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INTERVENTIONAL RADIOLOGY

REVIEW ARTICLE

Ultrasound-guided microwave ablation for breast tumors: current status and future perspectives

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ABSTRACT

Ultrasound (US)-guided microwave ablation (MWA) has emerged as a promising minimally invasive therapy for both benign and malignant breast tumors. This review comprehensively examines the current clinical status, technical principles, and therapeutic outcomes of US-guided MWA in breast tumor management. We discuss the biophysical mechanisms of MWA, its advantages over other ablation techniques—such as rapid temperature elevation, the ability to create more extensive coagulation areas, and diminished impact from heat sink phenomena—and the critical role of real-time US guidance in enhancing procedural precision and safety. Clinical evidence supports the efficacy of US-guided MWA in achieving high rates of complete ablation and significant volume reduction for benign tumors, such as fibroadenomas, with minimal complications and excellent cosmetic results. For early-stage breast cancers, initial studies indicate that US-guided MWA provides local tumor control comparable with surgical resection in the short- to mid-term, while also offering the benefits of shorter operation times, reduced hospitalization, and stimulation of systemic antitumor immune responses. However, challenges remain, including technical limitations in treating tumors near critical structures, the lack of long-term oncological data, and operator dependence. Future directions involve technological refinements, integration with artificial intelligence and advanced imaging, combination with immunotherapy, and standardization of protocols. US-guided MWA represents an important advancement toward personalized, organ-preserving breast tumor therapy, with ongoing innovations poised to expand its clinical applicability.

KEYWORDS

Microwave ablation, breast tumors, ultrasound guidance, minimally invasive therapy, thermal ablation

Breast tumors represent a frequently encountered clinical condition in women, often associated with factors such as dysregulation of endocrine hormones, genetic susceptibility, daily behavioral habits, and external environmental exposure. Common symptoms include detectable lumps in the breast tissue, localized pain or tenderness, and occasional nipple discharge. Based on pathological characteristics, these tumors are primarily classified into benign lesions, such as fibroadenomas, and potentially malignant tumors, including early-stage breast cancers.[1] Although benign tumors typically entail minimal health risks, they may still lead to physical discomfort, such as persistent pain. However, malignant tumors, including breast carcinoma, constitute a serious health concern and require timely intervention to prevent adverse outcomes, thereby considerably impacting overall prognosis and survival.[2] The widespread adoption of breast imaging screening has resulted in a rising incidence of small and asymptomatic tumors, necessitating effective and less invasive treatment strategies. The long-established standard for definitive diagnosis and treatment of suspicious or symptomatic tumors has been surgical excision, either by lumpectomy or mastectomy. Although effective, surgery is associated with inherent drawbacks, including general anesthesia risks, postoperative pain, scarring, potential deformity of the breast contour, and a prolonged recovery period.[3]

The last two decades have witnessed a paradigm shift in oncology and interventional radiology towards minimally invasive therapies (MITs). These techniques aim to achieve therapeutic efficacy comparable with surgery while minimizing morbidity, preserving organ func-

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tion and cosmesis, and reducing procedural time and cost. Within the realm of breast disease management, several image-guided MITs have been developed and clinically implemented.[4] Among these, thermal ablation modalities, particularly radiofrequency ablation (RFA) and microwave ablation (MWA), have garnered particular attention due to their ability to induce coagulative necrosis in targeted tissues via precise hyperthermia.[5] Although RFA is the most thoroughly investigated technique, MWA is gaining broader adoption due to its capacity to elicit more extensive ablation volumes with reduced procedure times.[6]

MWA, which originated in 1962, is categorized as a type of thermal ablation within physical ablation therapies and utilizes heat to inactivate local tissues.[7] MWA utilizes electromagnetic waves in the microwave energy spectrum to agitate water molecules within tissue, generating frictional heat and inducing coagulative necrosis.[8] It offers faster heating times than other thermal techniques, higher intratumoral temperatures, larger and more predictable ablation zones, less susceptibility to the heat-sink effect (cooling from adjacent blood vessels), and the ability to perform simultaneous multi-probe ablations.[9] The evolution of MWA technology, particularly with the integration of real-time imaging guidance, has further enhanced its precision and safety profile. Ultrasound (US), due to its widespread availability, cost-effectiveness, and real-time capabilities, has become the modality of choice for guiding MWA procedures. US guidance allows for accurate needle placement, continuous monitoring of the ablation zone, and immediate evaluation of treatment effectiveness, thereby reducing the risk of incomplete ablation or damage to adjacent normal structures (Figure 1).[10]

Main points

- Ultrasound (US)-guided microwave ablation (MWA) is a minimally invasive, highly effective alternative to surgery for treating breast tumors, achieving complete ablation with excellent cosmetic results and minimal complications.
- Real-time US is crucial for precision, enabling accurate targeting, continuous monitoring, and immediate assessment while protecting healthy tissues.
- US-guided MWA not only destroys tumors locally but also stimulates a systemic immune response, offering potential for combined therapies and expanded future applications.

US-guided MWA finds broad application in the treatment of diverse clinical conditions, such as hepatocellular carcinoma,[11] thyroid nodular goiter,[12] uterine leiomyomas,[13] and renal neoplasms,[14] with promising therapeutic efficacy observed in clinical practice. Compared with the liver and kidneys, the breast has a superficial location, less complex anatomical architecture, and relatively sparse vascularity, which contribute to excellent US visualization. These characteristics render it an ideal candidate for US-guided MWA. Several clinical studies have demonstrated the efficacy and safety of US-guided MWA in managing both benign and malignant breast tumors. For benign lesions, such as fibroadenomas, MWA offers a non-surgical alternative that can effectively reduce nodule size and alleviate symptoms, with minimal scarring and rapid recovery.[15,16] In the context of malignant tumors, particularly early-stage breast cancers, MWA has shown promising outcomes in terms of complete ablation rates, local tumor control, and cosmetic preservation, suggesting its potential role as a valuable alternative in selected cases, particularly for individuals unsuitable for surgery or those seeking less invasive therapeutic options.[17,18]

This review aims to summarize comprehensively the current state of US-guided MWA for breast tumors, encompassing technical principles, clinical applications, and limitations. To achieve this, a narrative synthesis of the literature was performed, which was conducted using electronic databases, primarily PubMed and Web of Science, with a focus on articles published between 2000 and 2025. Key search terms included "microwave ablation," "breast," "ultrasound-guided," "fibroadenoma," and "breast cancer," alone and in combination. Given the specialized and evolving nature of this topic, the selection of included studies was not restricted by study design alone but prioritized clinical relevance, scientific rigor, and the illustration of key technical or clinical concepts. This approach encompassed pivotal clinical trials, prospective and retrospective cohort studies, case series, and seminal review articles. The reference lists of retrieved articles were also screened for additional relevant publications. This strategy was chosen to capture comprehensively the most impactful evidence in a field where the total volume of dedicated literature, although growing, remains manageable for a narrative synthesis. Furthermore, we discuss future perspectives, including technological innovations, potential integration with artificial intelligence (AI) for treatment planning, and the role of US-guided MWA within multimodal breast cancer management pathways.

Biophysical principles and technology of microwave ablation

Mechanism of microwave ablation

MWA is a thermal ablation technique that employs electromagnetic waves within the microwave frequency spectrum (typically 915 MHz to 2.45 GHz) to generate localized hyperthermia and induce coagulative necrosis in target tissues. The underlying mechanism involves the agitation of water molecules within tissue, resulting in frictional heat due to dielectric hysteresis. This process rapidly achieves cytotoxic temperatures (60 °C–100 °C), causing instantaneous protein denaturation and irreversible cellular damage (Figure 1).[19,20] The efficacy of MWA depends critically on the inherent dielectric properties of the target tissue, particularly its water content and ionic composition, which determine the extent of energy absorption and heat generation.[21] Unlike RFA, MWA is theoretically and in many clinical scenarios less susceptible to the heat-sink effect from adjacent blood vessels, allowing for more consistent and predictable ablation zones. Furthermore, MWA supports simultaneous multi-probe activation, enabling the treatment of larger or multifocal tumors efficiently.[9]

System components

A standard MWA system comprises three integral components: a microwave generator, an antenna assembly, and a cooling mechanism. The generator is designed to produce microwave energy within specific frequency bands, commercially available at 915 MHz or 2.45 GHz, and the generated signal is subsequently amplified by a dedicated radiofrequency power amplifier. The antenna design is critical, as it dictates energy distribution and ablation morphology. Commonly used antennas include monopolar, bipolar, array-based, triaxial, choked, and slot designs, each suited to particular tumor sizes, depths, and anatomical contexts. For instance, monopolar antennas are cost-effective and suitable for superficial lesions, whereas array antennas are preferred for larger or deeper tumors due to their synergistic emission and reduced cold spots.[22] Recent technological advancements have focused on optimizing antenna design to create more spherical and predictable ablation zones with minimal charring and track seeding.[9] The third part is

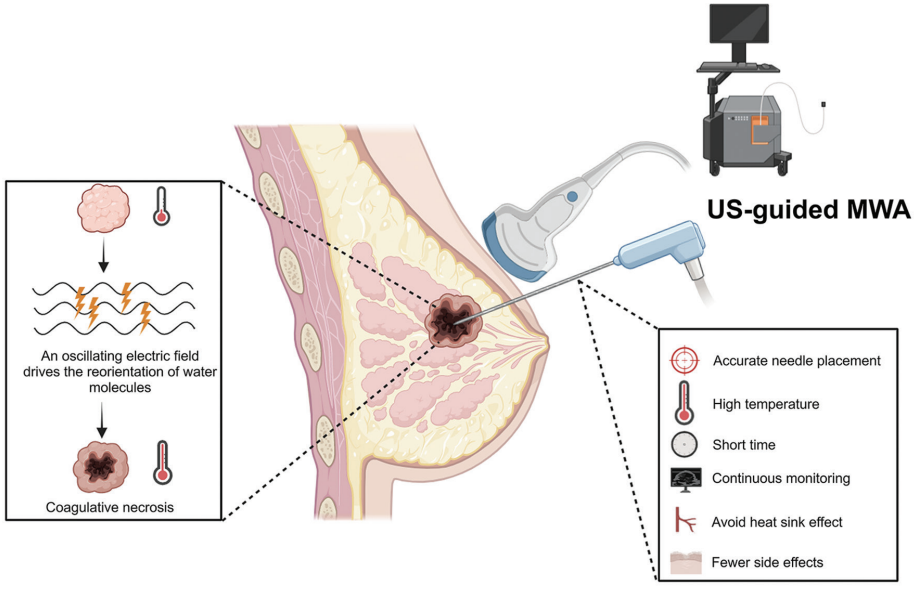


Figure 1. Overview of ultrasound-guided microwave ablation (created using BioRender). US, ultrasound; MWA, microwave ablation.

the cooling system, designed to reduce the probe's temperature using water or gas. This is vital to prevent tissue from carbonizing and to limit heat damage to nearby healthy tissues. In practice, thermal stability during water-cooling is maintained via the circulation of chilled water, whereas gas-cooling (e.g., with CO_2) is chosen for tissues that are sensitive to liquid.[23] Microwave frequency, applied power, and treatment duration are key factors affecting ablation performance. The selection of frequency determines the penetration depth and heating characteristics and should be optimized according to tumor size and anatomical location. The 915 MHz frequency achieves deeper energy penetration (3-4 cm), rendering it appropriate for larger or deeply situated tumors, such as those in the liver or kidneys, and is generally employed at higher power outputs (80–100 W) over extended periods (10–15 minutes) to facilitate larger ablation volumes. In comparison, operating at 2.45 GHz facilitates faster energy delivery, rendering it well-suited for ablating superficial and small lesions. Notably, breast tumors, which are often superficial, are well-suited to ablation at 2.45 GHz using a monopolar antenna. This is commonly achieved by employing moderate power levels of 40–60 W for short durations of 5–10 minutes, ensuring precise and confined treatment.[9,24,25]

Technical advancements

Recent advances in MWA have markedly extended its clinical utility, driven mainly by three key technological improvements. First, ongoing technical refinements, including more advanced generator systems and optimized ablation parameters, enable more controlled energy delivery and predictable ablation zones, enhancing treatment safety and efficacy across various tumor types.[22,26] Second, the integration of real-time imaging guidance, including US, allows precise antenna placement and continuous monitoring of the ablation process, considerably improving tumor targeting and margin assessment.[10,13] Third, MWA is increasingly recognized for stimulating a durable antitumor immune response, which complements its local effects and supports combination strategies with systemic therapies, such as immunotherapy or chemotherapy.[9,27,28] These developments together allow more personalized and effective management of tumors, including advanced cases where conventional monotherapies are insufficient.

The role of ultrasound guidance

US guidance is instrumental in optimizing the accuracy, safety, and overall therapeutic outcomes of MWA for breast tumors. As a real-time, radiation-free, and widely accessible imaging modality, US provides exceptional visualization of superficial structures, such as the breast, allowing for accurate needle placement, continuous monitoring of the procedure, and immediate evaluation of therapeutic efficacy.[10] The high-resolution capability of US enables clear differentiation between the target nodule and surrounding tissues, including critical anatomical structures, such as blood vessels and ducts, thereby minimizing the risk of collateral damage (Figure 1).

During the pre-procedural phase, US is used to locate the nodule precisely, determine its size and depth, and plan the optimal trajectory for antenna insertion. This step is crucial for ensuring complete coverage of the target area while avoiding vital structures. Intra-procedurally, real-time US monitoring allows clinicians to observe the formation and expansion of the hyperechoic ablation zone, which corresponds to the region of coagulative necrosis. This dynamic feedback facilitates adjustments in power output or antenna position as needed to achieve adequate margins and avoid under-treatment or overtreatment.[13] Moreover, color Doppler or contrast-enhanced US (CEUS) can be employed to evaluate vascularity and perfusion changes, providing additional information on treatment efficacy and helping to identify residual viable tissue. Post-procedural US assessment, often supplemented with contrast-enhanced imaging, is essential for confirming the completeness of ablation and detecting any complications, such as hematoma or edema. The ability to perform these evaluations immediately after the procedure contributes to the high clinical acceptability and patient satisfaction associated with US-guided MWA.[16]

The integration of US guidance with MWA is particularly advantageous in the breast due to its superficial location and relatively homogeneous parenchyma, which allow for excellent acoustic windows and minimal artifact interference. This synergy not only improves technical success but also supports the broader adoption of MWA as a minimally invasive alternative to surgery for both be-

nign and malignant breast tumors, aligning with the ongoing trend toward personalized and organ-preserving therapies.[5,15]

Clinical applications of ultrasound-guided microwave ablation for breast tumors

The utilization of US-guided MWA in breast disease management has expanded markedly, encompassing both benign and malignant tumors. Its efficacy is underpinned by the favorable anatomical location of the breast, which allows for excellent US visualization, precise antenna placement, and real-time monitoring of the process.

Treatment of benign breast tumors

Approximately 80% of breast tumors are benign, and with advances in detection technologies, the diagnosis of benign breast tumors has become increasingly common. This trend underscores a growing need for effective treatment strategies. A variety of therapeutic approaches are available for benign breast tumors.[29,30] As the most common benign breast disease,[31] fibroadenomas are a common indication for US-guided MWA. This technique offers a minimally invasive alternative to surgical excision for patients seeking to avoid scarring, general anesthesia, or a prolonged recovery period. The primary goals include decreasing tumor volume and relieving co-occurring symptoms, such as pain or palpable discomfort.

In a prospective study, US-guided MWA was applied to 44 benign breast tumors (≤ 3 cm) in 39 patients. The procedure, performed under local anesthesia (mean duration: 74 seconds), achieved complete ablation in 97.5% of cases, as confirmed by CEUS during follow-up. Tumor volume decreased significantly ($P = 0.005$), and no skin burns occurred despite a mean skin-to-tumor distance of 7.5 mm.[32] Further supporting evidence comes from a larger cohort study evaluating US-guided MWA in 205 benign breast lesions. Post-ablation, both CEUS and magnetic resonance imaging (MRI) were used to assess treatment efficacy. Results showed a notable decrease in lesion size and volume at 3, 6, or 12 months after the procedure, with 21.5% of lesions completely disappearing by the 12-month follow-up. The CEUS and MRI indicated technical success rates of 87.32% and 82.93%, respectively. The procedure proved safe, with no reports of major complications.[33] Another study focusing on larger benign breast lesions (≥ 2 cm) further supports the efficacy of MWA. In this prospective analysis of 104 lesions treated with US-guided MWA, complete ablation was achieved in all cases, as confirmed by contrast-enhanced imaging (Figure 2). Over a median follow-up of 12.5 months, the mean volume reduction rate reached 80.2% ($P < 0.001$), with no major complications reported. Multivariate analysis identified lesion location as an independent predictor of volume reduction; adjacency to the areola was associated with greater shrinkage, whereas proximity to the skin correlated with reduced regression. These findings affirm US-guided MWA as a viable and well-tolerated therapeutic approach even for larger benign breast lesions.[34] Further evidence from a larger cohort study specifically assessed the therapeutic effects of US-guided MWA in the treatment of breast fibroadenomas. Among 271 lesions in 171 patients, US-guided MWA led to progressive volume reduction and complete regression over time (Figure 3), with complete disappearance observed in 24.3%, 45.5%, and 40.9% of lesions at 1–6, 6–12, and > 12 months, respectively. Smaller lesion diameter (< 1.5 cm) was significantly correlated with more favorable treatment outcomes ($P < 0.05$), whereas factors such as patient age, lesion location, and blood flow showed no significant correlation with outcomes.[16] A comparative analysis was conducted to further evaluate US-guided MWA versus vacuum-assisted excision (VAE) for breast lesions with uncertain malignant potential (B3 lesions). The results indicated comparable technical success rates between the two techniques, with no residual lesions observed in the MWA group (Figure 4), compared with a 3.4% residue rate in the VAE group. Notably, the MWA group experienced significantly fewer postoperative adverse events, particularly in lesions > 2.5 cm, and was associated with lower recurrence, reduced need for re-intervention, and higher patient satisfaction.[35] In a comparative retrospective study, US-guided MWA demonstrated marked advantages over both open surgery and US-guided minimally invasive rotary cutting. Patients receiving MWA experienced briefer procedures, less blood loss during surgery, minimal scarring, quicker healing, and reduced postoperative pain at 24–72 hours. Both MWA and rotary cutting resulted in fewer complications and better cosmetic outcomes than open surgery (Figure 5), while showing comparable efficacy between the two minimally invasive approaches. The study highlights US-guided MWA as a particularly effective option, offering rapid recovery, minimal invasiveness, and enhanced patient satisfaction in the management of benign breast lesions.[36]

For rare benign breast tumors, such as giant leiomyoma, which pose significant cosmetic concerns due to large size or periareolar location, US-guided MWA has also demonstrated promising outcomes. In a case report involving an 8 cm leiomyoma, MWA achieved a volume reduction rate of 69.8% at 10-month follow-up (Figure 6), with excellent cosmetic results and no major complications, highlighting its potential as a tissue-sparing alternative to surgery in selected cases.[37]

Therefore, accumulating evidence supports US-guided MWA as a feasible and effective minimally invasive treatment for benign breast tumors. This technique is associated with high rates of complete ablation, large volume reduction, and even complete disappearance of tumors over time (Table 1). It offers a favorable safety profile with minimal complications, preserves cosmetic outcomes, and reduces vascular supply to treated areas. Compared with conventional surgical excision, US-guided MWA demonstrates satisfactory therapeutic efficacy, shorter procedure times, reduced intraoperative blood loss, less postoperative pain, and faster recovery. These advantages position US-guided MWA as a promising non-surgical alternative, particularly for selected tumors based on size and location.

Treatment of malignant breast tumors

Globally, breast cancer continues to be the most common cancer and foremost cause of cancer death in women. The disease encompasses a highly heterogeneous group of tumors, classified by histological type, growth patterns, and molecular profiles, all of which are critical for prognostic stratification and therapeutic decision-making. Current treatment strategies include surgery, radiotherapy, chemotherapy, endocrine therapy, targeted agents, and immunotherapy. The selection of treatment modalities is highly individualized and depends on tumor stage, biological subtype, and patient preferences.[38,39] In addition, various studies have reported comparable overall survival and distant metastasis-free survival between breast-conserving surgery (BCS) and mastectomy, with some evidence suggesting even improved long-term outcomes and lower recurrence rates among patients undergoing conservation therapy.[40-43] Within this context, techniques such as US-guided MWA are being investigated as promising minimally invasive alternatives that align with the principles of conserving breast tissue while achieving effective tumor control.

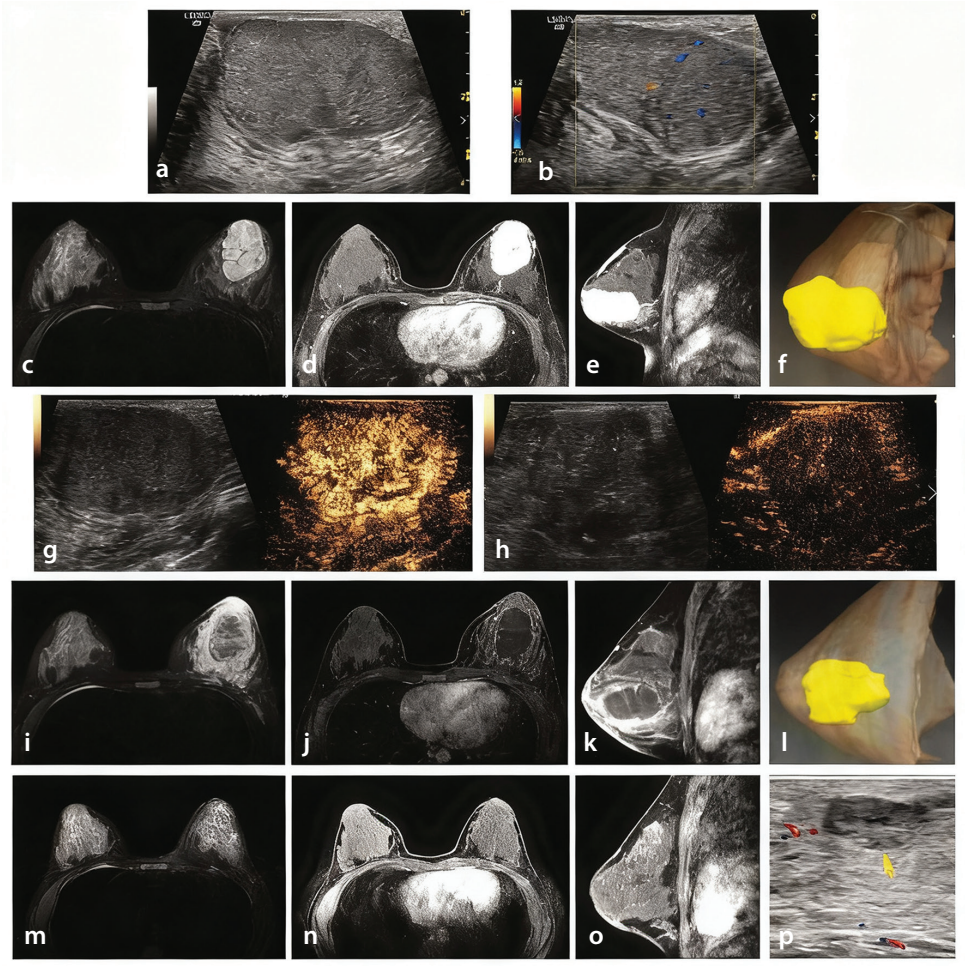


Figure 2. Imaging evaluation before and after microwave ablation (MWA) in one representative case. **(a)** Benign breast lesion (BBL) with 6.0 × 3.5 × 4.9 cm size showing hypoechogenicity with a clear margin on ultrasound (US); **(b)** color Doppler flow imaging before MWA showing the arterial blood flow signal in the BBL parenchyma; **(c)** a hyper-signal in the BBL parenchyma on magnetic resonance imaging (MRI) T2-weighted images before MWA; **(d, e)** contrast-enhanced MRI in axial and sagittal sections showing a hyper-enhancement in the BBL parenchyma in the arterial phase before MWA; **(f)** three-dimensional (3D) visualization showing the spatial structure of BBL; **(g)** BBL before MWA showed hyper-enhancement in the arterial phase of contrast-enhanced ultrasound (CEUS); **(h)** after MWA, a hypoechoic ablation zone with a size of 5.0 × 3.6 × 4.5 cm is shown in the tumor region by CEUS; **(i)** hypo-signal in the BBL parenchyma on MRI T2-weighted images after MWA; **(j, k)** contrast-enhanced MRI in axial and sagittal sections showing no enhancement in the BBL parenchyma in the arterial phase after MWA; **(l)** 3D visualization showing the spatial structure of the ablation zone; **(m-p)** after 12 months follow-up, the ablation debris decreased gradually to a size of 1.1 × 0.4 × 1.2 cm on T2-weighted images **(m)** and arterial phase **(n, o)** of MRI images and the US image (yellow arrows in **p**).[34]

Several recent clinical studies have further validated the therapeutic profile of US-guided MWA for managing malignant breast tumors, particularly in early-stage disease. For instance, a feasibility study involving 41 patients with solitary breast cancers (≤ 3 cm) demonstrated that US-guided MWA achieved complete ablation in 90% of cases (95% confidence interval: 76.9%–97.3%) as confirmed by histochemical staining, with a mean ablation time of only 4.48 minutes and minimal reversible complications.[44] Another pilot cohort study compared US-guided MWA with nipple-sparing mastectomy in patients with invasive ductal carcinoma (≤ 5 cm) (Figure 7). With a median follow-up of 26.7 months, both groups showed comparable tumor progression rates ($P = 0.16$), no cancer-related deaths, and no major complications. However, the MWA group exhibited significantly shorter hospitalization times and superior cosmetic outcomes ($P < 0.001$), supporting its suitability, especially for elderly populations ineligible for surgery.[45] In a multicenter prospective cohort research focusing on elderly individuals with hormone receptor-positive/human epidermal growth factor receptor 2-negative breast cancer, US-guided MWA combined with endocrine therapy yielded disease-free and overall survival outcomes comparable with those of standard surgery with adjuvant therapy (Figure 8), while significantly reducing the hospitalization period (7.1 vs. 13.0 days, $P < 0.001$).[46] Additionally, a propensity score-matched study comparing US-guided MWA with BCS in patients with early breast cancer found no significant differences in tumor progression, overall survival, or disease-specific survival after a median follow-up of 43 months. US-guided MWA exhibited shorter procedure times, fewer complications, and significantly better cosmetic satisfaction (Figure 9) ($P < 0.001$), highlighting its potential as a minimally invasive alternative to BCS in selected cases.[47] In a pioneering window-of-opportunity trial focusing on a particularly challenging patient subset where tumors affect the skin or nipple–areola complex (NAC), it demonstrated the viability of US-guided MWA as a local therapeutic option.[48] The study enrolled 15 inoperable patients with advanced disease, employing innovative techniques such as hydro-dissection and variable power ablation (20–60 W) to protect superficial structures while achieving complete tumor necrosis. Technical success and effectiveness were both 100%, with a median follow-up of 33.5 months. Although instances of skin burns

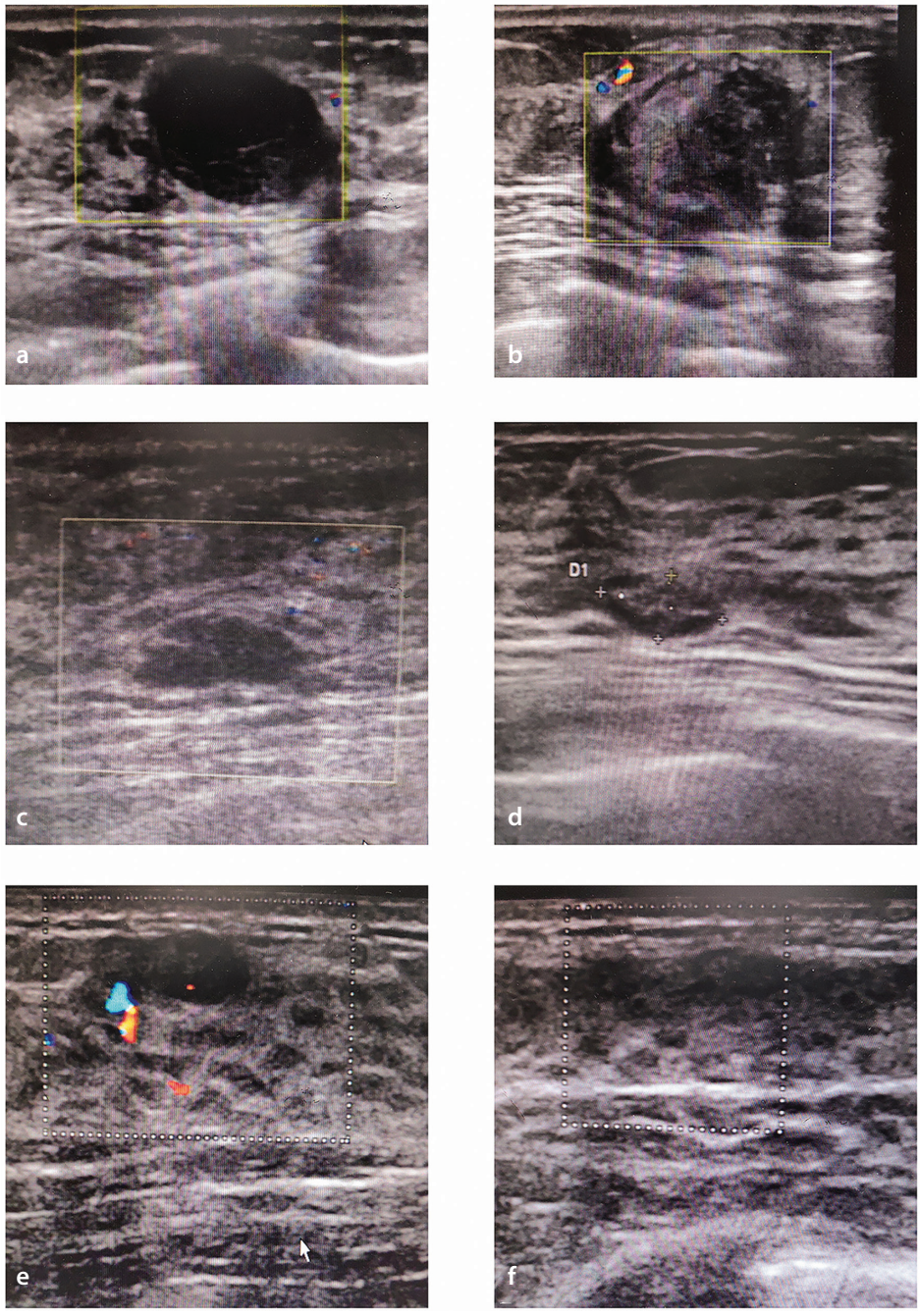


Figure 3. Depicts three cases of patients with different responses to treatment. Ultrasound before microwave ablation (MWA) showed three lesions with clear boundaries **(a, c, e)**. At 8 months, 9 months, and 11 months after the MWA, the figure shows the results of enlargement **(b)**, reduction **(d)**, and complete regression **(f)**, respectively.[16]

and nipple loss occurred in some cases, all wounds healed within a median duration of 3.7 months, and > 93% of patients rated their aesthetic results as excellent or good. Importantly, MWA markedly improved the quality of life and even enabled subsequent curative surgery in two patients by reducing tumor burden. This study supports MWA as a promising minimally invasive alternative for complex breast cancers with skin/NAC involvement, particularly in patients ineligible for standard surgical treatment.

Besides ablating tumors locally, MWA can elicit systemic antitumor immune responses, which contribute to sustained therapeutic benefits and may inhibit the growth of distant untreated tumors.[9] This immunostimulatory effect positions MWA as a valuable component within combinatorial therapeutic approaches for breast cancer. A clinical study in early-stage breast cancer revealed that US-guided MWA not only achieved a high complete ablation rate (91.4%) but also significantly promoted a Th1-polarized immune response, characterized by an increase in inducible costimulator (ICOS)-activated $CD4^+$ T-cells (Figure 10) and elevated IFN-γ levels. T-cell receptor sequencing further indicated clonal expansion of T lymphocytes recognizing breast tumor-specific antigens, suggesting the induction of a durable adaptive immune response.[49] Single-cell transcriptomic analysis revealed that US-guided MWA induced activation of NK cells and $CD8^+$ T-cells (Figure 11), along with enhanced ICOS expression in $CD4^+$ T-cells. Immune checkpoint blockade on post-MWA samples resulted in higher T-cell activity, supporting the

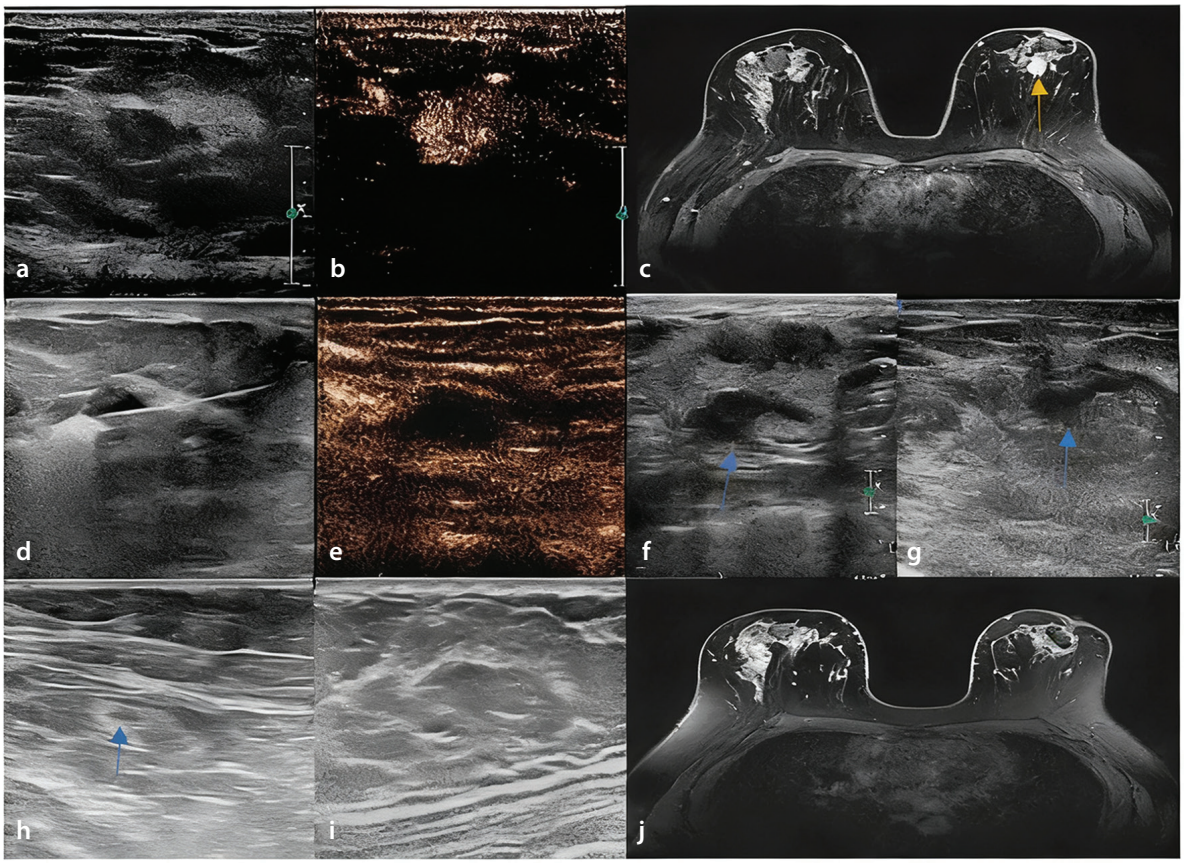


Figure 4. Technical success of microwave ablation (MWA) in one representative case (a 36-year-old woman with a left intraductal papillary pattern of the breast of 17 × 11 × 9 mm in size). **(a)** Ultrasound (US) before MWA showed a hypoechoic mass with clear boundary; **(b)** the tumor before ablation with contrast-enhanced US (CEUS) showed homogeneous enhancement on CEUS; (the yellow arrow points to the mass) **(c)** magnetic resonance imaging (MRI) showed the tumor before ablation with notable enhancement; **(d)** US showed the tumor was being treated with MWA; **(e)** the ablated mass without enhancement on CEUS; **(f-i)** US variance of the breast benign tumor after MWA during follow up at 3, 6, 12, and 24 months, respectively. During the process, the tumor size decreased gradually and finally disappeared on the US image; (the blue arrow points to the mass); **(j)** at the follow-up of 24 months, no masses were detected on MRI. Reprinted from[35] with permission from John Wiley and Sons.

potential synergy between MWA and immunotherapy.[27] A window-of-opportunity trial combining preoperative MWA with a single dose of anti-PD-1 antibody (camrelizumab) demonstrated that the regimen was well-tolerated and practicable, without delaying surgery. This approach led to enhanced cytotoxic and memory functions in $CD8^+$ T-cells, with monocyte-mediated MHC-I pathway activation contributing to the improved T-cell response.[50] Moreover, when compared with RFA, US-guided MWA was found to induce superior cytolytic activity in peripheral T-cells and promote memory $CD4^+$ T-cell expansion (Figure 12). Single-cell analyses indicated that these differences may stem from distinct antigen presentation mechanisms, with dendritic cells and altered fatty acid metabolism playing a crucial role in the MWA-induced immune environment.[18]

Based on the evidence presented, US-guided MWA has emerged as a safe and effective minimally invasive therapeutic option for selected patients with malignant breast tumors, particularly those with early-stage disease. Clinical studies demonstrate high rates of complete ablation, short- to mid-term local tumor control that appears comparable with surgical interventions, and superior cosmetic outcomes with reduced procedural times and shorter hospital stays (Table 1). Importantly, US-guided MWA not only achieves localized tumor destruction but also stimulates systemic antitumor immune responses, including Th1 polarization and T-cell activation, which may enhance long-term disease control and support combination strategies with immunotherapy. These attributes suggest that US-guided MWA could become a valuable alternative to conventional surgery in selected patient populations, especially in elderly patients or those ineligible for standard operative management, while also offering a promising platform for multimodal treatment approaches in breast oncology.

Limitations and challenges of ultrasound-guided microwave ablation for breast tumors

The application of US-guided MWA, although promising, is constrained by several technical, biological, and clinical challenges, which must be carefully considered for patient selection and procedural planning.

Technical and procedural limitations

Key technical constraints are often related to tumor characteristics and the physical principles of MWA. Treating tumors near critical structures, such as the skin (< 0.5 cm), NAC, or chest wall, remains challenging due to the inherent risk of thermal injury, including burns or deformity. Techniques such as hydro-dissection can create protective fluid barriers, but they add procedural complexity.[48] Furthermore, intraprocedural monitoring, although feasible with US, is imperfect. The hyperechoic gas microbubbles generated during ablation can obscure the true ablation margin and the underlying tumor, potentially compromising the assessment of complete coverage, especially for less experienced operators.[51] This is of particular concern with larger tumors, which may require multiple overlapping ablations or moving techniques, increasing the risk of incomplete treatment or collateral damage due to the

cumulative thermal effect and obscured visibility. Finally, as a destructive modality, MWA does not provide a specimen for definitive post-procedural histopathological analysis, which is a major drawback compared with surgical excision or VAE. This underscores the paramount importance of a conclusive histopathological diagnosis via core needle biopsy prior to ablation. The risk of false-negative biopsies necessitates meticulous sampling from multiple sites within a suspicious lesion to minimize the chance of missing a malignancy before proceeding with ablation.

Methodological heterogeneity and evidence gaps

Beyond technical and biological considerations, the current body of evidence on US-guided MWA for breast tumors has several methodological limitations that warrant careful interpretation. There is substantial heterogeneity across the available clinical studies, including variability in patient inclusion criteria, tumor subtypes, applied MWA parameters (power, duration), and techniques for assessing treatment efficacy (e.g., CEUS, MRI, histology). This heterogeneity complicates direct cross-study comparisons and meta-analyses. Furthermore, many published studies are limited by small sample sizes and a predominance of single-arm, non-randomized designs. Consequently, although short- and mid-term outcomes reported in cohorts[45,48] are encouraging, the absence of large-scale, randomized controlled trials (RCTs) with long-term (> 5 years) follow-up currently represents the most critical evidence gap. The lack of Level I evidence precludes definitive conclusions regarding its long-term oncological equivalence to surgery and underscores the need for rigorously designed, prospective RCTs to validate these preliminary findings.

Figure 5. Postoperative complications in the ablation, rotary cutting, and open surgery groups.[36]

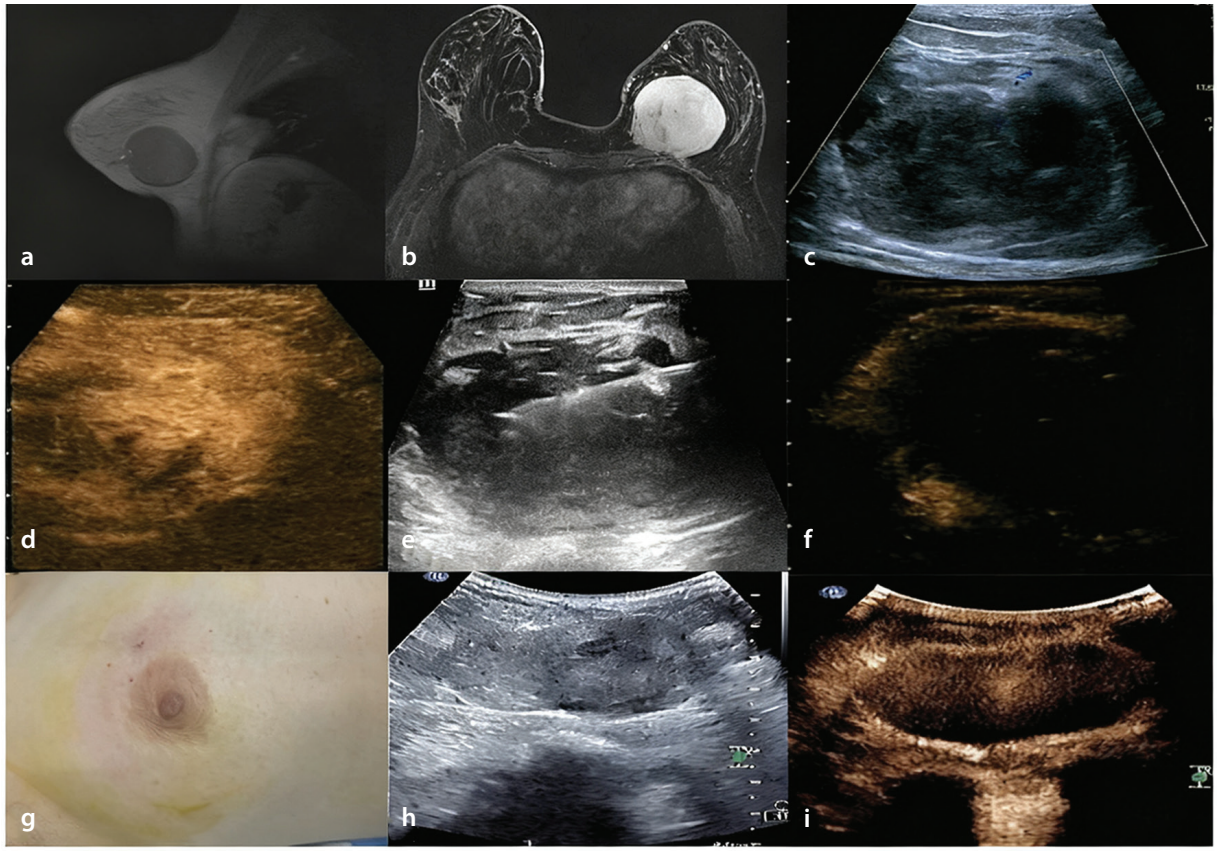


Figure 6. A 37-year-old female with a huge mass in the left breast. **(a, b)** The location of the tumor on enhanced magnetic resonance imaging; **(c)** sonographic appearance of the tumor on two-dimensional ultrasound (2D-US); **(d)** contrast-enhanced US (CEUS) showed homogeneous hyperenhancement of the tumor during the arterial phase; **(e)** during US-guided microwave ablation; **(f)** the area of ablation showed no enhancement in arterial phase and venous phase after ablation; **(g)** the skin of the breast was slightly ecchymosis after ablation, and the appearance of the breast was intact; **(h, i)** after 10 months of follow-up, 2D-US showed that the mass was considerably reduced, and CEUS showed that there was no enhancement in the arterial phase and venous phase of the ablation area.[37]

Table 1. Summary of complication profiles from selected US-guided MWA studies

Tumor type	Study ID	Study type	Patients/lesions (n)	Key efficacy	Minor complications (incidence)	Major complications (incidence)	Definitions/notes
Benign tumors	Zhou et al.[32]	Prospective	39 patients/44 lesions (37/41 with follow-up)	Complete ablation: 97.5% (40/41); significant volume reduction ($P = 0.005$)	Slight to moderate pain: 34.1% (14/41); slight skin depression: 5.4% (2/37); oedema and swelling (incidence not reported)	None	Safe (no epidermal burn) even with mean skin-to-tumor distance of 7.5 mm
	Zhang et al.[33]	Prospective	182 patients/205 lesions	Complete ablation: 87.32% (179/205) by CEUS, 82.93% (170/205) by MRI	Local pain and skin erythro swelling: 8.2% (15/182); duct ectasia: 4.9% (9/182); fat liquefaction: 2.2% (4/182)	None	Serious complications: hemorrhage, serious pain and fat necrosis, etc.
	Cui et al.[34]	Prospective	80 patients/104 lesions	Complete ablation: 100% (104/104); volume reduction: 80.2% at 12 months ($P < 0.001$)	Pain (slight to moderate): 100% (80/80); skin redness and edema: most patients (incidence not reported)	None	No immediate or delayed complications (skin burn, pectoralis injury, infection or nipple discharge)
	Liu et al.[16]	Retrospective	171 patients/271 lesions	Complete ablation: 24.29% (34/140) at 1–6 months, 45.45% (50/110) at 6–12 months, and 40.91% (18/44) at > 12 months	Slight/moderate pain: 14.6% (25/171); severe pain: 1.7% (3/171); skin scalding: 0.6% (1/171)	None	No fat liquefaction or serious complications occurred during the operation
	Zhang et al.[35]	Retrospective	101 lesions	Technical success: 100%; no recurrence: 100% at 24-month follow-up	Localized swelling/pain: 11.9% (12/101); skin ecchymosis: 5.9% (6/101); tape allergy: 1.0% (1/101); infection: 2.0% (2/101); self-absorbable hematoma: 1.0% (1/101)	Skin fistula: 1.0% (1/101)	The technical success rate was defined as no enhancement in any part of the lesion on the first postoperative follow-up imaging
	Lu et al.[36]	Retrospective	12 patients	Operation time: 18.39 ± 7.05 minutes; blood loss: 4.12 ± 1.51 mL; healing time: 2.18 ± 1.02 days; complication rate: 8.33%	Subcutaneous hematoma: 8.33% (1/12); no infection, ecchymosis, skin damage, or deformity reported	None	Compared with open surgery and rotary cutting: superior cosmesis (100% excellent/good); minimal invasiveness; low pain scores (VAS 1.02–3.05)
	Zhang et al.[37]	Case report	1 patient/1 lesion	Volume reduction: 69.8% at 10-month follow-up; complete ablation confirmed by CEUS	Postoperative pain (VAS 4); slight skin ecchymosis, redness and swelling (resolved in 4 weeks)	None	Giant leiomyoma (7.6 × 6.6 × 7.5 cm); first MWA report for breast leiomyoma; excellent cosmetic outcome

Table 1. Continued

Tumor type	Study ID	Study type	Patients/lesions (n)	Key efficacy	Minor complications (incidence)	Major complications (incidence)	Definitions/notes
Malignant tumors	Zhou et al.[44]	Prospective	41 patients/41 lesions	Complete coagulation: 90% (37/41) overall; 95% (36/38) for invasive ductal carcinoma; mean ablation time: 4.48 minutes	Skin burn: 2.4% (1/41); pectoralis muscle thermal injury: 4.9% (2/41)	None	No necrosis of the skin flaps, infection, or other adverse effects were noted in all 41 patients during and after the procedure
	Yu et al.[45]	Retrospective	21 patients/22 lesions	Technical efficacy: 100%; LTP: 4.5% (1/22)	A mild sensation of heat, pain, and local swell in the ablation site: 100%	None	Technical efficacy was defined as the rate of no residual tumor 1 month after the procedure; major complication included severe skin injury, abscess, hematoma, pneumothorax, tumor cell implantation, wound dehiscence, skin flap necrosis and nipple areola complex necrosis
	Zhong et al.[46]	Prospective	33 patients/33 lesions	Technical effectiveness: 100%; local recurrence: 3.0% (1/33); DFS/OS comparable with surgery	Not specified in detail; only "no ablation-related adverse events" reported	None	Technical effectiveness of MWA was defined as complete ablation at follow-up enhanced imaging 1 month after MWA
	Dai et al.[47]	Retrospective	21 patients/28 lesions	Technical success: 100%; local recurrence: 4.8% (1/21); comparable OS/DSS with BCS	Slight skin redness and subcutaneous edema (subside within 3 days) (most patients)	None	The technical success of MWA is defined as no enhancement of the entire tumor area during the arterial phase; no skin burns or fat necrosis; excellent cosmetic results: 100%; shorter operation time vs. BCS; suitable for early breast cancer up to 5 cm
	Dai et al.[48]	Retrospective	15 patients/16 lesions	Technical success: 100% (15/15); technical effectiveness: 100% (15/15); local recurrence: 26.7% (4/15)	Mild skin redness and swelling: 46.6% (7/15); slight bleeding: 26.6% (4/15); mild pain: 20.0% (3/15); mild tenderness: 26.6% (4/15)	Nipple loss: 6.7% (1/15); skin burn and nipple loss: 26.7% (4/15); infection: 6.7% (1/15)	Technical success: tumors treated per protocol and completely covered by ablation zone; technical effectiveness: no enhancement on follow-up imaging at 1 month
	Zhou et al.[49]	Prospective	35 patients/35 lesions	Complete ablation: 91.4% (32/35) confirmed by pathology or follow-up (median 36 months)	Local swelling at treatment site: 100%, resolved within 1 week	None	Study focused on immune response; MWA induced antitumor immunity

US, ultrasound; MWA, microwave ablation; CEUS, contrast-enhanced ultrasound; MRI, magnetic resonance imaging; LTP, local tumor progression; VAS, visual analog scale; DFS, disease-free survival; OS, overall survival; DSS, disease-specific survival; BCS, breast-conserving surgery.

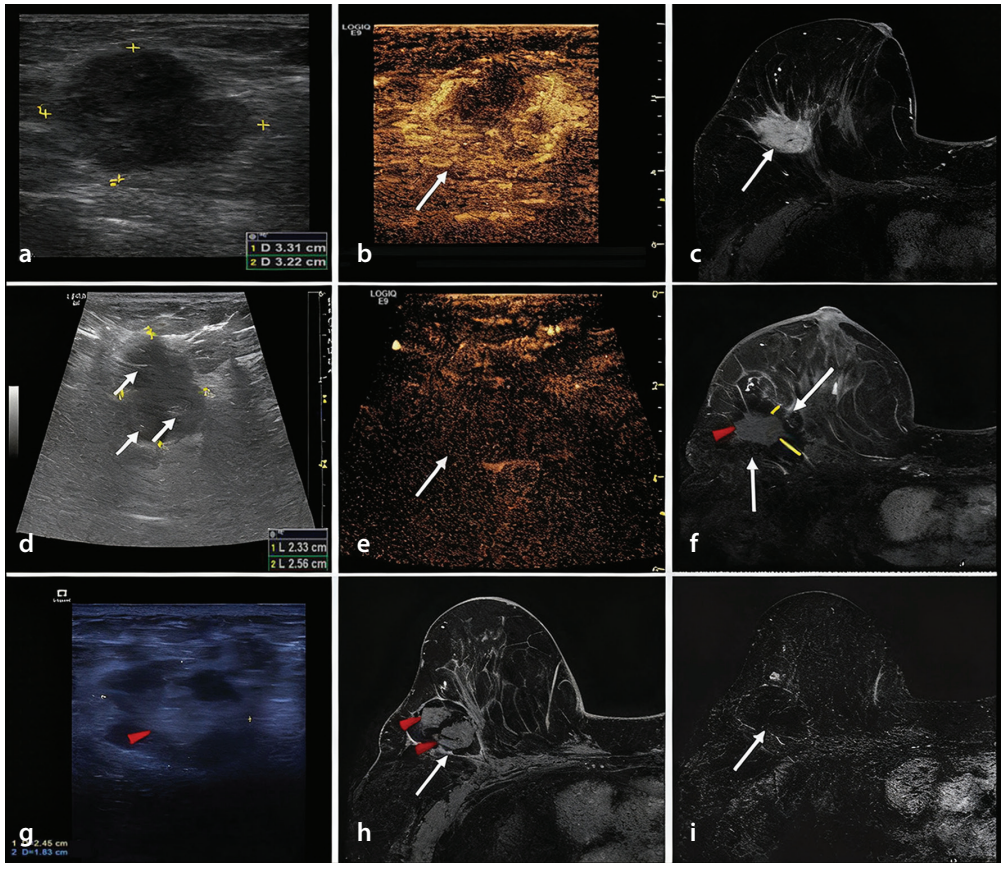


Figure 7. A 68-year old woman with invasive ductal carcinoma of the right breast. **(a)** Ultrasound (US) scan before microwave ablation (MWA) shows the hypoechoic mass (arrow) with a size of 3.3 × 3.2 cm; **(b)** contrast-enhanced US (CEUS) before MWA shows the mass is hyper-enhanced (arrow) in arterial phase; **(c)** transverse contrast-enhanced magnetic resonance imaging (MRI) shows hyperintensity masses (arrow) before MWA in arterial phase; **(d)** US scan shows the heterogeneously hypoechoic mass (marker) with a size of 2.6 × 2.3 cm immediately after MWA (ghost size). Hyperechoic needle tracts can be seen in the ablated mass (arrow); **(e)** CEUS immediately after MWA shows the mass is non-enhanced (arrow) in arterial phase; **(f)** contrast-enhanced MRI image shows hyperintensity ghost of mass (red arrow) and the peripheral hypointensity treatment zone (white arrow) in the arterial phase 3 days after MWA. The ablation margin is from 1.2 to 2.2 cm (yellow lines), which can be measured in the hospital information system; **(g)** US scan shows the heterogeneously ablation zone (marker) shrinks to a size of 2.5 × 1.8 cm at 18 months after MWA. The ghost of mass (arrow) is surrounded by hypoechoic adipose tissue; **(h)** contrast-enhanced MRI image shows the treatment zone (white arrow) is non-enhanced with a clear capsule and the central hyperintensity ghost of mass (red arrow) in arterial phase at 18 months after MWA; **(i)** MRI silhouette shows no signal for the ablation zone with clear fibrous capsule and margin (arrow).[45]

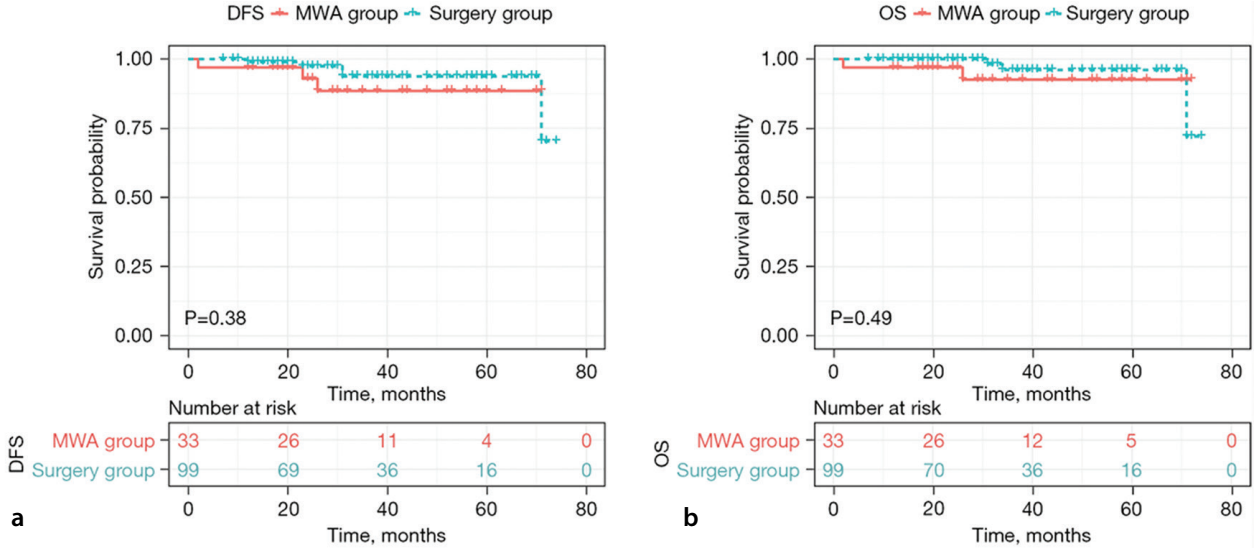


Figure 8. Kaplan–Meier curves for **(a)** disease-free survival and **(b)** overall survival.[46] DFS, disease-free survival; MWA, microwave ablation; OS, overall survival.

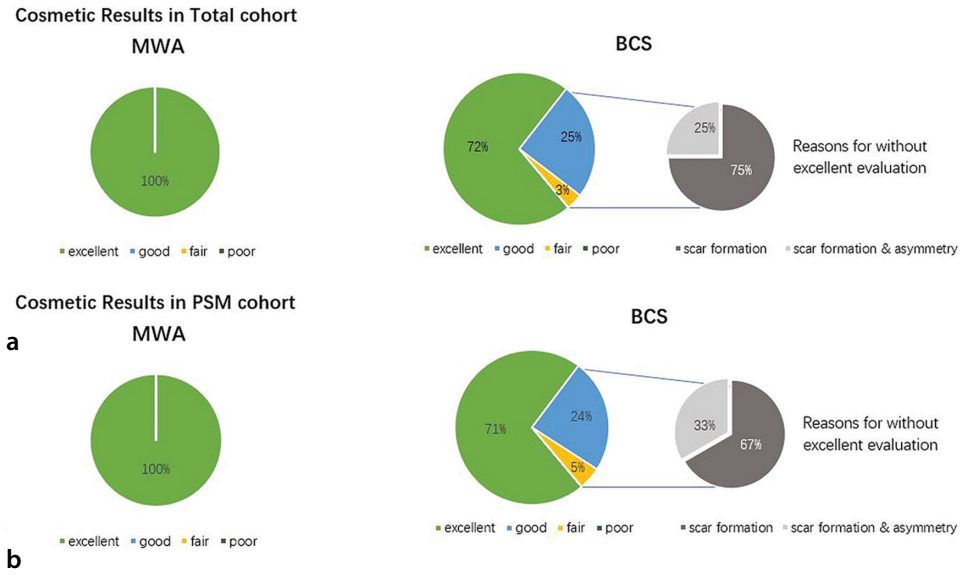
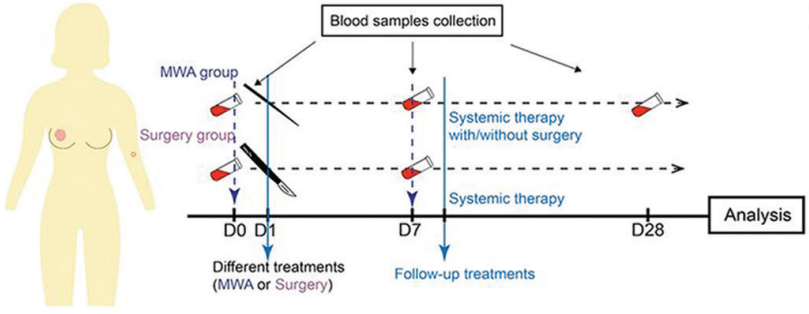


Figure 9. Cosmetic results and reasons for without excellent evaluation between selected patients with early breast cancer who underwent MWA and breast-conserving surgery. **(a)** Cosmetic results in total cohort; **(b)** cosmetic results in propensity score matching cohort.[47] MWA, microwave ablation; BCS, breast-conserving surgery; PSM, positive surgical margin.



Baseline characteristics of study population

Variables	Surgery (13)	Microwave ablation (35)
Median age, y	46 (32-64)	59 (38-87)
Tumor size		
T1	6 (46.2%)	20 (57.1%)
T2	7 (53.8%)	15 (42.9%)
Node status		
N0	4 (30.8%)	29 (82.9%)
N1	5 (38.5%)	4 (11.4%)
N2	4 (30.8%)	2 (5.7%)
Molecular subtype		
Luminal-HER2-negative	8 (61.5%)	20 (57.1%)
HER2-positive	2 (15.4%)	7 (20.0%)
Triple negative	3 (23.1%)	8 (22.9%)
Local treatment		
Surgery	13 (100%)	0 (0%)
MWA	0 (0%)	15 (42.9%)
MWA followed by surgery	0 (0%)	20 (57.1%)
Ablation time, minutes (mean, range)	/	2.5 (2-5)

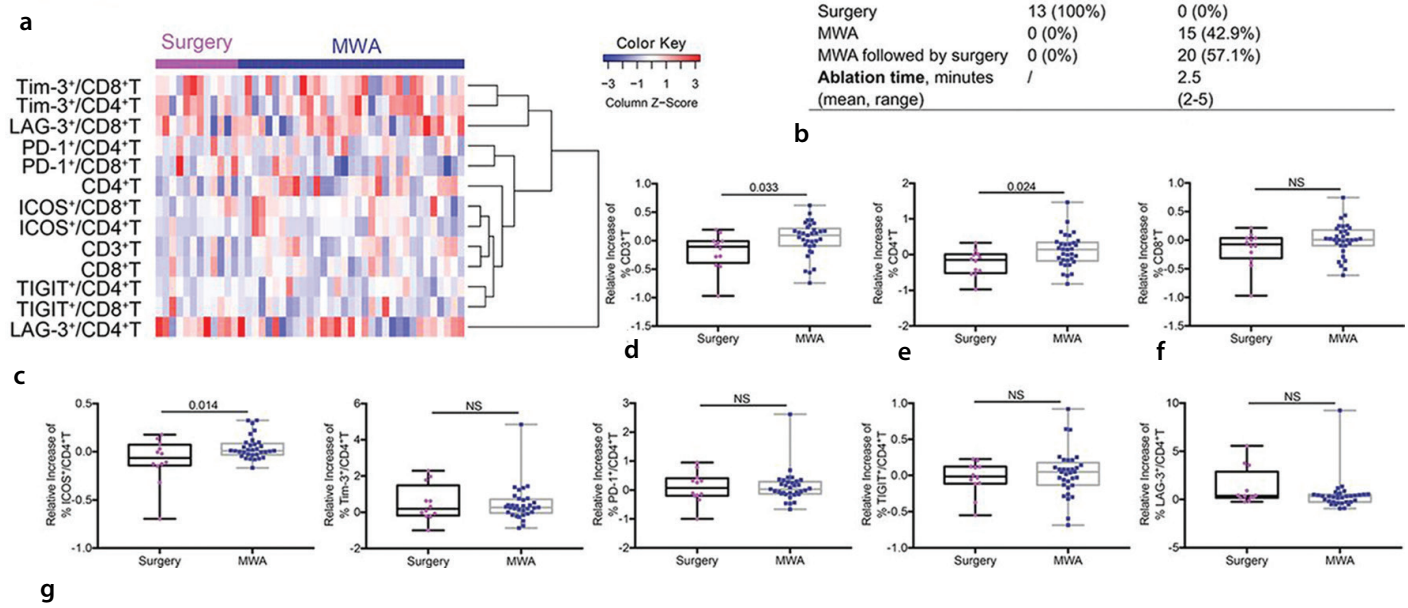


Figure 10. Phenotypical characterization of peripheral T-cells in patients treated with microwave ablation (MWA). **(a)** Schematic illustrating the study design; **(b)** basic characteristics of enrolled patients; **(c)** heat map of the changes in peripheral T-cells, $CD4^+$, and $CD8^+$ T-cell subsets in the MWA group (n = 33) and the surgery group (n = 12). The increased frequencies of peripheral T-cells **(d);** $CD4^+$ **(e);** but not $CD8^+$ **(f)** T-cells in patients treated with MWA were compared with those in surgery; (g) scatter plots showing the changes in the activated (inducible costimulator) and exhausted (LAG-3, TIGIT, TIM-3, and PD-1) $CD4^+$ T-cells. Data are presented as mean ± standard deviation.[49]

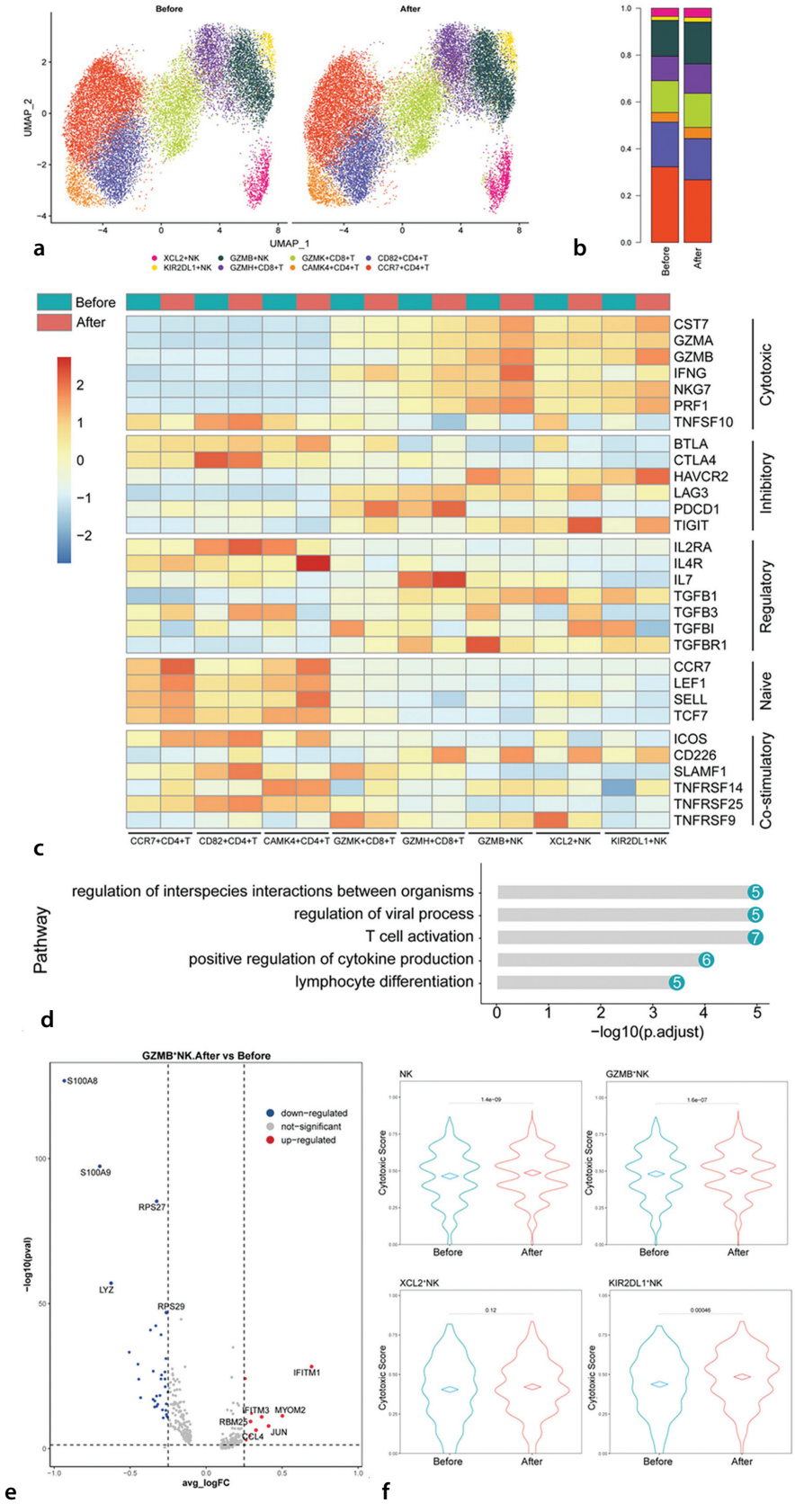


Figure 11. Overview of changes in the NK and T-cells, and the activated phenotypes of NK cells induced by microwave ablation (MWA) of breast cancer (n = 6). **(a)** UMAP analysis of peripheral NK and T-cells showing eight clusters before and after MWA; **(b)** the proportions of each cell cluster before and after ablation; **(c)** heatmap of the gene sets of cytotoxicity, exhaustion/inhibitory, regulatory, naïve and co-stimulation of these eight cell clusters; **(d)** gene ontology enrichment pathway analysis of genes preferentially upregulated in XCL2$^+$NK cells; **(e)** volcano plot showing upregulated genes of peripheral GZMB$^+$NK cells induced by MWA; **(f)** the cytotoxic scores of different peripheral NK cell clusters before and after MWA.[27]

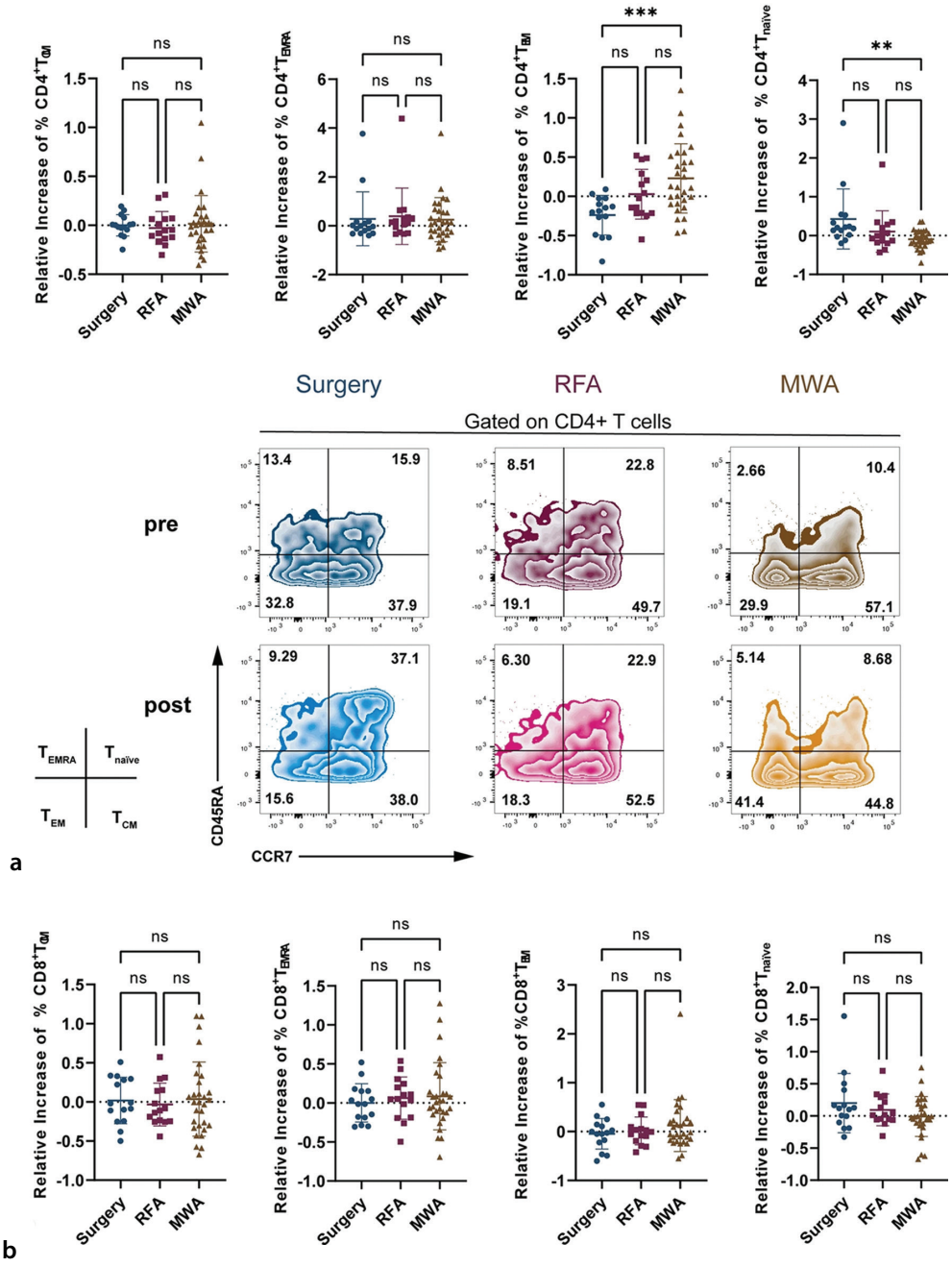


Figure 12. Changes in peripheral memory CD4+ and CD8+ T-cell subsets among different treatment groups. Flow cytometry gating graphs of CD4 + T-cells and relative increases in CD4+ **(a)** and CD8+ **(b)** TCM, TEMRA, TEM, and Tnaïve subsets in patients treated with RFA (n = 15) or MWA (n = 30) compared with surgery (n = 15). Data are shown as mean ± standard deviation. $^{**}P < 0.01$; $^{***}P < 0.001$.[18] ns, not significant; RFA, radiofrequency ablation; MWA, microwave ablation.

Biological uncertainties and standardization barriers

Considerable biological and diagnostic uncertainties persist. For benign disease, there is a lack of consensus on whether to intervene in certain conditions, such as hyperplastic nodules (excluding severe or atypical hyperplasia), often leading to management based on patient symptoms or preference rather than standardized guidelines. For malignant applications, the biological response to thermal ablation may vary based on tumor biology (e.g., molecular subtypes, presence of an extensive intraductal component) and microenvironmental factors, influencing the risk of residual disease or recurrence.[52] Finally, widespread adoption is hindered by a lack of universally standardized protocols and guidelines regarding power settings, ablation time, and endpoint determination. Success remains operator-dependent, requiring significant expertise in both ultrasonography and interventional technique.

Future perspectives

The continued evolution of US-guided MWA for breast tumors will be shaped by interdisciplinary innovations aimed at enhancing precision, expanding clinical applicability, and integrating within broader oncological frameworks. Based on current evidence and emerging technological trends, the following key directions are envisioned:

Technological refinements and smarter ablation systems

Future MWA systems will likely feature miniaturized and adaptive antenna designs (e.g., triaxial, slot, or multi-tine configurations) capable of conforming to complex tumor morphologies while sparing critical adjacent structures. Coupled with real-time

temperature monitoring through non-invasive methods, such as MRI thermography or integrated fiber-optic sensors, these advances will allow dynamic modulation of energy delivery, reducing the risk of incomplete ablation or collateral damage. Furthermore, the integration of AI for pre-procedural planning and intraprocedural guidance could standardize treatment precision;[53] AI algorithms trained on multi-parametric imaging and radiomic data may predict optimal ablation parameters, antenna trajectories, and even early signs of treatment response.

Advanced imaging integration and radiomics

The fusion of real-time US with pre-procedural MRI or CT will enhance spatial accuracy and margin assessment, particularly for tumors adjacent to critical anatomy. US radiomics,[54] which involves extracting high-throughput quantitative features from grayscale, Doppler, and CEUS, holds significant promise for personalizing US-guided MWA. Radiomic signatures may predict dielectric properties, ablation susceptibility, and immune microenvironment features, enabling patient-specific therapy planning. Post-ablation, delta-radiomics could serve as a non-invasive biomarker for treatment efficacy and residual disease.[55]

Immunomodulation and combination strategies

US-guided MWA-induced immunogenic cell death provides a strong rationale for combining ablation with immunotherapy. Future studies should focus on optimizing the timing and sequencing of immune checkpoint inhibitors (e.g., anti-PD-1) with US-guided MWA to amplify systemic antitumor responses. Nanotechnology represents a research avenue that could further enhance this synergy through thermally responsive nanocarriers co-loaded with immunomodulators or chemotherapeutics, enabling targeted delivery to the ablation zone and residual tumor niches.[9,56] Research into spatial immune dynamics via single-cell transcriptomics will help identify novel biomarkers and combination targets.

Standardization and validation

There is a critical need for standardized international guidelines on technical parameters, endpoint definitions, and patient selection criteria for both benign and malignant applications. Large-scale prospective registries and RCTs with long-term follow-up (> 5 years) are essential to validate oncological outcomes, including local recurrence, survival, and cosmetic results. Incorporating patient-reported outcomes and cost-effectiveness analyses will further support the integration of US-guided MWA into clinical care pathways.

Cost-effectiveness, economic considerations, and accessibility

The economic viability of US-guided MWA, as an emerging technology, is a key factor influencing its broader adoption. The initial costs associated with the acquisition of MWA equipment and specialized operator training present major barriers. Moreover, variability in medical insurance coverage for ablation procedures remains a challenge. However, the inherent advantages of US-guided MWA, such as its ability to be performed under local anesthesia, its shorter operative times, and the reduced need for hospitalization, suggest a potential for long-term cost savings compared with traditional surgical resection, though this requires formal validation. These savings would stem from decreased use of operating room resources, shorter inpatient stays, and faster patient recovery. Concurrently, expanding the clinical indications for US-guided MWA to complex scenarios (e.g., tumors involving the skin or NAC) and patients ineligible for surgery can enhance its clinical value. To improve global accessibility, future efforts should focus on developing more portable and affordable systems, particularly for resource-limited settings. Coupled with the implementation of tele-proctoring and simulation-based training platforms to disseminate expertise efficiently,[57] these strategies can help lower economic and training barriers. Nonetheless, comprehensive health-economic analyses and large-scale cost-effectiveness studies are urgently needed to evaluate and quantify these economic benefits formally against the current standard of care.

US-guided MWA represents a promising minimally invasive modality for treating both benign and malignant breast tumors. Supported by robust clinical evidence, US-guided MWA demonstrates high rates of complete ablation, considerable tumor volume reduction, and favorable cosmetic outcomes, with a low incidence of complications. For benign lesions, such as fibroadenomas, it offers a viable non-surgical alternative that avoids general anesthesia, minimizes scarring, and facilitates rapid recovery. For early-stage breast cancer, preliminary studies indicate that US-guided MWA can achieve local tumor control comparable with surgical resection in the short- to mid-term, while offering notable clinical benefits, such as shorter procedure times, reduced hospitalization, and enhanced patient satisfaction.

Beyond its local ablative effects, US-guided MWA stimulates systemic antitumor immune responses, including Th1 polarization and T-cell activation, which may synergize with immunotherapy and other systemic treatments, opening new avenues for multimodal cancer management. However, the adoption of US-guided MWA is not without challenges. Technical limitations related to tumor proximity to critical structures, intraprocedural monitoring difficulties, and the lack of long-term oncological data from randomized trials necessitate cautious patient selection and procedural planning. Future advancements in antenna design, real-time imaging integration, AI-assisted treatment planning, and combination immunotherapies hold great potential to enhance the precision, efficacy, and accessibility of US-guided MWA. Standardized international guidelines and large-scale prospective studies are urgently needed to validate long-term outcomes and establish US-guided MWA as a mainstream option in breast tumor management.

In summary, US-guided MWA represents a major advancement in the shift toward minimally invasive, organ-preserving therapies. With ongoing technological refinement and clinical validation, it is poised to meet the demand for personalized, minimally invasive care in breast oncology, particularly for patients seeking alternatives to traditional surgery.

Footnotes

Conflict of interest disclosure

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