0.9% saline ($\epsilon_r = 76.6$, $\Sigma = 2.48$ S/m)	Metallic bath with coupling liquid	Matching ceramic	No matching medium, air only	No matching medium, air
Image	2D and 3D	2D	3D	2D	2D and 3D
Clinical trial	Yes	No	Yes	No	No

Table 1. Various MI measurement systems.

Open-ended coaxial probes were employed in MI systems to measure dielectric properties of biological tissues [47–56]. Advantages of using probes include that tissue manipulation or preparation is not required, dielectric-properties measurements can be integrated in a straightforward manner with surgical and pathology protocols, they are easy to use, they can respond at broadband frequencies and there is a capacity for noninvasive measurements. However, accuracy and reliability of the measurements depend on the aperture of probe as it is the only part of the system in direct contact with the imaged object.

A compact tapered slot antenna (TSA) was applied in an UWB MI system by Bialkowski et al. [58], and the benefits include high directivity, wide bandwidth, simple feed structure and relatively low in cost, which makes TSA become a popular choice for implementation of MI systems [59–63].

UWB bow-tie sensors were used by John et al. [70]. The system is made of an imaging cavity formed from 12 panels soldered together, and each panel is made of three UWB bow-tie sensors as shown in **Figure 4**. The coupling medium was filled in the cavity, and an image of a spherical object was reconstructed by using inverse scattering algorithm. Advantages of using bow-tie sensor include compact, wideband and easy-to-manufacture.

Researchers at Dartmouth College developed an MWT system that is made of a cylindrical array of 16 monopole antennas (see **Figure 1**), one antenna acting as transmitter and others acting as receivers, and sensors were placed in a coupling medium that is made of material close to fatty tissues. The system was validated on breast phantoms and real human subjects [35]. Advantages of using monopole antennas include easy to model, compact, can be placed at different geometries and can be impedance-matched across a wide bandwidth when immersed in a lossy medium.

Figure 4. Imaging cavity demonstrated in John's publication [82].

Open-ended waveguide antennas were applied in the HMI system by the authors [46]. The HMI system was made of an array of 16 open-ended waveguide antennas, one acting as transmitter and other being receivers. During data collection, the transmitter continuously generated RF signals to the breast phantom and the scattered electric fields were measured by receivers. No matching medium was required in this measurement system.

3.3.2. Microwave sensor array

Investigators also studied the performance of producing high-resolution images at lower costs, including image algorithms, sensor design and sensor array geometry. People paid much attention to image algorithm and sensor design, but very little attentions have been paid to sensor arrays and their applications in the biomedical field. Most of the existing MI systems use circular- [18], planar- [38] and spherical [85]-shaped sensor array. The circular sensor array is more suitable for clinical settings. To generate a high-resolution image, a large number of sensors (from several to several hundreds) are required for the existing MI system. The image is improved with increasing the total number of sensors used in the system. However, limitations of increasing sensor numbers include the increased cost, size and complexity.

Recently, Klemm et al. [85] proposed a spherical array of 16 patch antennas for the clinical applicable CMI system. During data collection, the patient was lying in a prone position, which was felt to offer the best chance of the breast forming a gentle and uniformly curved shape. Experimental results showed that the image quality can be improved by improving the bandwidth of the array element.

More recently, the authors [46] proposed a spiral and random sensor array that contains 16 waveguide antennas for HMI system as shown in **Figure 5**. The experimental results showed that the breast phantom image can be improved by using spiral and random sensor arrays compared to the regular spaced sensor array. Color bar plots signal intensity on a linear scale.

Figure 5. (a) Spiral array; (b) random array; (c) regularly spaced; reconstructed images of two inclusions using (d) spiral array; (e) random array and (f) regularly spaced array.

4. Challenges and future work

There are several major limitations for practical implementations of MI approaches. First, breast phantoms were made of simple materials, which cannot represent real human tissues accurately. Second, the electrical properties contrasts between the normal and the malignant tissues are much smaller than people thought, which caused more difficulty in imaging the structures. Choosing a suitable operating frequency range is also a challenging task. These challenges can be solved by developing a high dynamic system to capture the small difference in the scattered field or by developing a contrast agent to enhance the electrical properties of the malignant tissues. The spatial resolution is another major challenge. To enhance spatial resolution of an MI system, many researchers increased the number of microwave sensors for the implementation system. For example, the sensor number has been increased from 16 to 256 to increase the image quality [86]. However, the detection accuracy may be reduced due to the mutual coupling signals produced between sensors. Moreover, the system became very complex and the implementation costs increased significantly.

To address these problems, one single scanning antenna may be used instead of several antennas. Investigation of sensor arrays such as unequally spaced sensor arrays and applying

compressive sensing approach [87, 88] may be another solution. Some recently proposed techniques such as multiple-input-multiple-output technique [89] may be able to reduce the complexity of the system. Finally, most of the existing experimental systems require the coupling medium between sensors and the imaged object, which increased the system cost significantly.

Many promising indicators suggested that MI systems in the future will be a successful clinical complement to conventional mammography. Investigations may improve the imaging algorithms and hardware implementation systems with particular focus on highly sensitive, compact and low-cost microwave sensors and sensor arrays to achieve high-quality images at relatively low cost. Significant contributions from existing MI commercial companies may be greatly helpful in developing the well-established MI modalities to clinical trials.

5. Conclusion

In conclusion, this chapter presented an exhaustive summary of MI approaches with particular focus on implementations of microwave breast imaging theory, including image algorithms, experimental setups, microwave sensors and sensor arrays. Several MI implementation apparatuses were reviewed in detail. MI systems have direct impacts on spatial resolution, operating frequencies, detection accuracy and quality of imaging. Several advantages of existing MI approaches, open challenges, possible solutions and future research directions were also discussed. Successful clinical trials of MI for breast imaging made the worldwide excitement, and this achievement confirmed that MI has potential to become a low-risk alternative to existing medical imaging tools such as X-ray mammography for breast cancer detection. However, MI-based techniques are still far from maturity due to the fact that many challenges have to be addressed before MI can be implemented in clinical environments.

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References

- [1] Fass L. Imaging and cancer: A review. *Molecular Oncology*. 2008;**2**(2):115-152
- [2] Kerlikowske K, Gard CC, Sprague BL, Tice JA, Miglioretti DL. One vs. two breast density measures to predict 5- and 10-year breast cancer risk. *Cancer Epidemiology, Biomarkers and Prevention: A Publication of the American Association for Cancer Research, Cosponsored by the American Society of Preventive Oncology*. 2005; **24**(6):889
- [3] O'Halloran M, Conceicao RC, Byrne D, Glavin M, Jones E. FDTD modeling of the breast: A review. *Progress in Electromagnetics Research B*. 2009;**18**:1-24
- [4] Chan V, Perlas A. *Basics of Ultrasound Imaging*. New York: Springer; 2011
- [5] Jacobs MA, Ibrahim TS, Ouwerkerk R. MR imaging: Brief overview and emerging applications. *Radiographics*. 2007;**27**4:1213-1229
- [6] Baltzer PA, Berndorf M, Dietzel M, Gajda M, Runnebaum IB, Kaiser WA. False-positive findings at contrast-enhanced breast mri: A bi-rads descriptor study. *Breast Diseases: A Year Book Quarterly*. 2011;**22**(1):44-45
- [7] Wang Z, Lim EG, Tang Y, Leach M. *Medical applications of microwave imaging*. IEEE Press, New York, 1985.
- [8] Fallahpour M, Case JT, Ghasr M, Zoughi R. Piecewise and Wiener filter-based SAR techniques for monostatic microwave imaging of layered structures. *IEEE Transactions on Antennas and Propagation*. 2014;**62**(1):1-13
- [9] De Zaeytijd J, Franchois A, Eyraud C, Geffrin JM. Fullwave three-dimensional microwave imaging with a regularized Gauss–Newton method—Theory and experiment. *IEEE Transactions on Antennas and Propagation*. 2007;**55**(11):3279-3292
- [10] Chandra R, Zhou H, Balasingham I, Narayanan RM. On the opportunities and challenges in microwave medical sensing and imaging. *IEEE Transactions on Biomedical Engineering*. 2015;**62**(7):1667-1682
- [11] Meaney PM, Goodwin D, Golnabi A, Zhou T, Pallone M, Geimer S, Burke G, Paulsen K. Clinical microwave tomographic imaging of the calcaneus: A first-in-human case study of two subjects. *IEEE Transactions on Biomedical Engineering*. 2012;**59**(12): 3304-3313
- [12] Semenov SY, Corfield DR. Microwave tomography for brain imaging: Feasibility assessment for stroke detection. *International Journal of Antennas and Propagation*. 2008;2548301-2548308
- [13] Shea JD, Hagness SC, Van Veen BD. Hardware acceleration of FDTD computations for 3-D microwave breast tomography. *IEEE Antennas and Propagation Society International Symposium*. 2009. pp. 1-4

- [14] Mashal A, Sitharaman B, Li X, Avti PK. Toward carbon-nanotube-based theranostic agents for microwave detection and treatment of breast cancer: Enhanced dielectric and heating response of tissue-mimicking materials. *IEEE Transactions on Biomedical Engineering*. 2010;**57**(8):1831
- [15] Van Veen BD, Hagness SC, Bond EJ, Li X. Space-time microwave imaging for cancer detection. US Patent. 2009;US 7570063 B2
- [16] Koutsoupidou M, Karanasiou IS, Kakoyiannis CG, Groumpas E, Conessa C, Joachimowicz N. Evaluation of a tumor detection microwave system with a realistic breast phantom. *Microwave and Optical Technology Letters*. 2017;**59**(1):6-10
- [17] Mohammed AM, Abbosh S, Mustafa D, Ireland D. Microwave system for head imaging. *IEEE Transactions on Instrumentation and Measurement*. 2014;**63**(1):117-123
- [18] Fear EC, Bourqui J, Curtis C, Mew D. Microwave breast imaging with a monostatic radar-based system: A study of application to patients. *IEEE Transactions on Microwave Theory and Techniques*. 2013;**61**(5):2119-2128
- [19] Schulz S, Pusch S, Pohl E, Dielkus S, Herbst-Irmer R, Meller A. Investigation of tumor using an antenna scanning system. *IEEE Microwave Symposium*. 2014;**171**:1401-1406
- [20] Lazebnik M, Watkins CB, Hagness SC, Booske JH. The dielectric properties of normal and malignant breast tissue at microwave frequencies: Analysis, conclusions, and implications from the Wisconsin/Calgary study. *IEEE Antennas and Propagation Society International Symposium*. 2007. pp. 2172-2175
- [21] Lazebnik M, Okoniewski M, Booske JH, Hagness SC. Highly accurate Debye models for normal and malignant breast tissue dielectric properties at microwave frequencies. *IEEE Microwave and Wireless Components Letters*. 2007;**17**(12):822-824
- [22] Said T, Varadan VV. Variation of Cole-Cole model parameters with the complex permittivity of biological tissues. In: 2009. MTT'09. IEEE MTT-S International Microwave Symposium Digest; IEEE; 2009. pp. 1445-1448
- [23] Kim T, Oh J, Kim B, Lee J, Jeon S, Pack J. A study of dielectric properties of fatty, malignant and fibro-glandular tissues in female human breast. *Asia-Pacific Symposium on Electromagnetic Compatibility and International Zurich Symposium on Electromagnetic Compatibility*. 2008;216-219
- [24] Garrett JD, Fear EC. Average dielectric property analysis of complex breast tissue with microwave transmission measurements. *Sensors*. 2015;**15**(15):1199-1216
- [25] Fu F, Xin SX, Chen W. Temperature- and frequency-dependent dielectric properties of biological tissues within the temperature and frequency ranges typically used for magnetic resonance imaging-guided focused ultrasound surgery. *International Journal of Hyperthermia*. 2014;**30**(1):56
- [26] O'Rourke AP, Lazebnik M, Bertram JM, Converse MC, Hagness SC, Webster JC. Dielectric properties of human normal, malignant and cirrhotic liver tissue: In vivo and

ex vivo measurements from 0.5 to 20 GHz using a precision open-ended coaxial probe. *Physics in Medicine and Biology*. 2007;**52**(15):4707-4719

- [27] Zhang L, Liu P, Shi X, You F, Dong X. A comparative study of a calibration method for measuring the dielectric properties of biological tissues on electrically small open-ended coaxial probe. *IEEE International Conference on Biomedical Engineering and Biotechnology*. 2012. pp. 658-661
- [28] Zhang L, Shi X, You F, Liu P, Dong X. Improved circuit model of open-ended coaxial probe for measurement of the biological tissue dielectric properties between megahertz and gigahertz. *Physiological Measurement*. 2013;**34**(10):N83
- [29] Yamamoto T, Koshiji K, Fukuda A. Development of test fixture for measurement of dielectric properties and its verification using animal tissues. *Physiological Measurement*. 2013;**34**(9):1179
- [30] Lazebnik M, McCartney L, Popovic D, Watkins CB, Lindstrom MJ, Harter J. A large-scale study of the ultrawideband microwave dielectric properties of normal, benign and malignant breast tissues obtained from cancer surgeries. *Physics in Medicine and Biology*. 2007;**52**(20):6093-6115
- [31] Abeyrathne CD, Halgamuge MN, Farrell PM, Skafidas E. An ab-initio computational method to determine dielectric properties of biological materials. *Scientific Reports*. 2013;**3**(5):1796
- [32] Rossmanna C, Haemmerich D. Review of temperature dependence of thermal properties, dielectric properties, and perfusion of biological tissues at hyperthermic and ablation temperatures. *Critical Reviews in Biomedical Engineering*. 2014;**42**(6):467-469
- [33] Ibrahim WMA, Algabroun HM. The Family Tree of Breast Microwave Imaging Techniques. In: 4th Kuala Lumpur International Conference on Biomedical Engineering; Springer: Berlin Heidelberg; 2008
- [34] Nikawa Y. Microwave diagnosis using MRI and image of capillary blood vessel. *IEEE Asia Pacific Microwave Conference*. 2009. pp. 595-598
- [35] Meaney PM, Fanning MW, Raynolds T, Fox CJ, Fang Q, Kogel CA. Initial clinical experience with microwave breast imaging in women with normal mammography. *Academic Radiology*. 2007;**14**(2):207-218
- [36] O'Halloran M, Byrne D, Elahi MA, Conceição RC, Jones E, Glavin M. Confocal Microwave Imaging. *An Introduction to Microwave Imaging for Breast Cancer Detection, Part of the series Biological and Medical Physics, Biomedical Engineering*. Springer International Publishing, AG Switzerland. 2016. pp. 47-73.
- [37] Salvador SM, Fear EC, Okoniewski M, Matyas JR. Exploring joint tissues with microwave imaging. *IEEE Transactions on Microwave Theory and Techniques*. 2010;**58**(8):2307-2313
- [38] Ricci E, Maggio F, Rossi T, Cianca E, Ruggieri M. UWB radar imaging based on space-time beamforming for stroke detection. *IFMBE Proceedings*. 2015;**45**:946-949

- [39] Li X, Davis S K, Hagness S C, Van D W, Van Veen B D. Microwave imaging via space-time beam forming: Experimental investigation of tumor detection in multilayer breast phantoms. *IEEE Transactions on Microwave Theory & Techniques*, 2004, **52**(8):1856-1865.
- [40] Smith D, Livingstone B, Elsdon M, Zheng H. The development of indirect microwave holography for measurement and imaging applications. 2015 IEEE Microwave Symposium. 2015;**722**:1-4
- [41] Smith D, Yurduseven O, Livingstone B. The use of indirect holographic techniques for microwave imaging. *IEEE Microwave Techniques*. 2013;**10**:16-21
- [42] Yurduseven O, Smith D, Livingstone B, Schejbal V, You Z. Investigations of resolution limits for indirect microwave holographic imaging. *International Journal of RF and Microwave Computer-Aided Engineering*. 2013;**23**(4):410-416
- [43] Smith D, Yurduseven O, Livingstone B, Schejbal V. Microwave imaging using indirect holographic techniques. *IEEE Antennas and Propagation Magazine*. 2014;**56**(1):104-117
- [44] Wang L, Al-Jumaily AM, Simpkin R. Imaging of 3-D dielectric objects using far-field holographic microwave imaging technique. *Progress in Electromagnetics Research B*. 2014;**61**:135-147
- [45] Wang L, Al-Jumaily AM, Simpkin R. Three-dimensional far-field holographic microwave imaging: An experimental investigation of dielectric object. *Progress in Electromagnetics Research B*. 2014;**61**(1):169-184
- [46] Wang L, Al-Jumaily AM, Simpkin R. Investigation of antenna array configurations using far-field holographic microwave imaging technique. *Progress in Electromagnetics Research M*. 2015;**42**:1-11
- [47] Bobowski JS, Johnson T. Permittivity measurements of biological samples by an open-ended coaxial line. *Progress in Electromagnetics Research B*. 2012;**40**(40):159-183
- [48] Reinecke T, Hagemeyer L, Ahrens S, Klintschar M. Permittivity measurements for the quantification of edema in human brain tissue Open-ended coaxial and coplanar probes for fast tissue scanning. *IEEE Sensors conference*. 2014, Nov, 681-683
- [49] Sato Y, Hirata A, Fujiwara O. In-vivo measurement of complex relative permittivity for human skin tissues using open-ended coaxial probe. *IEEE Transactions on Electronics Information and Systems*. 2011;**131**(131):2040-2045
- [50] Huang R, Zhang D. Analysis of open-ended coaxial probes by using a two-dimensional finite-difference frequency-domain method. *IEEE Transactions on Instrumentation and Measurement*. 2008;**57**(5):931-939
- [51] Michiyama T, Nikawa Y, Kuwano S. Measurement of complex permittivity for soft material using easy sticking open ended coaxial probe. *Transactions of the Institute of Electronics Information and Communication Engineers C*. 2010;**93**:167-174
- [52] Jung JH, Cho JH, Kim SY. Accuracy enhancement of wideband complex permittivity measured by an open-ended coaxial probe. *Measurement Science and Technology*. 2016;**27**(1):015011

- [53] Habibi M, Klemer DP, Raicu V. Two dimensional dielectric spectroscopy: Implementation and validation of a scanning open-ended coaxial probe. *Review of Scientific Instruments*. 2010;**81**(7):255-258
- [54] Brusson M, Rossignol J, Binczak S, Laurent G. Determination of burn depth in the ablation of atrial fibrillation using an open-ended coaxial probe. *Sensors & Actuators B Chemical*. 2015, **209**: 1097-1101.
- [55] Misra DK, Mckelvey JA. A quasistatic method for the characterization of stratified dielectric materials using an open-ended coaxial probe. *Microwave & Optical Technology Letters*. 2010;**7**(7):650-653
- [56] Misra DK. Evaluation of the complex permittivity of layered dielectric materials with the use of an open-ended coaxial line. *Microwave and Optical Technology Letters*. 2015;**11**(11):183-187
- [57] Meaney P M, Gregory A P, Epstein N R, Paulsen K D. Microwave open-ended coaxial dielectric probe: interpretation of the sensing volume re-visited. *BMC Medical Physics*. 2014, **14**(1):1-11.
- [58] Tiang SS, Ain MF, Abdullah MZ. Compact and wideband wide-slot antenna for microwave imaging system. *IEEE RF and Microwave Conference*. 2011. pp. 63-66
- [59] Gopikrishna M, Krishna DD, Aanandan CK, Mohanan P. Compact linear tapered slot antenna for UWB applications. *Electronics Letters*. 2008;**44**(20):1174-1175
- [60] Costa JR, Medeiros CR, Fernandes CA. Performance of a crossed exponentially tapered slot antenna for UWB systems. *IEEE Transactions on Antennas and Propagation*. 2009;**57**(5):1345-1352
- [61] Azim R, Islam MT, Misran N. Compact tapered-shape slot antenna for UWB applications. *IEEE Antennas and Wireless Propagation Letters*. 2011;**10**(3):1190-1193
- [62] Wu J, Zhao Z, Liu J, Nie ZP, Liu QH. A compact linear tapered slot antenna with integrated Balun for UWB applications. *Progress in Electromagnetics Research C*. 2012;**29**:163-176
- [63] Lu WJ, Zhang ZY, Liu R, Zhu HB. Design concept of a narrow-wideband antenna for spectrum sensing applications. *IEEE China-Japan Joint Microwave Conference*. 2011. pp. 1-4
- [64] Mehdipour A, Mohammadpour-Aghdam K, Faraji-Dana R, Sebak AR. Modified slot bow-tie antenna for UWB applications. *Microwave and Optical Technology Letters*. 2008;**50**(2):429-432
- [65] Hirata A. Double-sided printed bow-tie antenna with notch filter for UWB applications. *Journal of Electromagnetic Waves and Applications*. 2012;**23**(2):247-253
- [66] Sayidmarie KH, Fadhel YA. A planar self-complementary bow-tie antenna for UWB applications. *Progress in Electromagnetics Research C*. 2013;**35**:253-267
- [67] Kumar R, Surushe G. Design of microstrip-fed printed uwb diversity antenna with tee crossed shaped structure. *Engineering Science and Technology, an International Journal*. 2016;**19**(2):946-955

- [68] Jalilvand M, Li X, Kowalewski J, Zwick T. Broadband miniaturised bow-tie antenna for 3D microwave tomography. *Electronics Letters*. 2014; **50**(4):244-246
- [69] Ünal Ø, Türetken B, Canbay C, Ünal Ø, Türetken B. Spherical conformal bow-tie antenna for ultra-wide band microwave imaging of breast cancer tumor. *Applied Computational Electromagnetics Society Journal*. 2014; **29**(2):124-133
- [70] John S, Mark H, Paul C, Mahta M. A preclinical system prototype for focused microwave thermal therapy of the breast. *IEEE Transactions on Biomedical Engineering*. 2012; **59**(9):2431-2438
- [71] Ojaroudi M, Kohneshahri G, Noory J. Small modified monopole antenna for UWB application. *IET Microwaves Antennas and Propagation*. 2009; **3**(5):863-869
- [72] Ni W, Nakajima N. Small printed inverted-l monopole antenna for worldwide interoperability for microwave access wideband operation. *IET Microwaves Antennas and Propagation*. 2010; **4**(1):1714-1719
- [73] Halili K, Ojaroudi M, Ojaroudi N. Ultrawideband monopole antenna for use in a circular cylindrical microwave imaging system. *Microwave and Optical Technology Letters*. 2012; **54**(9):2202-2205
- [74] Golezani JJ, Abbak M, Akduman I. Modified directional wide band printed monopole antenna for use in radar and microwave imaging applications. *Progress in Electromagnetics Research Letters*. 2012; **33**:119-129
- [75] Latif S, Flores-Tapia D, Pistorius S, Shafai L. A planar ultrawideband elliptical monopole antenna with reflector for breast microwave imaging. *Microwave and Optical Technology Letters*. 2014; **56**(4):808-813
- [76] Ojaroudi N, Ojaroudi M, Ebazadeh Y. UWB/omni-directional microstrip monopole antenna for microwave imaging applications. *Progress in Electromagnetics Research C*. 2014; **47**:139-146
- [77] Ojaroudi N, Ojaroudi M, Ghadimi N. UWB omnidirectional square monopole antenna for use in circular cylindrical microwave imaging systems. *Wireless Personal Communications*. 2015; **11**(3):1350-1353
- [78] Ojaroudi M, Civi OA. Bandwidth enhancement of small square monopole antenna using self-complementary structure for microwave imaging system applications. *Applied Computational Electromagnetics Society Journal*. 2015; **30**(12):1360-1365
- [79] Saenz E, Guven K, Ozbay E, Ederra I, Gonzalo P. Decoupling of multifrequency dipole antenna arrays for microwave imaging applications. *International Journal of Antennas and Propagation*. 2010; **4**:252-260
- [80] Ahdi Rezaeieh S, Bialkowski K, Zamani A, Abbosh A. Loop-dipole composite antenna for wideband microwave-based medical diagnostic systems with verification on pulmonary edema detection. *IEEE Antennas and Wireless Propagation Letters*. 2015; **15**:1

- [81] Ali M, Tailor A. Broadband coplanar waveguide-fed slot antenna for wireless local area networks and microwave imaging applications. *Microwave and Optical Technology Letters*. 2007;**49**(4):846-852
- [82] Saleh W, Qaddoumi N. Potential of near-field microwave imaging in breast cancer detection utilizing tapered rectangular waveguide probes. *Computers and Electrical Engineering*. 2009;**35**(4):587-593
- [83] Diener L. Microwave near-field imaging with open-ended waveguide—Comparison with other techniques of nondestructive testing. *Research in Nondestructive Evaluation*. 2009;**7**(2-3):137-152
- [84] Brovko AV, Murphy EK, Yakovlev VV. Waveguide microwave imaging: Neural network reconstruction of functional 2-D permittivity profiles. *IEEE Transactions on Microwave Theory and Techniques*. 2009;**57**(2):406-414
- [85] Klemm M, Craddock IJ, Leendertz JA, Preece A. Radar-Based breast cancer detection using a hemispherical antenna array-experimental results. *IEEE Transactions on Antennas and Propagation*. 2009;**57**(6):1692-1704
- [86] Kurrant D, Bourqui J, Curtis C, Fear E. Evaluation of 3d acquisition surfaces for radar-based microwave breast imaging. *IEEE Transactions on Antennas and Propagation*. 2015;**63**(11):1-1
- [87] Craven D, O'Halloran M, McGinley B, Conceicao RC, Kilmartin L, Jones E. Compressive sampling for time critical microwave imaging applications. *Healthcare Technology Letters*. 2014;**1**(1):6-12
- [88] Bevacqua MT, Scapaticci R. A compressive sensing approach for 3D breast cancer microwave imaging with magnetic nanoparticles as contrast agent. *IEEE Transactions on Medical Imaging*. 2016;**35**(2):665-673
- [89] Qi Y. Application of sparse array and MIMO in near-range microwave imaging. *Proceedings of SPIE - The International Society for Optical Engineering*. 2011;**8179**(4):81790X-81790X-12