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Microwave Breast Imaging for Cancer Detection: Progress,Challenges and Future Prospects

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تصوير الثدي باستخدام الميكروويف للكشف عن السرطان: التقدم، التحديات، والآفاق المستقبلية

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Abstract:
Breast cancer remains one of the most common and life-threatening diseases worldwide. Standard diagnostic techniques such as mammography, ultrasound, magnetic resonance imaging (MRI), computed tomography (CT), and positron emission tomography (PET) have provided important clinical benefits but are often limited by high cost, exposure to ionizing radiation, or reduced performance in dense breast tissue. Microwave breast imaging (MBI) has recently gained attention as a safe, non-ionizing, cost-effective, and patient-friendly approach. This paper reviews the latest advances in MBI, focusing on dielectric property characterization, antenna technologies, and imaging methodologies. Current barriers—including computational complexity, safety constraints, and limited clinical validation—are discussed. The review concludes with future research priorities such as algorithmic improvement, hybrid imaging frameworks, and large-scale clinical trials that may accelerate the clinical adoption of MBI.

Keywords: Microwave breast imaging, dielectric properties, tomography, radar-based imaging, breast cancer detection.

الملخص
يُعدّ سرطان الثدي من أكثر الأمراض شيوعًا وخطورة على مستوى العالم. وعلى الرغم من أن تقنيات التشخيص التقليدية مثل التصوير الشعاعي للثدي، التصوير بالموجات فوق الصوتية، التصوير بالرنين المغناطيسي (MRI)، التصوير المقطعي المحوسب (CT)، والتصوير المقطعي بالإصدار البوزيتروني (PET) قد ساهمت بشكل كبير في الممارسة السريرية، إلا أنها تواجه تحديات تشمل التكلفة العالية، والتعرض للإشعاع المؤين، وانخفاض الدقة لدى النساء ذوات الأنسجة الثديية الكثيفة.وقد برز التصوير الميكروي للثدي (MBI) مؤخرًا كخيار واعد، حيث يوفر طريقة آمنة، غير مؤينة، منخفضة التكلفة، ومريحة للمريض. يستعرض هذا البحث أحدث التطورات في مجال MBI، مع التركيز على خصائص الثدي العازلة، وتصميم الهوائيات، ومنهجيات التصوير الحديثة. كما يناقش البحث التحديات الحالية مثل التعقيد الحسابي، ومعايير السلامة، ونقص التحقق السريري الواسع ويختتم بمناقشة أولويات البحث المستقبلية، والتي تشمل تحسين الخوارزميات، وتطوير أطر التصوير الهجينة، وإجراء تجارب سريرية موسعة MBI في الممارسة السريرية.

الكلمات المفتاحية: التصوير الميكروي للثدي، الخصائص العازلة، التصوير بالرادار، التصوير المقطعي، كشف سرطان الثدي.

1. Introduction

. Breast cancer is the leading cause of cancer-related deaths among women worldwide, with more than 310,720 new cases and 42,250 deaths reported in the United States in 2024 alone [1]. Conventional imaging modalities—such as mammography, ultrasound, magnetic resonance imaging (MRI), computed tomography (CT), and positron

emission tomography (PET)—have significantly contributed to diagnosis but face important limitations. Mammography, despite its accessibility and reproducibility, is unsuitable for women with dense breasts or during pregnancy, and exposes patients to ionizing radiation [2–4]. Ultrasound offers safer imaging yet suffers from low sensitivity in fatty tissues [5], while MRI provides higher accuracy in dense tissue but is costly and uncomfortable [6]. CT and PET, though valuable in advanced cases, remain restricted by high expenses, radiation exposure, and limited effectiveness in early detection [7,8].
To overcome these challenges, microwave imaging (MI) has emerged as a promising alternative. MI uses non-ionizing electromagnetic waves, exploits dielectric contrasts between malignant and healthy tissues, and offers non-invasiveness, cost-effectiveness, and improved detection in dense breasts [9–12]. Recent developments—including ultra-wideband (UWB) systems, radar-based techniques, advanced reconstruction algorithms, and 3D phantom modeling—have further enhanced its clinical potential [13,14]. This paper reviews the progress of microwave breast imaging (MBI), focusing on dielectric characterization, imaging methods, clinical challenges, and future perspectives.

2. Dielectric Properties of Breast Tissues

The potential of microwave imaging (MI) for breast tumor detection primarily arises from the clear contrast in dielectric properties between healthy and malignant tissues. Two parameters are particularly significant: the relative permittivity (εr), which reflects the ability of tissues to store electric energy, and the conductivity (σ), which represents their ability to conduct electric energy within the 300 MHz to 30 GHz frequency range [15]. The main source of this contrast is the variation in water content across different tissues. Malignant tumors, being richer in water, typically exhibit higher permittivity, whereas adipose tissue—abundant in normal breasts—shows much lower values [16]. As electromagnetic waves propagate through breast tissue, their scattering and reflection differ depending on these dielectric properties, providing the foundation for MI-based tumor detection.
The earliest systematic study of breast tissue dielectric properties was carried out by Chaudhary et al. in 1984 [11], followed by numerous experimental and numerical investigations [17,18]. Although the methodologies and reported values varied, these studies consistently demonstrated the feasibility of using microwave techniques to identify malignant breast tissue. Later studies by Sabouni et al. [19] and Nazeri et al. [20] highlighted those dielectric properties may change rapidly after tissue excision due to temperature and water content variations, underscoring the importance of in vivo measurements.
As illustrated in Figure 1, Debye and Cole–Cole models are widely used to describe the nonlinear frequency-dependent behavior of breast tissue dielectric properties [21,22]. In the Debye model [23], the static permittivity (εs), permittivity at infinite frequency (ε∞), and relaxation time (τ) define the tissue's electromagnetic response. Experimental data have shown that tissue permittivity is highly sensitive to water and salt content as well as relaxation duration [24–27]. Chaudhary et al. [11] reported a strong dielectric contrast between normal and cancerous tissues in the range of 3–100 MHz, a result later validated by Joines et al. [28]. Gabriel et al. [25,26] extended this characterization to a wider range (0.01–20 GHz), while Surowiec et al. [29] observed elevated dielectric properties at the infiltrating edges of tumors. Similarly, Lazebnik et al. [27] provided comprehensive data on malignant, benign, and normal tissues over 0.5–20 GHz. Halter et al. [30] further demonstrated that in vivo measurements minimize the deviations associated with excised tissues.
Phantom-based research has also advanced the understanding of tissue dielectric behavior. For instance, Martellosio et al. [31] investigated properties of 222 tissue samples from 53 patients over 0.5–50 GHz, employing Cole–Cole models to capture frequency-dependent variations. Meo et al. [32] designed breast phantoms mimicking ex vivo tissue properties, while Eliana et al. [33] confirmed that dielectric characterization within 0.5–9 GHz could effectively distinguish malignant from benign lesions. Fernández et al. [34] reported that benign tumors generally exhibit permittivity values below 35, whereas malignant ones range from 40 to 60, with mucinous carcinoma showing the highest values. Their findings also demonstrated that tumor permittivity decreases with frequency, with significant changes observed at 2 GHz and 4 GHz. The Double Cole–Cole model provided the most accurate fit, suggesting that the 2–4 GHz range may be sufficient for reliable tumor discrimination.

$$\varepsilon_r = \varepsilon_\infty + \frac{\varepsilon_s + \varepsilon_\infty}{1 + j\omega\tau} - j\frac{\sigma}{\omega\varepsilon_0}$$

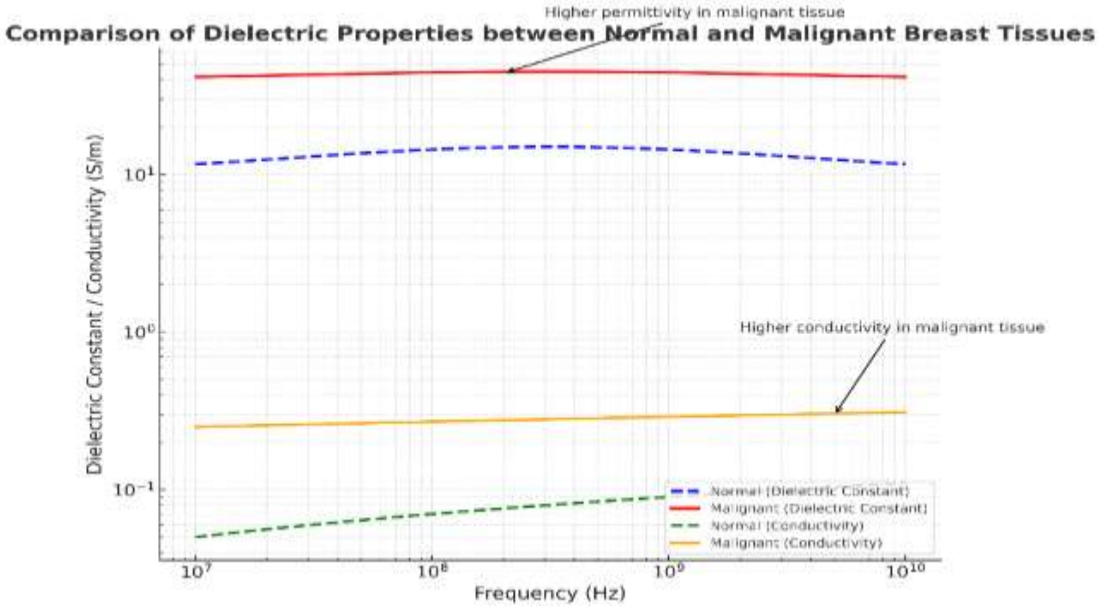

Figure 1. Single-pole Debye models applied to baseline dielectric property data of healthy and cancerous breast tissues across radio and microwave frequency ranges. [21]

Clinically, these findings highlight the diagnostic value of permittivity differences, offering opportunities to accelerate tumor detection and potentially reduce reliance on conventional histopathology. A summary of key studies conducted over the past decade on breast tissue dielectric characterization is presented in Table 1.

Table 1. Summary of studies on dielectric properties of breast tissues (2015–2024).

Year	Author	Measurement Method	Antenna Type	Frequency Range	Tissue Type	Samples	Clinical Trials / Notes
2015	Martellosio et al. [35]	Dielectric spectroscopy (reflectometry, VNA)	Open-ended coaxial probe	0.5–50 GHz	Human breast (normal & malignant), animal	–	Ex vivo measurements on surgical specimens; no formal clinical trial
2016	Martellosio et al. [31]	Reflectometry (VNA)	Open-ended coaxial probe	0.5–50 GHz	Healthy & malignant tissues	220	Ex vivo measurements, not a clinical trial
2017	Meo et al. [37]	Reflectometry (VNA)	Open-ended coaxial probe	0.5–50 GHz	Healthy & malignant breast tissues	330	Ex vivo samples from 100 women (ages 28–85); no live-patient clinical trials
2018	Yiou Cheng et al. [36]	VNA with open-ended coaxial probe	–	0.5–8 GHz	Benign, malignant, tumor tissues	509	Ex vivo study on 509 surgical samples from 98 patients; diagnostic, not therapeutic
2019	Hussein et al. [38]	Microwave spectroscopy (VNA)	Open-ended coaxial probe	200 MHz–13.6 GHz	Normal & tumor cell lines	48	In vitro study; no clinical trial
2022	Kensuke Sasaki et al. [39]	Open-ended coaxial probe, waveguides, THz-TDS	Hybrid (probe & imaging-based)	Up to 1 THz	Normal & malignant tissues (skin, brain, liver, colon, breast)	–	Ex vivo dielectric characterization across multiple organs
2024	Fernández et al. [40]	Open-ended coaxial probe (VNA)	–	1–8 GHz	Malignant & benign breast tumors	279	Ex vivo diagnostic study; dielectric characterization, no clinical interventions

3.Antennas Used in microwave Imaging for breast tissues

Antennas are a crucial element in microwave breast imaging (MBI) systems. They transmit microwave signals into the breast tissue and receive the reflected waves, which are then analyzed to detect, localize, and characterize tumors. Over the years, various antenna types have been investigated and optimized for breast imaging, aiming to achieve high resolution, deep tissue penetration, and accurate tumor detection. The design of the antenna—including frequency range, radiation pattern, polarization, and impedance matching—directly affects the sensitivity and effectiveness of the MBI system.The most commonly used antennas in MBI systems include in table 2.Choosing the right antenna type is essential for effective MBI. Trade-offs between size, bandwidth, gain, and ease of integration determine the suitability of each antenna for clinical breast imaging applications. Continuous research focuses on developing compact, wearable, and ultra-wideband antennas to enhance tumor detection accuracy and patient comfort.

Table 2. Common Antenna Types Used in Microwave Breast Imaging

Antenna Type	Description	Advantages	Limitations
Microstrip Patch Antenna	Flat, planar antenna often printed on a substrate.	Compact, lightweight, easy to fabricate, suitable for array configurations.	Limited bandwidth, lower penetration depth.
Horn Antenna	Flared metal waveguide that radiates microwave energy.	High gain, directional radiation pattern.	Bulky, not easily wearable for clinical applications.
Vivaldi Antenna	Tapered slot antenna with wideband characteristics.	Ultra-wideband, high resolution, good tumor detection capability.	Larger size compared to patch antennas.
Dipole Antenna	Simple wire or rod antenna.	Easy to design, wide bandwidth.	Moderate gain, requires precise placement.
Slot Antenna	Aperture cut into a conducting surface.	Wide bandwidth, flexible design.	Complex feeding network for arrays.

3.1 Antenna Characteristics for MBI

Effective antennas are essential for high-quality microwave breast imaging. Key characteristics include:

- **Low-profile and lightweight design:** Compact, portable antennas are preferred because they can scan breast tissue at multiple points, collecting more data and enhancing detection accuracy. Simple designs also reduce manufacturing costs. Microstrip patch antennas are a common example of low-profile antennas used in MBI [43,44].
- **High-gain antennas:** High-gain antennas focus the radiated energy in a specific direction, producing higher-resolution images of breast tissue. They also require less power to achieve effective signal strength, improving the system's energy efficiency [45,46].
- **Low reflection:** Antennas should exhibit a low reflection coefficient to minimize power loss, ensuring that most of the transmitted energy penetrates the breast tissue. Reducing reflected power enhances the likelihood of detecting tumors and generating detailed images [47].
- **Specific Absorption Rate (SAR) compliance:** Antennas must adhere to international safety standards. According to ICNIRP guidelines, SAR should not exceed 2 W/kg over a 10-gram tissue mass. Measuring SAR ensures safe exposure levels for patients during imaging [20,48].
- **Ultra-wideband (UWB) capability:** UWB antennas, operating over a broad frequency range (typically 3.1–10.6 GHz), are ideal for MBI because they provide superior tissue contrast and differentiation, improving tumor detection and image quality [49–52].

Microwave imaging systems employ antennas for both signal transmission and reception. Based on the number of antennas, MBI systems can be categorized as follows:

- **Monostatic systems:** A single antenna serves as both transmitter and receiver. These systems are simple and cost-effective but may offer lower image quality [55,56].
- **Bi-static systems:** Two separate antennas are used for transmission and reception. This configuration improves imaging resolution compared to monostatic systems [55,56].
- **Multi-static systems:** An array of antennas is used, with one antenna transmitting at a time while the others receive. Multi-static systems provide the highest image quality and flexibility, though they are more complex and costly [55,56].

Overall, selecting the appropriate antenna type and system configuration is crucial for achieving accurate, safe, and high-resolution microwave breast imaging.

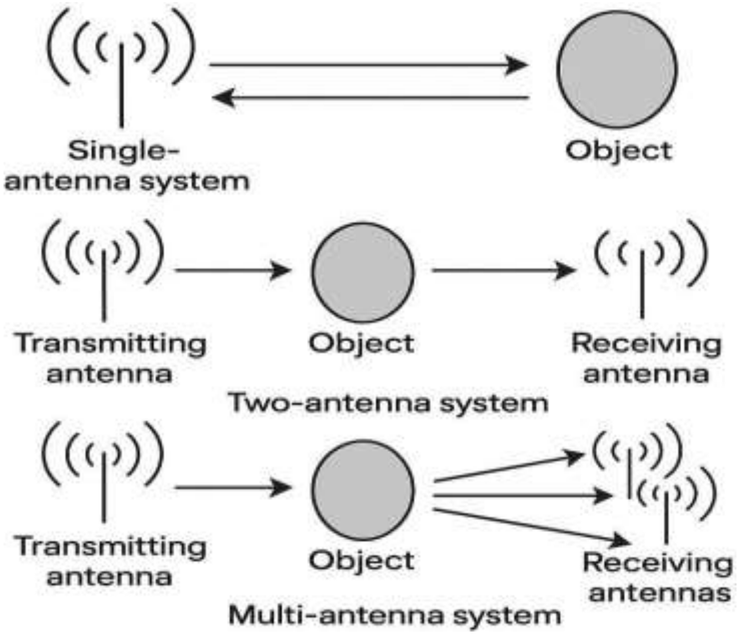

Figure 2: Monostatic, Bi-static, and Multi-static Antenna Configurations in Microwave Breast Imaging.

4. Microwave breast Imaging techniques

Microwave breast imaging (MBI) techniques are generally classified into three categories: active, passive, and hybrid approaches, each with distinct strengths and limitations (Figure 3)

- Active MBI Techniques.
- Active methods, such as microwave tomography (MT) and radar-based imaging, use externally applied microwave signals to examine breast tissue. These techniques are particularly sensitive, capable of detecting small or early-stage tumors, and show strong potential for accurate lesion diagnosis.
- Passive MBI Techniques.
- Passive approaches rely on the natural thermal radiation emitted by breast tissues to form images. This non-invasive method eliminates the need for external radiation, reducing patient exposure. However, its relatively lower sensitivity can limit detection of small or deeply located tumors.
- Hybrid MBI Techniques.
- Hybrid methods integrate microwave imaging with other modalities, including ultrasound, MRI, or optical imaging, to provide a more comprehensive evaluation of breast tissue. By combining different techniques, hybrid MBI can enhance diagnostic accuracy and tissue characterization.
- Among these, microwave tomography and radar-based imaging are the primary active techniques, widely recognized for their capability to detect early-stage breast cancer and their unique diagnostic advantages.

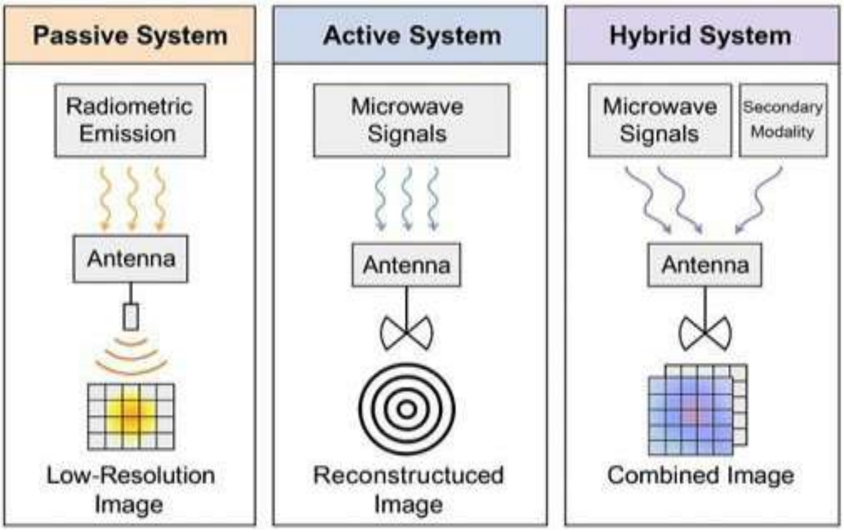

Figure 3: Microwave Tomography and Radar-Based Imagine.

4.1 Microwave Tomography Imaging (MTI).

Microwave Tomography Imaging (MTI) is based on the contrast in dielectric properties between different biological tissues. This contrast enables the reconstruction of dielectric maps of the breast when exposed to microwave radiation. In a typical MTI setup, the patient lies on a scanning table while an array of antennas directs microwave signals toward the breast. As the waves propagate through tissues of varying dielectric properties, part of the energy is scattered and reflected back. These scattered signals are collected by the antenna system and then processed using inversion algorithms to generate two- or three-dimensional tomographic images [58], [59], [60], [61], [62], [63]. Such images provide valuable information about the size, location, and dielectric profile of tumors. Despite these advantages, solving the inverse problem associated with MTI remains one of the most critical challenges [18].

The image reconstruction process in MTI involves addressing both forward and inverse problems. The forward problem focuses on predicting the scattered electromagnetic fields based on known tissue properties and boundary conditions [64]. The complexity of this step depends on the computational resources available, particularly for 3D models, which require considerably more processing time than 2D simulations. Numerical approaches commonly applied include finite-difference (FD), finite-difference time-domain (FDTD), finite element (FE), and method of moments (MoM) [42], [65].

The inverse problem, on the other hand, seeks to reconstruct the dielectric distribution from the measured scattered fields. This problem is often ill-posed, meaning that solutions may lack uniqueness or stability. Various algorithms have been developed to address this challenge, such as the Born Iterative Method (BIM), the Distorted Born Iterative Method (DBIM), and Contrast Source Inversion (CSI). Figure 3 illustrates the sequential process of microwave breast tomography

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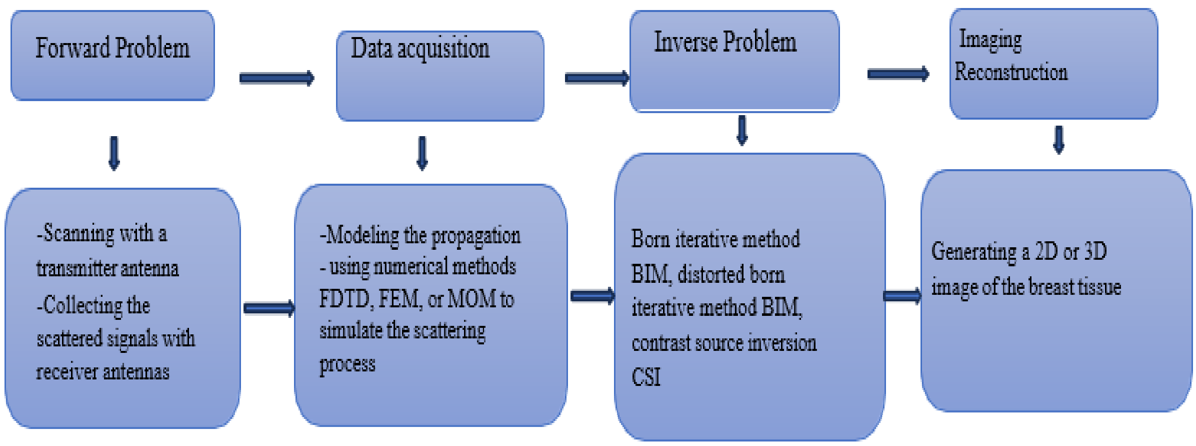

Figure 3. Flow chart illustrating the procedure of microwave tomography breast imaging.

Several research efforts have advanced the practical implementation of MTI systems. For instance, Simonov et al. [66] described a microwave imaging system developed at the Electronics and Telecommunications Research Institute (ETRI) for breast cancer detection. This system utilizes a 16-element monopole antenna array operating between 500 MHz and 3 GHz. The antennas are placed in a coupling medium that mimics breast tissue, with one antenna functioning as the transmitter and the remaining 15 as receivers. The forward problem was modeled using the FDTD method, while a modified iterative Gauss–Newton approach was applied to solve the inverse problem. Experimental validation using a 40 mm tumor-mimicking sphere confirmed the system's ability to localize abnormal tissue within a breast phantom.

In another recent study, Alibakhshikenari et al. [67] investigated a planar antenna array consisting of eight elements operating in the 2–12 GHz band, with a gain of approximately 4.8 dB. One antenna acted as a transmitter and the rest as receivers, with frequency-domain data transformed into the time domain using the Inverse Fast Fourier Transform (IFFT). As shown in Figure 4, the reflected signals were notably stronger in the presence of a tumor, demonstrating the effectiveness of the proposed setup in detecting malignant tissue.

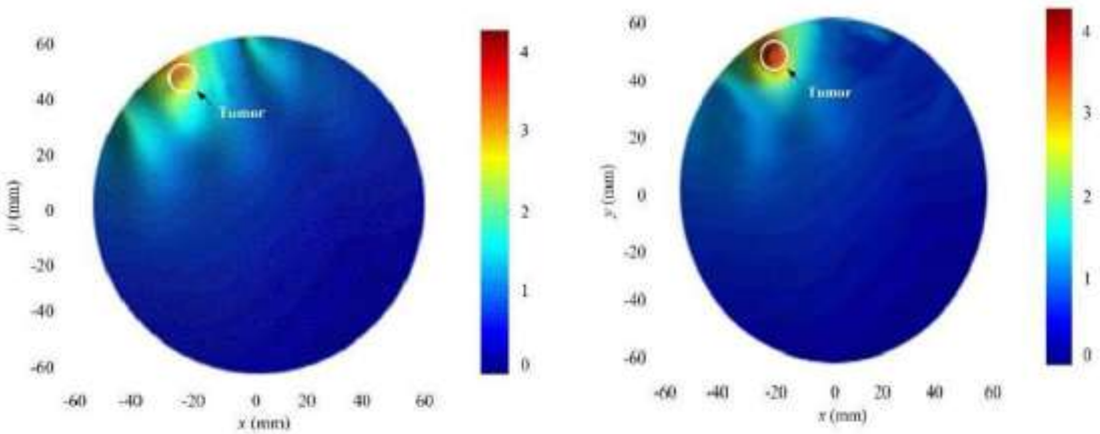

Figure 4: Tumor detection imaging using microwave tomography: (a) reference antenna array with standard patches at 5.5 GHz, and (b) the proposed antenna array at 5.5 GHz [67].

4.2 Microwave Radar-Based Imaging

Radar-based microwave imaging is a relatively simpler technique compared to tomography microwave imaging. They both involve scanning the tissue, but radar-based MI processes the reflected signals through a focusing algorithm to create the final image, rather than using tomographic reconstruction. This document reviews the research and findings from simulation studies, physical experiments, and clinical trials in specific areas of using radar-based microwave Radar-based MBI techniques are developed such as Confocal Microwave Imaging (CMI) [69], Delay-Multiply-and-Sum (DMAS), Delay and Sum (DAS) [70, 71], multi-static adaptive microwave imaging (MAMI) [71], Time shift and sum, Generalized likelihood ratio test (GLRT), time domain data-adaptive (TDDA) etc. These use various methods to measure and resolve electromagnetic signals to create high-resolution.

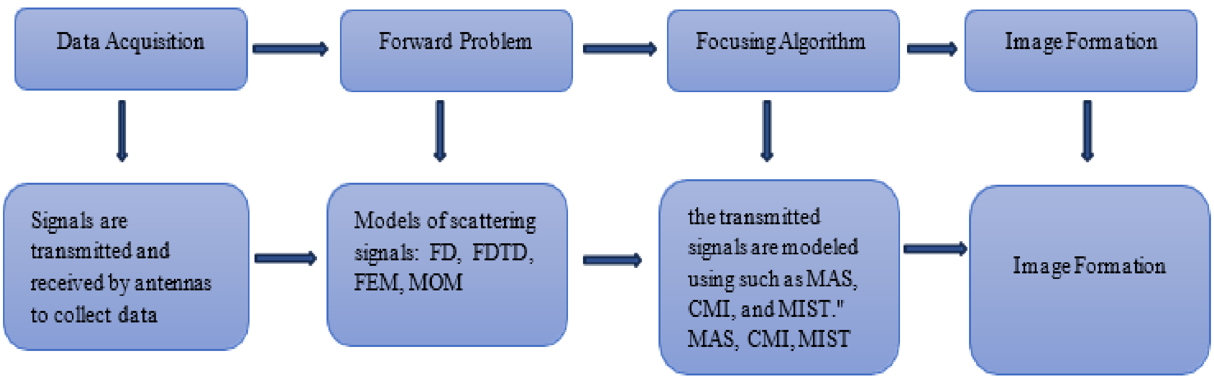

Figure 5: Flow chart showing the procedure in Radar Microwave breast imaging

Several researchers have investigated radar-based microwave imaging for breast cancer detection since 1998. Bridges et al. [72]. presented one of the earliest radar-based microwave imaging systems for breast cancer detection. Their approach involved: Exposing the breast to an electromagnetic wave generator, which focused the waves on a small section of the breast. Capturing the backscattered signals reflected from within the breast. This system can detect the size and location of tumours inside the breast. This was possible due to the high contrast in the dielectric properties between healthy breast tissue and cancerous tumours.

Recently, Qashlan et al. [73]. proposed a radar-based microwave imaging system for breast cancer detection. The system employed an array of nine Vivaldi antennas, modified with slots and parasitic elements to improve performance. The breast phantom, simulating skin, tissue, and tumor layers were exposed to the antenna array. Using the Microwave Radar Based Imaging Toolbox (MERIT), the system successfully detected tumors as small as 5 mm, as shown in Figure 6.

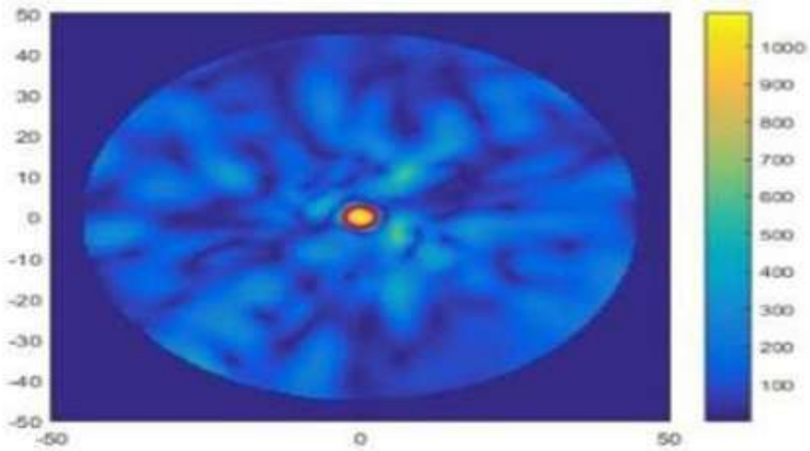

Figure 6: Radar-based MBI) detected tumor [73].

Comparison of Microwave Tomography and Radar-Based Microwave Breast Cancer Detection
Microwave breast imaging MBI techniques, which include both Microwave Tomography (MT) and radar-based methods, effect the distinct dielectric properties of breast tissues to detect abnormalities, while both are active microwave breast imaging systems that utilize external microwave radiation to probe breast tissue, they differ in their approach to signal processing and image reconstruction. Although multiple studies have discussed MWT and RBMI extensively, a "side-by-side technical comparison summarizing their key distinctions especially in breast cancer imaging has not been consolidated in tabular from. Table 2 aims to fill this gap by integrating insights from the literature.

Table 2: Comparison between Microwave Tomography and Radar-Based Microwave Breast Imaging Techniques

Aspect	Microwave Tomography (MT)	Radar-Based Microwave Imaging (RBMI)
Principle of Operation	Reconstructs the full dielectric property map of the breast, providing a comprehensive image of tissue characteristics.	Focuses on detecting and localizing tumors by analyzing reflected microwave signals, typically through beamforming or scattering-based approaches.
Computational Complexity	Requires solving complex inverse problems for dielectric reconstruction, which can be computationally intensive.	Less computationally demanding, as it emphasizes tumor localization rather than full dielectric property mapping.
Application and Clinical Status	Clinical prototypes have demonstrated the ability to detect tumors as small as 25 mm with sub-centimeter resolution in under 2 minutes. Several MT systems have progressed to clinical trial stages.	Radar-based systems are safe for repeated examinations and penetrate dense breast tissue effectively. Clinical evaluations of prototypes have shown promising sensitivity: e.g., MARIA (76%) and MammoWave (74%).

Clinical trials, challenges and future work in MBI
This section highlights representative microwave breast imaging (MBI) systems tested in clinical trials, the challenges faced by these techniques, and directions for future development. Meaney et al. [74]–[76] have been investigating microwave tomography imaging (MTI) since the 1990s. In 2000, they reported the first clinical prototype [77], which has since been evaluated in several trials with encouraging results. At Dartmouth College, the MTI system employed a 16-element monopole antenna array operating between 300 MHz and 1 GHz (Figure 7).

Figure 7. Microwave breast imaging prototype developed at Dartmouth College [77].

In 2010, Son et al. [78] introduced a preclinical prototype at the Electronics and Telecommunications Research Institute (ETRI), South Korea. As shown in Figure 8, the patient lies in a prone position with the breast immersed in a coupling bath containing a circular 16-element antenna array operating between 500 MHz and 3 GHz. One antenna acts as the transmitter while the remaining serve as receivers, yielding 240 measurements. Tomographic images are reconstructed using a nonlinear inverse algorithm, which successfully demonstrated tumor detection capability.

Figure 8. ETRI microwave imaging system for preclinical breast cancer detection [78].

Another promising system, known as **Wavelia**, was deployed at Galway University Hospital, Ireland, in 2018. In this study, 25 women were scanned, and the system demonstrated the ability to differentiate between benign and malignant tumors [79]. Figure 9 illustrates the Wavelia setup. University Hospital, Ireland [79].

Figure 9. Wavelia radar-based microwave imaging system used in clinical trials at Galway.

More recently, the **MammoWave** system has undergone prospective clinical evaluation. Designed to scan up to 600 volunteers, the device is certified for clinical research and applies a radar algorithm based on the Huygens principle to reconstruct breast images. The resulting intensity maps reflect the dielectric distribution within the breast. Early results show promise for reliable multicentric breast cancer detection and warrant larger-scale trials [80].

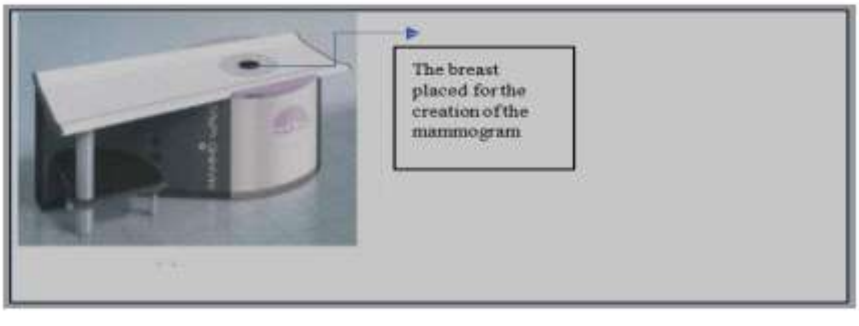

Figure 10: Mammo Wave device [80].

Conclusion and future perspectives

Microwave breast imaging (MBI) has emerged as a promising alternative to conventional imaging due to the distinct dielectric properties of healthy and cancerous tissues. Antennas play a pivotal role in MBI, whether as single elements performing dual functions or as arrays with dedicated transmitters and receivers. Recent advances in tomography and radar-based imaging highlight the potential of these techniques for accurate tumor detection.
Tomography provides detailed dielectric maps of the entire breast through complex reconstruction algorithms, while radar-based methods offer targeted, less computationally intensive imaging of suspected tumor regions.
The clinical potential of MBI is supported by encouraging trial results; however, further developments are required. Integrating the strengths of tomography and radar-based imaging could enhance diagnostic accuracy. Addressing challenges related to cost, efficiency, and patient comfort is essential for broader adoption.
Continued innovation in antenna design, system usability, and public awareness will be critical to establishing MBI as a reliable, accessible modality. Overall, MBI holds significant promise for improving breast cancer detection and may serve as a valuable complement or alternative to existing imaging techniques

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