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Review
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Cross-Domain Comparative Analysis of Microwave Imaging Systems for Medical Diagnostics and Industrial Testing

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Abstract

Microwave imaging is gaining significant traction as a non-ionizing, low-cost, and portable alternative to conventional diagnostic and inspection modalities in both medical and industrial domains. Leveraging the dielectric contrast between healthy and anomalous tissues or materials, microwave imaging systems enable early-stage detection and characterization of pathological or structural anomalies. This review provides a detailed comparative analysis of microwave imaging systems tailored for three critical applications: breast cancer detection, brain stroke imaging, and non-destructive testing (NDT). Each domain presents unique challenges and performance demands that influence the design and implementation of imaging systems. We examine key algorithmic strategies, including delay-and-sum, back-projection, compressive sensing, and emerging deep learning models, used for image reconstruction and anomaly detection. Hardware considerations such as antenna design, system architecture, and frequency selection are discussed in the context of application-specific constraints. Furthermore, we analyze the inherent trade-offs among spatial resolution, penetration depth, and signal-to-noise ratio, offering insights into optimization strategies for each use case. By highlighting both commonalities and distinctions across medical and industrial applications, this study identifies technological gaps and outlines future research directions aimed at enhancing image quality, real-time operability, and the practical viability of microwave imaging systems in real-world scenarios.

Keywords: Microwave imaging systems, breast cancer detection, brain stroke imaging, non-destructive testing (NDT)

INTRODUCTION

Microwave imaging has emerged as a compelling imaging modality across diverse domains due to its ability to detect variations in dielectric properties within biological tissues and engineered materials [1]. Compared to conventional imaging techniques such as X-ray, MRI, CT, and ultrasound, microwave imaging offers several advantages including non-ionizing radiation, portability, cost-effectiveness, and real-time imaging capability [2]. These features make it particularly attractive for point-of-care medical diagnostics and on-site industrial inspection tasks [3].

The fundamental principle behind microwave imaging is the contrast in dielectric permittivity and conductivity between different materials or tissues [4]. In medical applications, this contrast is exploited to detect anomalies such as malignant tumors or hemorrhagic/ischemic strokes. In industrial settings, it enables the detection of internal defects, voids, or inclusions within composite materials, ceramics, or concrete structures [5]. Despite its potential, widespread adoption of

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microwave imaging remains constrained by technical challenges related to image resolution, signal penetration, system calibration, and computational complexity [6].

This review focuses on three critical application areas where microwave imaging shows particular promise: breast cancer detection, brain stroke imaging, and non-destructive testing (NDT). The study aims to analyze current advancements in imaging algorithms, hardware system design, and performance trade-offs, while identifying emerging trends and future research opportunities essential for clinical and industrial deployment.

Motivation

Early and accurate detection of anomalies, whether pathological in biological tissues or structural in engineered materials, is critical for improving outcomes, reducing costs, and ensuring safety. Traditional imaging modalities such as MRI, CT, and X-ray, while highly developed, are often limited by high operational costs, ionizing radiation exposure, immobility, or dependency on specialized infrastructure. These limitations restrict their frequent use in point-of-care diagnostics and real-time industrial monitoring [7].

Microwave imaging offers a promising alternative by utilizing non-ionizing electromagnetic waves in the GHz range to detect dielectric contrasts within a target. In medical applications, this enables the differentiation between healthy and diseased tissues, such as distinguishing malignant tumors from benign structures or identifying ischemic versus hemorrhagic brain strokes. In industrial contexts, microwave imaging allows for internal inspection of complex materials without requiring physical disassembly or causing damage [8].

Translating microwave imaging into practical systems demands overcoming several technical hurdles. These include optimizing image reconstruction algorithms for accuracy and speed, designing efficient and miniaturized hardware components, and managing the inherent trade-offs between resolution and penetration depth. This review is motivated by the need to address these challenges comprehensively and to guide future innovations that bridge the gap between laboratory research and real-world deployment [9].

LITERATURE REVIEW

Tabata *et al.* present a novel approach for accurate phase calibration in multistatic imaging systems, which are widely used in medical diagnostics and industrial inspection [10]. The authors address the critical issue of phase errors that arise due to system instability, which can significantly degrade image quality. Their method leverages a reference object-based calibration technique, enabling precise correction of phase deviations without the need for complex hardware modifications. The study demonstrates improved image reconstruction accuracy in both simulated and experimental environments, showing potential for real-time applications. This work is particularly relevant for enhancing the reliability and resolution of non-invasive imaging systems in diverse fields.

Bing *et al.* proposed a tuned microwave resonant system designed for subcutaneous imaging, aimed at improving the detection and visualization of soft tissue structures beneath the skin [11]. The system operates by leveraging microwave resonance behavior to enhance contrast and penetration depth in biological tissues, offering a non-invasive and portable alternative to traditional imaging modalities. The authors optimized the resonator design to increase sensitivity and spatial resolution, demonstrating its effectiveness through phantom and *in vivo* experiments. This research contributes significantly to the development of compact and efficient microwave-based biomedical imaging tools, especially for point-of-care and remote diagnostic applications.

Naghibi and Attari present a method for enhancing image quality in single-frequency microwave imaging systems using a multistatic full-view array [12]. The key innovation lies in a sidelobe reduction technique, which significantly improves image clarity and target localization without increasing system complexity or bandwidth. By optimizing the array configuration and applying advanced signal processing, the authors demonstrate substantial suppression of unwanted sidelobe artifacts, which are common in limited-view or monostatic systems. Their simulation and experimental results confirm the method's ability to deliver high-resolution images with improved contrast, making it suitable for applications in medical diagnostics, security screening, and industrial evaluation.

Naghibi and Attari investigated a near-field radar-based microwave imaging system specifically designed for breast cancer detection, with a focus on analyzing image resolution and overall quality [13]. The study utilizes a multistatic antenna configuration to collect high-fidelity backscattered signals and applies an advanced reconstruction algorithm to generate accurate images of breast tissue. Key performance metrics such as spatial resolution, artifact suppression, and tumor detectability are evaluated. Results demonstrate that near-field multistatic setups can achieve enhanced imaging performance with greater sensitivity to small anomalies, reinforcing the method's potential as a non-ionizing, low-cost alternative to conventional breast imaging techniques like mammography.

Sekehravani and Leone focused on evaluating the spatial resolution in the inverse scattering problem involving dielectric cylinders, with implications for medical imaging applications such as tissue characterization [14]. Using a controlled simulation environment, the study analyzes how factors like object size, contrast, and measurement configuration affect the reconstruction quality. The authors compare different inverse scattering algorithms to assess their ability to resolve fine structural details in biological tissues. Their findings provide insights into the trade-offs between resolution, computational complexity, and robustness, offering guidance for designing efficient microwave imaging systems for clinical use.

Song *et al.* proposed a Fast Factorized Kirchhoff Migration (FFKM) algorithm to improve the efficiency and image quality of near-field radar imaging using sparse MIMO (Multiple-Input Multiple-Output) arrays [15]. The algorithm is designed to handle large-scale data with reduced computational burden while maintaining high-resolution image reconstruction. By factorizing the imaging operator and exploiting the structure of sparse arrays, the method significantly accelerates processing without sacrificing accuracy. Simulation and experimental results validate the algorithm's effectiveness in generating detailed images of complex scenes, showing promise for real-time, high-resolution imaging in applications like security screening, subsurface mapping, and biomedical diagnostics.

Table 1. Summary of key literature on microwave imaging systems.

Theme	Study	Contribution	Application area
1. Fundamentals and applications	Wu (2014) [16]	Overview of microwave tomography principles and applications in heterogeneous media; discusses inverse scattering.	Medical and Industrial
2. Image quality enhancement	Naghibi and Attari (2021a) [12]	Side lobe reduction method in single-frequency multistate arrays improves image clarity.	Medical and Industrial
	Sekehravani and Leone (2023) [14]	Assesses resolution in inverse scattering of dielectric cylinders; compares algorithms.	Medical (Tissue Imaging)
3. Near-field and multistatic imaging for medical use	Naghibi and Attari (2021b) [13]	Near-field radar imaging for breast cancer detection using multistate configuration.	Medical (Breast Imaging)
	Tabata *et al.* (2024) [10]	Accurate phase calibration in multistate imaging systems via reference-object technique.	Medical and Industrial
4. System and algorithmic innovations	Song *et al.* (2024) [15]	Fast Factorized Kirchhoff Migration (FFKM) algorithm for sparse MIMO near-field imaging.	Medical, Security, Subsurface
	Bing *et al.* (2023) [11]	Tuned microwave resonator improves contrast and depth for subcutaneous imaging.	Medical (Point-of-Care)
5. Trends and gaps	Synthesis of all	Common trends: enhanced resolution, real-time imaging, efficient hardware; gaps: clinical validation, integration with other modalities.	All

Wu explored the development and application of microwave tomographic imaging systems for both industrial inspection and medical diagnostics [16]. The paper discusses the fundamental principles of microwave tomography, including electromagnetic wave propagation in inhomogeneous media and the use of inverse scattering algorithms for image reconstruction. Wu emphasized the advantages of microwave tomography, such as non-invasiveness, low cost, and functional imaging capability, and highlighted several case studies demonstrating its effectiveness in detecting structural flaws and biological anomalies. The study underscores the versatility and growing potential of microwave imaging in real-world scenarios where traditional imaging methods may be limited. Table 1 shows summary of key literature on microwave imaging system.

MICROWAVE IMAGING FOR BREAST CANCER DETECTION

Algorithmic Approaches

Microwave image reconstruction algorithms are central to system performance, impacting resolution, detection accuracy, computational cost, and robustness in clinical environments. Various algorithms have been proposed, each tailored to the trade-offs among complexity, fidelity, and speed.

Delay-and-Sum (DAS)

DAS is one of the simplest beam forming techniques used in microwave imaging. It works by time-shifting the backscattered signals from multiple antennas to focus on a point within the imaging domain and summing them coherently.

Eq. (1): $I(\mathrm{r}) = \sum_{i=1}^{N} s_i\left(t = \tau_i(\mathrm{r})\right)$ (1)

Where:

- $I(\mathrm{r})$: intensity at position r,
- $s_i(t)$: signal received by the i-th antenna, and
- $\tau_i(\mathrm{r})$: round-trip delay from the i-th antenna to r.

DAS is computationally efficient and suitable for real-time imaging but suffers from limited spatial resolution and high side-lobe artifacts.

Back-Projection (BP)

- Back-projection improves upon DAS by integrating signals along estimated propagation paths, considering wave dispersion and medium heterogeneity.
- While more accurate in localizing scatters, BP is computationally expensive and less suitable for real-time scenarios unless optimized via GPU acceleration or parallel processing.

Confocal Microwave Imaging (CMI)

- CMI focuses signals from all antennas onto a specific point to enhance localization accuracy. It is particularly effective when the target is well isolated and located near the imaging center.
- It improves image contrast by enhancing signals that originate from a common focal point, but its performance may degrade in cases with high clutter or complex breast tissue heterogeneity.

Compressive Sensing (CS)

CS techniques exploit the sparsely of anomalies (e.g., tumors) in the spatial domain to reconstruct high-quality images from a reduced number of measurements.

Eq. (2): $\min_{\mathrm{x}} \parallel \mathrm{x} \parallel_1 \quad \text{subject to} \quad \mathrm{y} = \Phi \mathrm{x}$ (2)

Where:

- y: measured signal vector,
- Φ: sensing matrix, and
- x: sparse image vector (to be reconstructed).

CS reduces hardware and acquisition time while maintaining fidelity, but it requires precise design of measurement matrices and efficient solvers.

Machine Learning-based Inversion

Recent developments incorporate supervised learning, particularly deep neural networks, to map raw or preprocessed signals directly to permittivity maps or anomaly labels.

Eq. (3): $\mathcal{L} = \| f(\mathrm{y};\theta) - \mathrm{x}_{\mathrm{true}} \|^2$ (3)

Where:

- $f(\mathrm{y};\theta)$: neural network mapping from signal to image,
- $\mathrm{x}_{\mathrm{true}}$: ground truth image, and
- θ: network parameters.

ML-based models can capture complex nonlinearities and improve robustness to noise, but require large, labeled datasets and may struggle to generalize to unseen cases or varied anatomies.

Hardware Considerations

The effectiveness of microwave imaging for breast cancer detection is critically influenced by the system's hardware design. Each component, from antennas to coupling media, must be carefully engineered to optimize resolution, sensitivity, and patient safety.

Antenna Arrays

Antenna design is a cornerstone of microwave imaging systems. Ultra-Wideband (UWB) antennas, such as Vivaldi antennas, monopole antennas, and tapered slot antennas, are preferred due to their broad frequency coverage (typically 1–10 GHz), compact size, and directional radiation characteristics.

- Vivaldi antennas offer good directivity and gain, making them well-suited for focusing energy deep into heterogeneous breast tissue.
- Circular or hemispherical multi-antenna arrays provide enhanced spatial diversity, enabling better target localization through multistate imaging.

Transceiver and Data Acquisition Systems

High-fidelity data acquisition requires:

- Fast-switching transceivers capable of time-gated or frequency-swept measurements.
- High dynamic range (≥80 dB) to detect weak reflections from deep tissue.
- Synchronization circuitry for accurate time-delay estimation across antennas.

Advanced systems may incorporate vector network analyzers (VNAs) or custom RF front-ends with embedded FPGAs or microcontrollers to manage real-time acquisition and signal processing.

Coupling Medium

Microwave propagation suffers from significant impedance mismatch at the skin-air interface. To minimize reflections and improve signal penetration, a dielectric coupling medium is often introduced between the antenna and breast surface. Common coupling media include:

- Canola oil, glycerin-water mixtures, or saline gels, selected for their dielectric properties similar to fatty tissue.
- These materials improve the signal-to-noise ratio (SNR) by suppressing multipath artifacts and stabilizing antenna impedance across wide frequency ranges.

Tissue-Mimicking Phantom Models

For preclinical development and calibration, realistic breast tissue phantoms are indispensable. These phantoms emulate the dielectric contrast between normal and malignant tissues. Important characteristics include:

- Anatomical realism (fibro glandular structure, tumor inclusions).

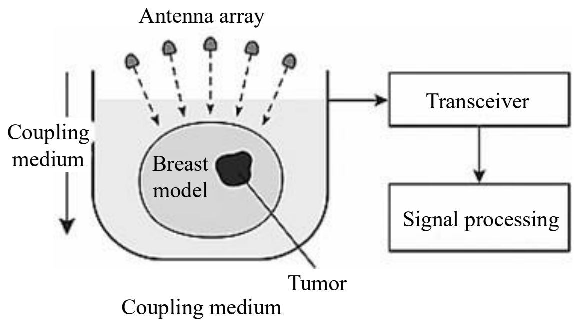

Figure 1. Schematic diagram of a microwave imaging system.

- Stability over time and frequency.
- Compatibility with coupling media and imaging system.

Figure 1 shows schematic diagram of a microwave imaging system for breast cancer detection, illustrating the antenna array, coupling medium, breast model, transceiver, and signal processing unit.

Resolution Trade-offs

Achieving high spatial resolution in microwave imaging for breast cancer detection involves navigating several intrinsic trade-offs between penetration depth, signal clarity, and hardware limitations.

Frequency vs. Resolution Trade-off

The spatial resolution of microwave imaging improves with higher operating frequencies, due to shorter wavelengths. However, higher frequencies suffer from increased attenuation in biological tissues, limiting penetration depth and reducing signal strength for deeper tumors.

- High frequencies (5–10 GHz).
- Lower frequencies (1–2 GHz).

A hybrid multi-frequency approach is often employed, where low frequencies are used for coarse localization and higher frequencies for detailed boundary mapping.

Signal-to-Noise Ratio (SNR) vs. Imaging Fidelity

Increasing system gain or using high-sensitivity receivers can enhance SNR, which improves detectability of weak tumor reflections. However, aggressive amplification may introduce thermal noise, intermodulation artifacts, or saturation effects.

- Use of time-gating, matched filtering, and adaptive thresholding can mitigate SNR-related artifacts while preserving image fidelity.

Skull Attenuation and Refraction (Contextual Note for Brain Imaging)

While not directly applicable to breast imaging, for completeness, it is worth noting that in brain stroke imaging, skull-induced attenuation and refraction severely degrade image quality. Compensation techniques such as inverse scattering corrections and model-based skull compensation are employed in those systems.

Mitigation Strategies

To address these trade-offs, the following strategies are implemented:

- Wideband UWB antennas to capture a range of frequencies for balanced penetration and resolution.
- Beam forming techniques (e.g., Minimum Variance Distortion less Response (MVDR)) to sharpen image focus.
- Image fusion combining outputs from different frequencies or imaging modalities (e.g., ultrasound, MRI priors).

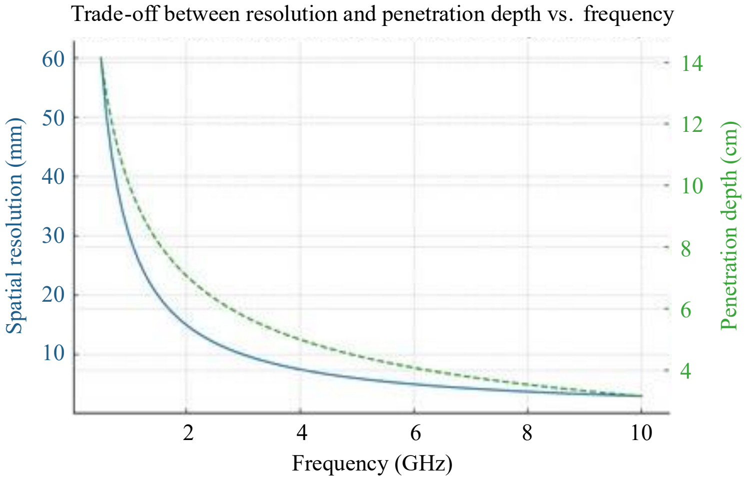

Figure 2. Trade-off between spatial resolution and penetration depth with respect to microwave frequency in breast tissue imaging. Higher frequencies yield better spatial resolution due to shorter wavelengths but suffer from reduced penetration depth because of increased tissue attenuation. Lower frequencies offer deeper penetration at the cost of degraded resolution, highlighting the need for a balanced or hybrid frequency approach in microwave imaging system design.

Figure 2 shows chart illustrating the trade-off between spatial resolution and penetration depth as a function of frequency.

COMPARATIVE ANALYSIS

Microwave imaging, while unified by core principles, presents distinct challenges and design considerations across different application domains. This section synthesizes the comparative aspects of breast cancer detection, brain stroke imaging, and non-destructive testing (NDT), focusing on resolution needs, hardware constraints, and algorithmic requirements.

Breast Imaging

Microwave imaging for breast cancer detection demands high spatial resolution to identify small and early-stage tumors. Moderate penetration depth (3–6 cm) is generally sufficient due to the anatomical confines of the breast.

- *Key priorities:* Tumor detectability, spatial resolution, and dielectric contrast sensitivity.
- *Design constraints:* Compact antenna arrays, coupling media for impedance matching, and realistic phantom-based validation.

Brain Imaging

Imaging the brain introduces additional complexity due to the high dielectric contrast and heterogeneity of the skull, which introduces severe refraction, attenuation, and scattering effects (Figure 3).

- *Key priorities:* Patient safety (non-ionizing exposure), penetration through cranial bone, and high signal-to-noise ratio (SNR).
- *Design constraints:* Specialized antenna designs for hemispherical coverage, frequency limitation (typically 0.5–2 GHz), and skull compensation algorithms.

Non-Destructive Testing (NDT)

In industrial applications, microwave imaging is adapted for inspecting composite structures, concrete, and dielectric materials for hidden defects. The balance between resolution and depth is dictated by the material properties and geometry of the object under test.

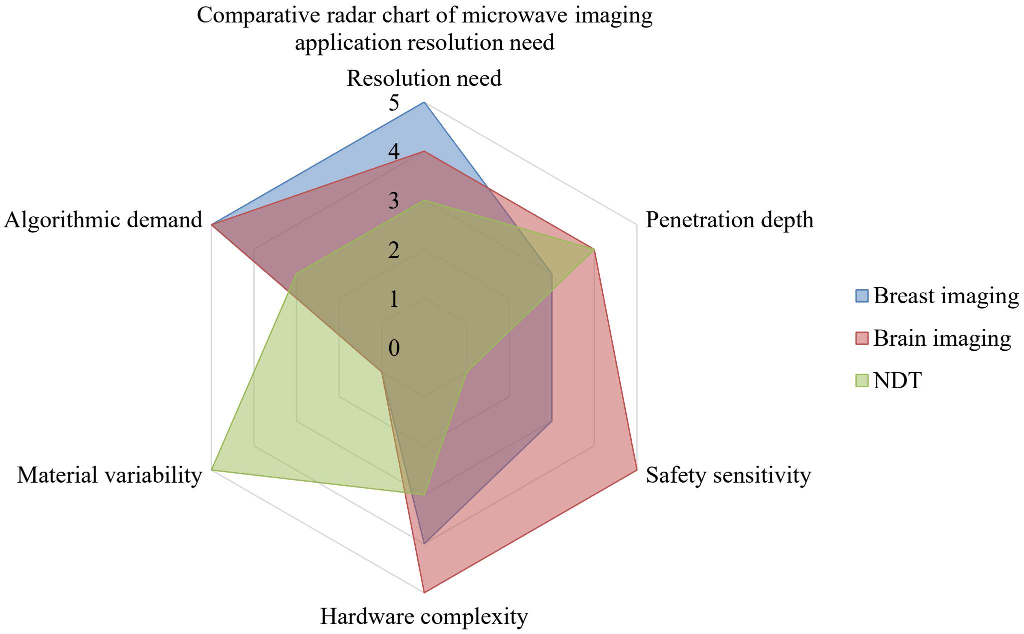

Figure 3. Radar chart comparing microwave imaging requirements across three application domains: breast cancer detection, brain stroke imaging, and non-destructive testing (NDT). Each axis represents a critical system parameter, scaled from 1 (low importance) to 5 (high importance). The chart illustrates how imaging objectives and system constraints vary significantly by application, necessitating tailored design strategies in hardware, algorithms, and operational frequency.

Table 2. Comparative analysis of application-driven customization required in microwave imaging systems.

Aspect	Breast imaging	Brain imaging	NDT
Operating frequency	1–10 GHz	0.5–2 GHz	Application-specific (1–6 GHz)
Primary challenge	Tumor resolution	Skull compensation	Material variability
Safety requirements	Moderate (non-ionizing)	High (cranial exposure)	Low (industrial setting)
Antenna configuration	Circular/UWB arrays	Hemispherical arrays	Planar or conformal arrays
Imaging depth	Moderate (3–6 cm)	Deep (~10 cm, through skull)	Variable (material-dependent)

- *Key priorities:* Defect characterization accuracy, adaptability to various material permittivity' and geometric conformity.
- *Design constraints:* Configurable scanning geometries, wideband antennas, and robustness to material heterogeneity.

Commonalities Across Applications

Despite differences, several technical themes are common across all domains:

- Dependence on strong dielectric contrast for target-background discrimination.
- Necessity for advanced signal processing (beam forming, inversion algorithms).
- Calibration techniques to mitigate environmental and system-induced variability.
- Importance of system integration for real-time performance and portability.

Table 2 shows the comparative analysis which highlights the application-driven customization required in microwave imaging systems. While the underlying physics remains consistent, effective system design must address domain-specific trade-offs in hardware, frequency selection, and image reconstruction techniques.

CONCLUSION

Microwave imaging has emerged as a compelling alternative to conventional modalities due to its non-ionizing nature, cost-effectiveness, and sensitivity to dielectric contrast. This review has examined the algorithmic, hardware, and performance aspects of microwave imaging systems across three critical domains: breast cancer detection, brain stroke imaging, and non-destructive testing (NDT). Each application presents distinct challenges, from high-resolution tumor localization in breast tissue to overcoming skull-induced signal distortion in brain imaging, and adapting to geometric and material variability in industrial inspections.

Algorithmically, advancements such as compressive sensing, confocal imaging, and machine learning-based inversion techniques have significantly improved reconstruction fidelity and diagnostic accuracy. Hardware innovations, including wideband antenna arrays, fast-switching transceivers, and realistic phantom models, are pivotal for practical deployment. Despite these advances, fundamental trade-offs remain between resolution, penetration depth, and signal-to-noise ratio, which must be carefully optimized for each use case.

Future research should focus on developing hybrid frequency systems, real-time imaging architectures, and robust algorithms capable of generalizing across patient variability and material inhomogeneity. Integration with AI-driven diagnostics, multimodal imaging fusion, and portable hardware design will be essential to transition microwave imaging from research laboratories to routine clinical and industrial practice.

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