Minimally Invasive Image-Guided Ablation for Lung Cancer

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Contents

Abstract

Lung ablation has emerged as a crucial intervention for managing both primary and metastatic lung tumors. While surgical resection remains the most effective treatment, only about 20% of lung lesions are operable due to advanced disease, comorbidities, poor functional status, and specific tumor characteristics (Scott et al., Chest 132 (3 suppl):234S–242S, 2007). For inoperable lesions, stereotactic body radiation therapy (SBRT) combined with adjuvant systemic therapy is a common alternative, albeit with significant side effects. Minimally invasive, image-guided percutaneous ablation offers a promising solution, providing effective treatment while preserving maximum functional lung volume and enhancing quality of life. Multiple medical societies endorse this method as a safe and effective lung-preserving treatment option for both primary lung cancer and metastases. The National Comprehensive Cancer Network (NCCN Guidelines 2024) supports thermal ablation for nonsmall cell lung cancer (NSCLC) in select patients with tumors up to T3 (up to 7 cm in diameter), although tumors larger than 3 cm have a higher risk of recurrence, and as one of the treatment options for dominant nodule in multifocal lung cancer (National Comprehensive Cancer Network. Non-small cell lung cancer (version 8.2020), 2020). The Society of Interventional Radiology (SIR) approves thermal ablation for patients with inoperable Stage IA NSCLC, recurrent NSCLC, and metastatic lung disease (Genshaft et al., J Vasc Interv Radiol 32:1241.e1–1241.e12, 2021). Available techniques include radiofrequency ablation, microwave ablation, cryoablation, laser ablation, and irreversible electroporation (IRE). Although comprehensive comparative studies are lacking, all methods

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demonstrate excellent tolerance and minimal complications. This chapter will explore the indications for lung ablation, various image-guided techniques, potential complications, and imaging follow-up.

Keywords

Thermal ablation · Ablation zone · Microwave ablation · Radiofrequency ablation · Cryoablation · Lung-preserving therapy · Imaging follow-up · Air embolism

1 Introduction

Lung cancer continues to be a major global health concern, representing the leading cause of cancer-related mortality. Despite significant advancements in diagnostic and therapeutic approaches, the prognosis for many patients remains poor, particularly for those with advanced or metastatic disease. Surgical resection is generally considered the gold standard, offering the best chance for long-term survival. However, only a limited number of patients are candidates for surgery due to factors such as comorbidities, compromised functional status, and unfavorable tumor characteristics [1]. For patients who are ineligible for surgery, alternative treatments such as stereotactic body radiation therapy (SBRT), often combined with systemic therapy, have been utilized. While radiation therapy can be effective, it frequently comes with notable side effects, especially for high-risk individuals.

In response to the limitations of conventional treatments, percutaneous image-guided ablation has emerged as a promising minimally invasive option. This technique, guided by real-time imaging, offers several advantages over traditional approaches, including reduced morbidity, preservation of healthy lung tissue, and lower procedural costs. Image-guided ablation includes various techniques such as radiofrequency ablation (RFA), microwave ablation (MWA), cryoablation, laser ablation, and irreversible electroporation (IRE). These methods have gained recognition for their effectiveness in treating both primary and metastatic lung tumors, especially in patients who are not ideal candidates for surgical intervention. Thermal ablation methods, including RFA, MWA, and cryoablation, are endorsed by organizations like the National Comprehensive Cancer Network (NCCN) and the Society of Interventional Radiology (SIR) as viable options for specific patient populations. The NCCN guidelines advocate for lung ablation in nonsmall cell lung cancer (NSCLC) larger than 6 mm, particularly when surgical resection is impractical due to tumor location or patient comorbidities [2]. Likewise, SIR supports image-guided thermal ablation for inoperable early-stage NSCLC, recurrent NSCLC, and metastatic lung disease [3].

This chapter aims to provide a comprehensive overview of lung ablation in the management of lung cancer, covering its indications, techniques, potential complications, and clinical outcomes. It will review guidelines and recommendations from leading organizations, analyze relevant studies, and offer insights into patient selection and procedural considerations. Additionally, the chapter will address potential complications. By elucidating the role of lung ablation, this chapter seeks to highlight its importance as a key component in modern lung cancer treatment strategies.

2 Thermal Ablation Techniques: Radiofrequency Ablation, Microwave Ablation, Cryoablation, Laser Ablation, and Irreversible Electroporation

Ablation techniques employ various energy sources to destroy tumor tissue, each with distinct mechanisms and benefits. RFA, MWA, and laser ablation use heat to induce coagulative necrosis of the targeted tissue. Cryoablation, in contrast, employs extreme cold to cause cell death through ice crystal formation and subsequent cellular disruption. IRE utilizes nonthermal electrical pulses to create nanopores in cell membranes, leading to apoptosis without significant heat generation. While all these methods aim to eradicate tumors, they differ in mechanisms, applications, and outcomes, each offering unique advantages. The distinct attributes of each technique determine its suitability for various clinical scenarios, patient profiles, and tumor characteristics, allowing for a personalized approach to lung cancer management.

2.1 Radiofrequency Ablation (RFA)

Mechanism: RFA employs electrical currents at radiofrequencies (375–500 kHz) to generate heat through resistive energy loss, also known as frictional heating. As electrons oscillate within the electrical circuit, they collide with tissue molecules, producing localized heat. The goal is to elevate the tissue temperature to 60–100 °C, which is lethal to the targeted tumor cells. The radiofrequency energy accumulates within the lung mass because the normal lung tissue acts as an insulator, effectively focusing the energy on the tumor. Additionally, medium to large blood vessels and airways create a "heat sink" effect, which pulls heat away from surrounding healthy tissue and concentrates it within the solid component of the tumor. However, this effect may also limit the efficacy of RFA for larger tumors [4, 5].

Applications: RFA is typically performed under moderate sedation, unless contraindicated. It typically used for treating small to medium-sized tumors, being the most effective for tumors less than 3 cm in diameter. Some RF electrodes are equipped with internal thermocouples to measure the temperature within the tissue. Additionally, some electrodes are connected to an infusion pump that either cools the electrode tip to prevent tissue charring, which can reduce current deposition, or infuses saline into the tissue to enhance thermal and electrical conductivity [6]. The duration of RFA treatments can range from 2 to 20 min, depending on factors such as the dielectric properties of the tumor, the surrounding tissue, and the presence of local thermal sinks like large vessels and bronchi [8]. RFA electrodes may come in various configurations, including single-tip or cluster electrodes (with three closely spaced tips), allowing for thermocoagulation diameters ranging from 2 to 5 cm (Fig. 1).

Benefits and Limitations: RFA is a well-established procedure with extensive clinical evidence supporting its effectiveness and holds Food and Drug Administration (FDA) approval for treating lung cancer [7]. It is associated with a relatively low risk of complications and generally offers a shorter recovery time compared to surgical options. However, its effectiveness diminishes as tumor size increases and when tumors are located near critical structures. Larger tumors, particularly those exceeding 3 cm, may require multiple overlapping ablations, multiple ablation sessions or combination therapies to achieve optimal results. There is also evidence suggesting interference with cardiac pacemaker devices and surgical hardware [8].

Fig. 1 Axial noncontrast CT image of the chest demonstrating a 3.5 cm right upper lobe mass with a 5 cm cluster electrode positioned centrally within the mass. Ablation was performed at this location prior to repositioning the electrode more peripherally within the mass and repeating the ablation

2.2 Microwave Ablation (MWA)

Mechanism: MWA, like RFA, uses heat to coagulate tissue. However, unlike RFA, which relies on an electrical current passing between a cathode and an anode positioned on separate parts of the body, MWA directly applies an electromagnetic field at frequencies between 900 and 2500 MHz to the surrounding tissue via a dielectric antenna. This electromagnetic field agitates water molecules within the tissue, causing them to oscillate rapidly and produce heat [9]. The temperature generated during the procedure is determined by the oscillation speed of water molecules in the target lesion, allowing MWA to achieve higher temperatures than RFA, even in highly ventilated and perfused areas.

Applications: MWA is particularly suitable for treating larger tumors, typically those ranging from 3 to 5 cm or larger. When dealing with tumors greater than 3 cm, multiple MWA applicators may be necessary to achieve a sufficiently large area of thermocoagulation. This technique is well established in hepatic malignancies. MWA also is usually performed under moderate sedation, unless contraindicated. Generally, lower-frequency MWA penetrates deeper into tissue and requires less power, while higher-frequency MWA is absorbed more readily and thus requires more power. Cooling of the antenna shaft is usually not needed with lower-frequency MWA but is essential with higher-frequency MWA to prevent thermal damage along the needle tract. Depending on the required volume of tissue necrosis, single or multiple MWA antennas may be used (Fig. 2). Unlike RFA, grounding is not required for MWA, and tissue charring does not significantly impact the effectiveness of electromagnetic wave propagation in this technique. MWA is particularly effective for lesions in difficult-to-reach locations and is increasingly used for both primary and metastatic lung cancers [5, 10].

Benefits and Limitations: MWA can treat larger tumors and has a faster ablation time compared to RFA. It also provides a larger ablation zone, which can be advantageous for heterogeneous tumor tissues. The higher tissue temperatures achieved with MWA make ablations less susceptible to the effects of thermal sink. Unlike RFA, MWA is more versatile because it doesn't rely on an electrically conductive path and is not limited by tissue thermal conductivity or the presence of charred tissue [10]. Therefore, MWA may be associated with a higher risk of collateral damage due to the broader heat zone. Its long-term outcomes and comparative effectiveness to other modalities are still under investigation. The wide variety of different device designs for MWA complicates training and reporting [11].

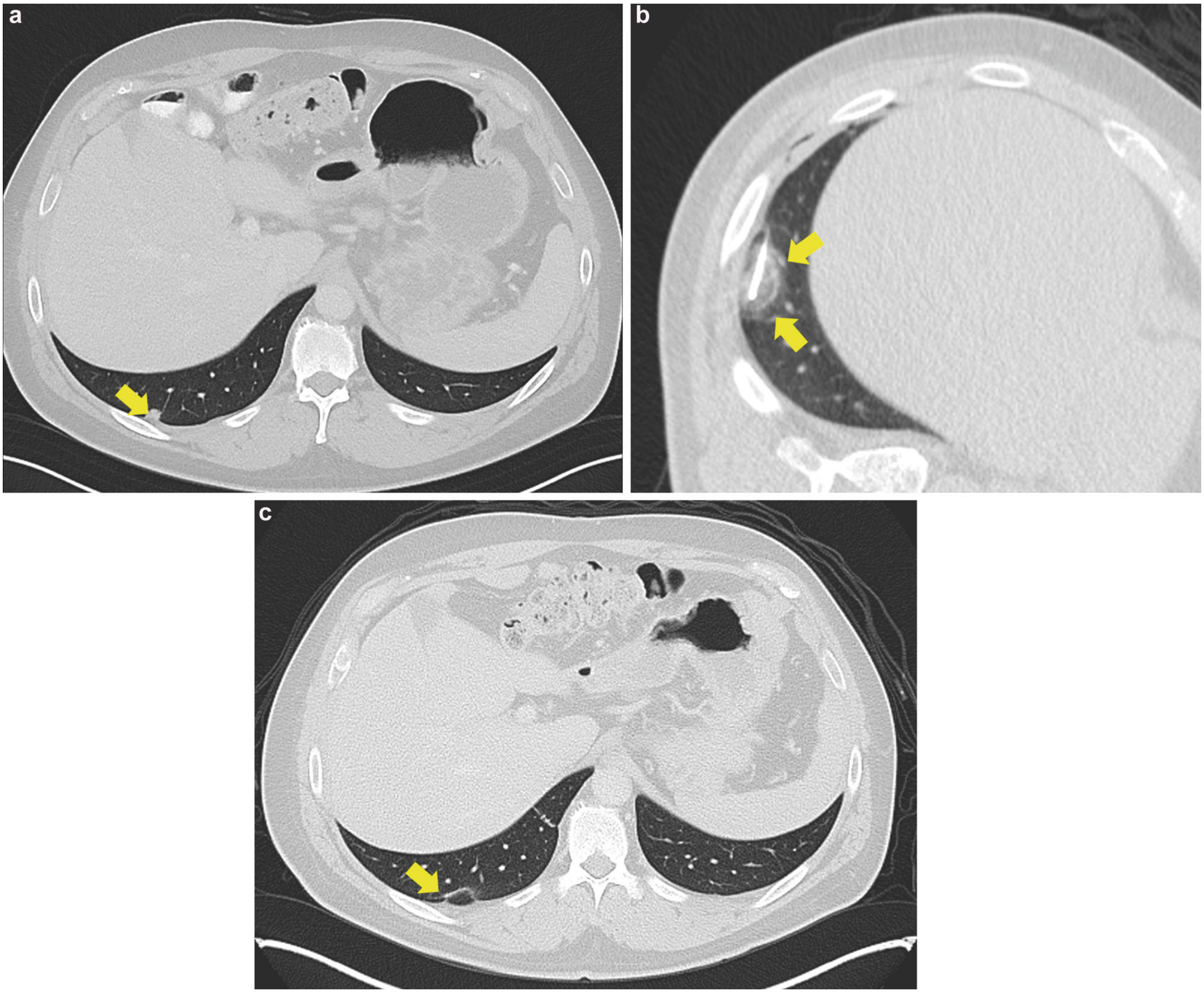

Fig. 2 A 54-year-old female with metastatic colon cancer to the right lower lobe. (**a**) Axial noncontrast CT of the chest demonstrating an 8 mm right lower lobe metastasis (*yellow arrow*). (**b**) Axial noncontrast CT image obtained during microwave ablation demonstrates an antenna within the targeted lesion and the typical ground-glass halo (*yellow arrows*) that surrounds the tumor during the ablation. (**c**) Axial noncontrast Ct of the chest performed 3 months postmicrowave ablation demonstrates minimal residual scarring at the site of the treated metastatic lesion (*yellow arrow*)

2.3 Cryoablation

Mechanism: Cryoablation freezes tissue by delivering pressurized gas to the tip of a cryoprobe, where the gas passes through an orifice into a low-pressure chamber, inducing extreme cold via the Joule–Thomson effect. This effect causes most gases, except hydrogen, helium, and neon, to cool as they transition from high to low pressure, thereby freezing and destroying the targeted tissue [12]. In this process, gas at a constant temperature is transported down the shaft of the cryoprobe and exits through an aperture into a lower pressure area, causing the gas to expand and cool. Cryoablation achieves target temperatures near −40 °C, causing ice crystals to form in the extracellular space and eventually creating an "ice ball" that defines the ablation zone's boundaries [13]. The ice ball ruptures both the plasma and organelle membranes, indirectly causing cell death by inducing endothelial damage, which promotes platelet aggregation and microvascular thrombosis during the thawing of the ice ball. Typically, cryoablation involves a number of freeze–thaw–freeze cycles, depending on the target tissue. Active thawing is based on the same Joule–Thomson effect but most often utilizes helium, which warms when moving from high pressure to low pressure [12].

Applications: Cryoablation is particularly useful for lesions located near critical structures where thermal ablation such as RFA and MWA might be risky. Although ice ball visualization is difficult in lung to predict necrotic lesion, the ice balls are great to ensure the ablation zone is not encroaching vulnerable structure. Like RFA and MWA, moderate sedation is typically used when targeting peripheral lesion but if targeting central lesion or high risk of bleeding, general anesthesia is recommended to keep the treated lung in under continuous positive airway pressure while mechanically ventilating the other lung [14]. The number of cryoprobes required is determined by the lesion size, with probes being positioned no more than 2 cm apart from each other and within 1 cm of the tumor margin [15]. The treatment protocol for targeted liver or renal tumors typically includes a 10-min freeze, an 8-min thaw, and another 10-min freeze. However, many different freeze–thaw cycle schemes have been reported in attempt to maximize tumor ablation zone and minimize the treatment time. The triple-freeze protocol has reported to be with decreased hemorrhage and allow earlier ice ball detection during the treatment and is most often utilized in treating lung lesions [16] (Fig. 3).

Benefits and Limitations: Cryoablation offers significant advantages for treating tumors near vital structures due to its ability to create a localized freeze zone with minimal collateral damage, making it safer for use near the airways, pericardium, blood vessels, and bones [17]. The risk of bronchopleural fistula is lower compared to RFA and MWA [18, 19]. Additionally, cryoablation can stimulate an immune response that may help target residual tumor cells and is

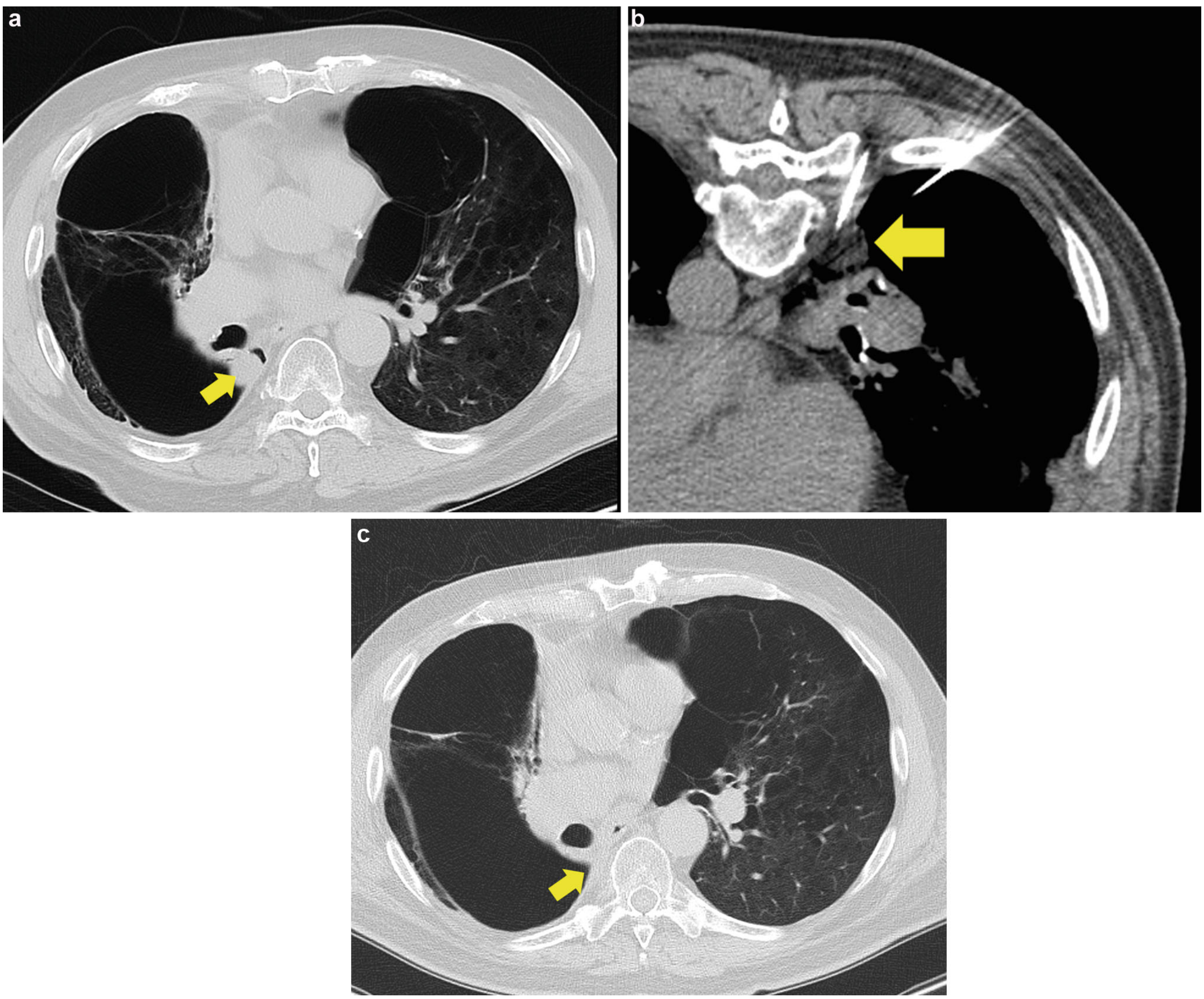

Fig. 3 A 74-year-old male with a right lower lobe adenocarcinoma felt to be a poor surgical candidate for surgery due to significant underlying emphysema and previous radiation. (**a**) Axial noncontrast CT of the chest demonstrating a 1.4 cm lung nodule within the medial right lower lobe, subjacent to the right mainstem bronchus (*yellow arrow*). (**b**) Axial noncontrast CT of the chest obtained during the freeze cycle demonstrates the low density ice ball within the targeted soft tissue mass (*yellow arrow*). Axial noncontrast CT of the chest performed 3 months postcryoablation demonstrates minimal atelectasis with no residual tumor within the medial right lower lobe. (**c**) Axial noncontrast CT of the chest performed 3 months post-ablation demonstrating no residual mass and minimal scarring (*yellow arrow*).

associated with less postprocedural pain compared to RFA and MWA [20]. However, cryoablation procedures typically take longer than those of RFA and MWA.

2.4 Laser Lung Ablation

Mechanism: Laser ablation employs targeted heat to precisely destroy tumor tissue using laser energy. The procedure begins with the introduction coaxial needle to the lesion. A neodymium-doped yttrium aluminum garnet (Nd) laser, emitting light at a wavelength of 1064 nm, then delivers energy via a thin fiberoptic cable [21, 22].

Applications: Laser ablation is typically performed under moderate sedation unless contraindicated. The procedure employs a 21-gauge Chiba needle or a 5.5-French catheter to deliver an optical laser fiber equipped with a flexible diffuser tip [23].

Benefits and Limitations: The primary benefits of laser ablation include its use of smaller, thin-caliber applicators for better control and predictability, and potentially lower procedural costs compared to other ablative methods [22, 23]. However, like RFA, laser ablation can result in tissue charring, which may impair treatment effectiveness. Additionally, laser ablation is not widely practiced, and there is a lack of comprehensive data on its safety and long-term effectiveness. This limited use and evidence contribute to its status as a less frequently employed option in clinical practice.

2.5 Irreversible Electroporation (IRE)

Mechanism: IRE differs from thermal ablation techniques by employing electrical pulses lasting microseconds to milliseconds to induce permanent nanopores in the cell membranes, leading to cell death [24, 25]. Unlike thermal methods, IRE creates a distinct zone of demarcation that specifically targets cell membranes while preserving surrounding tissues.

Applications: During the procedure, image-guided electrodes are placed either within or around the tumor, delivering high-voltage electrical pulses to the targeted area [26]. The procedure is performed under general anesthesia with complete muscle blockade. The patient's electrocardiogram should be synchronized to the IRE device, to prevent dysrhythmias during the intervention.

Benefits and Limitations: IRE is particularly beneficial for treating tumors situated near critical structures such as blood vessels or nerves, where traditional thermal ablation methods, including cryoablation, might pose risks. It is applicable for both primary and metastatic lung tumors, including those unsuitable for surgery or thermal ablation. IRE has been noted for preserving blood vessels and major extracellular matrix components shortly after treatment, and it is associated with increased infiltration of T cells and macrophages, potentially enhancing immune response. Given IRE specifically targets the cell membrane without damaging the extracellular matrix, structures such as bile ducts, blood vessels, and intestines remain intact, allowing for the preservation of their lumen and supporting postprocedural healing and regeneration [26]. However, IRE may not be effective for all tumor types or lesions with significant necrosis or calcification. As a relatively new technique, its safety, long-term outcomes and optimal protocols remain under investigation (Table 1).

In summary, while RFA, MWA, cryoablation, laser ablation, and IRE share the goal of localized tumor destruction, each technique has unique advantages and limitations based on the clinical scenario. Understanding these differences allows for informed decision-making that is tailored to the specific needs of the patient and the characteristics of the tumor, ultimately optimizing treatment outcomes.

3 Patient Selection Criteria for Lung Ablation

Patient selection for lung ablation involves a comprehensive assessment of factors such as tumor size, location, histology, and the patient's overall health. Patients with early-stage NSCLC, who are unsuitable for surgery due to medical conditions or poor lung function, may be candidates for ablation. Similarly, patients with recurrent or metastatic lung tumors, particularly those with oligometastatic disease, may benefit from ablation as a local therapy to control tumor growth and alleviate symptoms, while preserving overall lung capacity.

Considerations in patient selection also encompass tumor accessibility, proximity to critical structures, and concurrent medical conditions that may heighten the risk of complications. Overall, patient selection for lung ablation requires a thorough evaluation by a multidisciplinary team or tumor board to ensure alignment with the patient's needs and treatment goals while optimizing therapeutic outcomes and minimizing risks.

4 Clinical Evidence on the Efficacy of Lung Ablation for Different Lung Lesions

4.1 Lung Ablation for Oligometastatic or Recurrent Tumors

Lung ablation is increasingly recognized as a valuable strategy for managing oligometastatic or recurrent lung tumors. While the 2024 NCCN guidelines prefers resection over locally ablative procedures (e.g., image-guided thermal

Table 1 Comparative analysis of radiofrequency, microwave, cryoablation, laser ablation, and irreversible electroporation techniques in lung treatment

Aspect	Radiofrequency ablation	Microwave ablation	Cryoablation	Laser lung ablation	Irreversible electroporation
Mechanism	Uses electrical currents at 375–500 kHz to generate heat through resistive energy loss	Applies electromagnetic fields (900–2500 MHz) to agitate water molecules, generating heat	Delivers pressurized gas through a cryoprobe, creating extreme cold via the Joule–Thomson effect	Delivers heat from a neodymium-doped yttrium aluminum garnet (Nd) laser emitting 1064 nm light	Uses electrical pulses (microseconds to milliseconds) to create permanent nanopores in cell membranes.
Applications	Small- to medium-sized tumors (<3 cm). May use cooling or infusion to enhance efficacy	Suitable for larger tumors (3–5 cm or more)	Useful for lesions near critical structures. Various freeze–thaw–freeze cycle. Probes placed no more than 2 cm apart	Primarily for small, accessible lung lesions. The smallest access size	Effective for tumors near critical structures
Ideal tumor size	<3 cm	3–5 cm	<3 cm	<2 cm	Variable; depends on tumor size and complexity
Ideal tumor location	Tumors not close to major blood vessels or airways due to potential “heat sink” effect	Effective for difficult-to-reach locations, peripheral rather than central for potential harm for central critical structures	Anywhere. Okay for near vital structures like airways, blood vessels, and bones, where thermal damage is a concern	Accessible small peripheral lesions in the lung	Okay with near critical structures; less suitable for tumors with significant necrosis or calcification
Treatment time	2–20 min per session	Generally quick. 5–30 min, depends on tumor size	25–28 min per cycle. Variable depends on protocols but generally longer than RFA and MWA	Typically, 10–20 min, shorter than other thermal	20–60 min, depending on tumor size and complexity
Benefits	Well-established with FDA approval. Low risk of complications. Shorter recovery time	Can treat larger tumors. Faster ablation time. Provides a larger ablation zone. Not limited by electrically conductive paths	Creates localized freeze zones (better seen on a soft tissue window) with minimal collateral damage. Ice ball visualization. Lower risk of bronchopleural fistula. Less postprocedural pain	Provides precise control with thin-caliber applicators. Potentially lower procedural costs	Nonthermal; Preserves blood vessels and extracellular matrix. May enhance immune response
Limitations	Less effective for larger tumors or those near critical structures. Effectiveness diminishes with tumor size. Potential interference with pacemakers	Higher risk of collateral damage due to broader heat zone. Complicated data by varied device designs	Procedures can be longer compared to RFA and MWA	Can result in tissue charring, which may impair effectiveness. Limited data on long-term outcomes	Not effective for all tumors, especially those with necrosis or calcification. Long-term outcomes and protocols still under investigation

ablation or SBRT), these techniques are still viable options for treating lung oligometastases [2], especially in patients with limited metastatic disease where curative intent remains a viable option. The goal of ablation in this context is to effectively target isolated metastatic lesions or recurrent tumors, potentially improving overall disease control and patient outcomes.

Evidence supporting the use of lung ablation for oligometastatic disease is growing. A study published in 2021 reviewed those patients with oligometastatic NSCLC lung cancer who underwent thermal ablation experienced a significant reduction in tumor burden and improved progression-free survival compared to those receiving conventional treatments [27]. Additionally, research has shown that lung ablation can be an effective treatment modality for metastatic and recurrent tumors, offering a minimally invasive alternative with favorable outcomes and fewer complications compared to repeated surgical interventions [28, 29]. The SOLSTICE trial in 2020 [30] and the ECLIPSE trial in 2021 [31] reported local tumor control rates of 77% at 24 months and 75% at 5 months, respectively.

For oligometastatic and recurrent tumors, the choice of ablation technique depends on factors such as tumor size, location, and accessibility. RFA and MWA are commonly used for treating metastatic lesions due to their ability to generate substantial heat and achieve effective necrosis. Cryoablation is also utilized, particularly when dealing with tumors close to critical structures or when repeated interventions are required. Given the peri-procedural risk of pneumothorax or hemorrhage, it is advisable to treat one lung at a time when feasible. These techniques have proven effective in controlling metastatic or recurrent disease, with studies highlighting their role in achieving local disease control and potentially extending survival. However, further research is needed on patient selection and comparative effectiveness with alternative therapies such as SBRT and surgical resection.

Patients with oligometastatic lung cancer are ideal candidates for ablation if all metastatic sites are amenable to treatment and if curative intent is feasible. In cases of recurrent tumors, ablation offers a viable option for patients with limited pulmonary reserve or those who have previously undergone surgery or radiation therapy. Outcomes for these patients are generally favorable, with studies reporting effective tumor control and improved quality of life. However, careful patient selection and multidisciplinary evaluation are crucial to ensure optimal results and minimize risks.

4.2 Lung Ablation for Solitary Tumors or Multifocal Primary Lung Cancer

Lung ablation is a viable treatment for patients with solitary or multifocal primary lung tumors who are unsuitable for traditional lung resection due to various unfavorable characteristics. It is particularly beneficial for those with early-stage lung cancer who have significant comorbidities or compromised pulmonary function, including conditions such as pulmonary arterial hypertension, very severe obstruction (FEV1 less than 20% predicted), severe hypoxemia, and bronchiectasis. Even patients classified as ASA 4 or higher, who are at increased risk for surgical interventions, can undergo ablation with minimal sedation or local anesthesia, thereby significantly reducing procedural risks. Additionally, patients with a history of poor follow-up and low medical compliance may benefit more from ablation over SBRT, given that ablation typically requires only a single treatment session.

Recent retrospective analyses involving 64 patients have demonstrated comparable outcomes between thermal ablation and sublobar resection. Furthermore, local ablation is advantageous for patients who are medically unfit for more invasive procedures, providing effective tumor control while minimizing the risks associated with extensive surgery [29, 32]. Unlike surgery and radiation therapy, ablation does not lead to a measurable long-term reduction in lung function and does not necessitate the interruption of systemic therapy. Ablation is especially advantageous for treating ground-glass opacity lesions, where defining the target zone can be challenging. It also allows for tissue sampling during the procedure, which can provide crucial pathological information for targeted chemotherapy if needed.

Despite its effectiveness in tumor control and preservation of lung function, further research and long-term studies are essential to refine patient selection criteria and optimize treatment protocols.

4.3 Lung Ablation for Lesions Previously Treated with Radiation Therapy

Lung ablation is increasingly considered for lesions previously treated with radiation therapy, particularly when residual or recurrent tumors are detected. However, caution is warranted, as scar tissue and altered anatomy from prior radiation can complicate the procedure and increase risks. Radiation therapy, while effective for tumor targeting and shrinking tumors, can result in tissue changes such as fibrosis, altered tissue density and traction bronchiectasis, which may affect the precision and safety of ablation procedures. PET/CT imaging can help identify active disease, though radiation-induced hypermetabolic changes may persist for up to 6–9 months after treatment.

Despite these challenges, lung ablation techniques such as RFA, MWA, and cryoablation have demonstrated utility in managing such lesions. A 2015 study analyzed 12 patients with 17 lesions who underwent ablation as salvage therapy for recurrent nonsmall cell lung cancer after radiotherapy. The study found a 23-month local control rate for tumors smaller than 3 cm and a 14-month rate for tumors larger than 3 cm, with minimal morbidity [33]. However, data on lung ablation following radiation therapy remains limited.

Lung ablation serves as a valuable option for patients with recurrent or residual tumors following radiation therapy, offering a minimally invasive approach that can complement ongoing cancer management strategies. Proper follow-up and surveillance are essential for monitoring treatment efficacy and early detection of any complications or recurrence. A structured follow-up plan is essential for assessing the long-term outcomes and ensures timely intervention if issues arise (Table 2).

Table 2 Lung ablation indication, special consideration, and contraindication

Indication	Special consideration	Contraindication
Early-Stage Patients: Lung ablation is a valuable option for early-stage patients who cannot undergo surgery due to medical comorbidities or impaired lung function, often preserving pulmonary function with favorable outcomes **Oligometastatic Tumors**: For oligometastatic lung tumors, where cancer is confined to a few sites, lung ablation offers a localized treatment that can effectively control tumor growth and achieve long-term disease control if all lesions are treatable **Recurrent Tumors**: Lung ablation provides an alternative for managing recurrent lung tumors, especially in patients with limited pulmonary reserve from previous treatments, helping address disease recurrence effectively **Combination Therapy**: Lung ablation can be used alongside other treatments for intermediate-stage lung cancer, such as surgery or radiation, enhancing overall disease management **Oligoprogression**: In advanced lung cancer with oligoprogression, where disease progresses in a few sites while other areas remain stable, lung ablation can target these sites to potentially prolong survival **Palliative Care**: For symptom management in patients with discomfort from lung tumors, lung ablation can alleviate pain and respiratory distress, improving quality of life	**Poor Health Status**: Patients with poor overall health or functional status may face higher risks and complications from lung ablation **Tumor Proximity to Critical Structures**: Tumors near major blood vessels, airways, or the heart may be too risky for ablation, though cryoablation is generally safer near such structures **Severe Pulmonary Hypertension**: Patients with severe pulmonary hypertension may struggle with the changes in blood flow and pressure caused by ablation, increasing cardiovascular risks **Pre-existing Lung Conditions**: Patients with severe COPD, pulmonary fibrosis, or emphysema may face worsened respiratory symptoms or further lung impairment, requiring careful risk assessment	**Inaccessible Tumors**: Tumors in hard-to-reach or poorly visible areas may pose challenges for safe and effective ablation **Uncontrolled Bleeding Disorders**: Patients with bleeding disorders are at higher risk for hemorrhage during or after ablation **Active Infection or Sepsis**: Active systemic infections or sepsis are contraindications for lung ablation due to the risk of worsening infection or causing systemic complications

4.4 Sedation and Patient Positioning

In lung ablation procedures, moderate sedation is frequently used to balance patient comfort with procedural effectiveness. This level of sedation ensures sufficient relaxation and pain management, while maintaining the patient's ability to cooperate throughout the procedure, especially RFA and MWA can be quite painful. The exception is IRE, which again requires general anesthesia with complete muscle blockade and electrocardiogram synchronization. Patient positioning is crucial for optimal imaging visibility and access to the lesion. Typically, patients are placed in either a lateral decubitus or supine position, depending on the location of the tumor. Proper positioning enhances procedural precision and minimizes both stress and discomfort for the patient. When positioning a patient in the lateral decubitus position, the general practice is to position the nonintervened lung superiorly. This approach helps protect the healthy lung in the event of complications such as hemorrhage. However, positioning should be tailored to the specific characteristics of the target lesion to ensure the best possible outcome.

5 Complications of Lung Ablation

Despite its minimally invasive nature, lung ablation is associated with several risks. Incomplete ablation may result in tumor recurrence, necessitating careful monitoring and potential re-treatment. Biopsy is often performed concurrently with lung ablation, but care must be taken to avoid peri-lesional hemorrhage, which can obscure the target and complicate the procedure. Pneumothorax is a common complication; however, symptomatic or large pneumothorax can be effectively managed with prompt drainage. Since postprocedural chest tube placement is standard in lung resections, pneumothorax should be anticipated as part of the procedural course rather than an unexpected event. Intentional pneumothorax may be created when ablation is performed near critical structures to elevate the lesion and ablation zone away from these structures. Hemoptysis, though possible, is typically managed through supportive care and stabilization. Diaphragm injury, another potential complication, can be mitigated with precise techniques and accurate imaging. Bronchopulmonary fistula formation, particularly associated with RFA and MWA, is rare but requires diligent monitoring and may necessitate additional interventions. Systemic air embolism, although extremely rare, has the potential to cause end-organ ischemia, such as stroke or myocardial infarction. Early detection and appropriate management generally prevent severe outcomes. Pulmonary artery pseudoaneurysm, though infrequent, represents a serious complication that requires immediate intervention. Injury to adjacent critical structures, such as major blood vessels or the heart, is also a risk. Employing techniques like cryoablation or IRE and utilizing vigilant imaging can help mitigate these risks. Additionally, meticulous technique and protective measures are essential to prevent skin injury during the procedure.

6 Conclusion

In summary, percutaneous image-guided lung ablation offers a promising treatment option for managing various types of lung tumors, including solitary, oligometastatic, and recurrent lesions. With techniques such as RFA, MWA, cryoablation, and IRE, clinicians can tailor interventions to individual patient needs and tumor characteristics, improving outcomes and minimizing risks. While challenges such as patient selection, procedural complications, and posttreatment monitoring remain, ongoing advancements in technology and technique continue to enhance the efficacy and safety of lung ablation. Future research and clinical developments are expected to further refine these approaches, optimizing patient care and expanding the potential benefits of this therapeutic modality.

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