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Advances in Local Ablation Strategies for Treating Non-Small Cell Lung Cancer: A Systematic Review and Meta-Analysis

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A R T I C L E I N F O

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A B S T R A C T

Lung cancer represents foremost cause of cancer-related mortality globally. Non-small cell lung cancer (NSCLC) is the most prevalent, over 85% of all lung cancer diagnoses. The literature search was performed through databases including PubMed, Scopus, Web of Science, and ScienceDirect up to September 2025. In adverse events after both procedures including pneumothorax, bronchopulmonary hemorrhage, hemoptysis, and pleural effusion events between CA and MWA group were not significant reported (p = 0.97).. CA and MWA showed comparable effectiveness due to its minimally invasiveness, providing similar response for early and advanced-stage in NSCLC with small tumor size (<3 cm). Both procedures also offered minimizing adverse events. However, CA was a longer hospitalization than MWA.

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INTRODUCTION

Lung cancer continues to be the foremost cause of cancer-related deaths globally. Non-small cell lung cancer (NSCLC) represents about 85% of all lung cancer cases, while small cell lung cancer constitutes the remaining 15%. Among NSCLC subtypes, adenocarcinoma accounts for roughly 78% and squamous cell carcinoma for about 18%. Unfortunately, nearly 25% of patients with stage I NSCLC are ineligible for surgical treatment due to significant comorbid conditions, such as impaired cardiopulmonary function. Moreover, prior studies have indicated that perioperative complication rates following lobectomy in elderly NSCLC patients can exceed 50%.

The latest global epidemiological data reveal that lung cancer leads cancer-related deaths among 36 major types and ranks as the second most commonly diagnosed cancer worldwide. In 2020, across 185 countries, about 2,206,771 new lung cancer cases were identified (accounting for 11.4% of all cancers), with 1,796,144 deaths (18.0%). In Southeast Asia, lung cancer was the third most frequent cancer cases as 185,636 new cases, but it was the top cause of cancer mortality, resulting in 166,260 deaths (10.9%). In Indonesia, lung cancer is the third most common cancer after breast and cervical cancers, representing 8.8% of cases but causing the highest cancer death rate at 13.2% (30,843 deaths). Additionally, lung cancer causes about one-third of all male cancer deaths, being the most prevalent cancer in men and the fifth most common in women. Most lung cancer patients tend to be elderly with multiple health conditions, necessitating less invasive and shorter surgeries to lower postoperative risks. While lobectomy remains the preferred standard for early-stage NSCLC, other treatment approaches are required, such as thermal ablation.

Thermal ablation, a minimally invasive local treatment, eliminates tumor cells by applying extreme heat or cold through probes guided by imaging technologies like CT scans. The primary methods include radiofrequency ablation (RFA), microwave ablation (MWA), and cryoablation (CA). This technique offers survival rates similar to stereotactic body radiation therapy (SBRT) for patients who cannot undergo surgery, while maintaining lung function, making it particularly useful for patients with poor lung capacity or those needing repeated treatment. Although thermal ablation is gaining traction as an alternative for inoperable lung cancer, the comparative effectiveness and safety between methods like MWA and cryoablation are still unclear. Some studies suggest that MWA provides superior local control, particularly for larger lesions, with shorter procedural times, whereas cryoablation may offer the advantage of fewer complications, particularly in lesions adjacent to critical structures. However, the current evidence is sparse and varied. Thus, this study aims to systematically review and meta-analysis existing data to compare the effectiveness and safety of MWA versus cryoablation in lung cancer patients, offering clearer guidance for selecting the best ablation technique.

The adoption of advanced interventions such as CA and MWA has expanded, yet their comparative effectiveness and safety remain uncertain. Published studies report heterogeneous and sometimes conflicting results for key outcomes including overall survival (OS), hospital length of stay (HLoS), and procedure-related adverse events. Furthermore, comprehensive and high-quality analyses that aggregate comparative data remain scarce To provide a clearer understanding, this meta-analysis was conducted to systematically evaluate and compare the outcomes of CA and MWA, with the goal of providing clearer evidence to support treatment selection.

THEORETICAL REVIEW

Lung cancer is one of the most commonly diagnosed cancers worldwide and remains a major cause of death related to cancer. It is generally categorized into two main types: small cell lung cancer (SCLC) and non-small cell lung cancer (NSCLC). Among these, NSCLC represents about 80–90% of all lung cancer cases. Adenocarcinoma, arising from mucus-secreting cells in the airways, accounts for roughly 40% of NSCLC cases. Squamous cell carcinoma, strongly linked to smoking, makes up 25–30%, while large cell carcinoma, characterized by its undifferentiated appearance under the microscope, constitutes 10–15%. In Europe, over 470,000 new lung cancer diagnoses cases occurred in 2018 (with 312,000 in men and 158,000 women). Higher incidence rates are usually observed in developed nations, reflecting differences in tobacco use among populations.

With the increasing proportion of elderly patients and the frequent presence of comorbidities, treatment strategies for NSCLC have progressively evolved. Although lobectomy remains the gold standard, less invasive methods such as wedge resection, thermal ablation, and stereotactic body radiation therapy (SBRT) have been developed. Thermal ablation offers a promising localized treatment for early-stage NSCLC patients who cannot undergo surgery or curative radiotherapy. Research indicates that percutaneous techniques like microwave ablation (MWA) and radiofrequency ablation (RFA provide favorable local control for small lesions (≤2 cm) with minimal parenchymal damage. Data from the SEER database demonstrated that for tumors <1 cm, thermal ablation achieved overall and cancer-specific survival rates comparable to wedge resection, supporting its role as a potentially curative alternative in inoperable patients. Furthermore, recent meta-analyses suggest that thermal ablation provides local control and survival outcomes competitive with SBRT, particularly in patients with radioresistant histologies such as colorectal carcinoma or sarcoma metastases to the lung.

There are currently three main thermal ablation methods: cryoablation, MWA, and RFA. Cryoablation applies rapid cooling with argon or nitrogen gases, achieving tissue temperatures as low as -160 °C. This results in the formation of intracellular ice crystals and osmotic shock, ultimately causing cell death. Cryoablation is particularly advantageous near central airways or major vessels and is associated with stronger immunogenic effects, making it an attractive option for combination with immunotherapy. MWA generates heat with electromagnetic waves (900–2,500 MHz), allowing for larger and more uniform ablation zones less affected by tissue properties, making it better suited for larger tumors or those adjacent to vessels. RFA uses high-frequency alternating current to produce heat and cause tissue necrosis, though its efficacy may be reduced by the poor lung electrical conductivity and the heat-sink effect near large blood vessels.

The National Comprehensive Cancer Network (NCCN) guidelines support image-guided thermal ablation (IGTA) for NSCLC lesions smaller than 3 cm, as larger tumors have higher chances of local recurrence and complications. This method is indicated for selected cases, such as stage IA NSCLC, multiple primary lung tumors, or local recurrences causing symptoms. Pneumothorax is a common side effect after IGTA, especially when multiple tumors are treated simultaneously, occurring in 18.7% to 45.7% of patients. Mild pneumothorax that does not require chest tube insertion is considered an expected outcome rather than an adverse event. However, around 20.7% of cases need chest tube placement to manage more severe pneumothorax.

The aim of this research was to identify which treatment approach yields better results for patients diagnosed with NSCLC. The review followed the PRISMA guidelines established in 2020. A comprehensive search was conducted across PubMed, ScienceDirect, Web of Science, and Scopus databases up to September 2025. Data analysis was performed using RevMan version 5.4.

METHODOLOGY

This meta-analysis complied with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework. The study protocol was registered in the International Prospective Register of Systematic Reviews (PROSPERO) with the registration number CRD420251154537.

Literature Searching and Screening

The search strategy utilized specific terms to identify relevant studies concerning R.D.P.W and J.O.B: ((lung neoplasm) OR (lung carcinoma) OR (non-small-cell-lung) OR (NSCLC)) AND ((cryoablation) OR (cryotherapy) OR (cryosurgery)) AND ((microwaves) OR (radio waves) OR (microwave radiation)). Initially, titles and abstracts were independently screened to identify eligible studies, followed by a detailed evaluation of the full-text articles.

Eligibility Criteria

The selection of studies commenced with examining the titles and abstracts of full-text articles according to the established inclusion and exclusion criteria. The studies were subsequently reviewed and assessed by all two authors (R.D.P.W and J.O.B) to evaluate their eligibility. The authors reviewed the titles and abstracts of all retrieved studies according to the specified eligibility criteria:

(1) Primary lung cancer with or w/o metastasis
(2) NSCLC subtypes: adenocarcinoma and squamous cell carcinoma
(3) All genders (male and female)
(4) All stages of NSCLC (stage I-IV)
(5) Studies reporting at least two of the outcomes of interest
(6) English language full-text

This study excluded small cell lung cancer (SCLC), lung carcinoid, mesothelioma, sarcoma, duplicate publication, using data from non-human studies (animal), review articles, case reports, and foreign language.

Data Extraction and Quality Assessment

Two investigators (R.D.W.P. and J.O.B) used a pre-established table to extract data for the included studies. A third author (N.T.A) addressed disagreements. Following data comprised general study information and comprehensive: author, publication year, region, study range, study design, age, gender, sample size, tumor type, size, location, pulmonary lobes, stage of lung cancer, and clinical outcomes including overall survival rates and adverse events such as pneumothorax, bronchopulmonary hemorrhage, hemoptysis, pleural effusion. The quality of the studies was assessed using the Newcastle-Ottawa Scale (NOS) assessment tool. Quality ratings were reviewed as good, adequate, or poor.

Data Synthesis and Statistical Analysis

A meta-analysis was performed employing standard methodologies. Due to the considerable variability among studies stemming from differing research method sand participant characteristics, we employed random effects to pool the data for each outcome. Both fixed-effect and random-effects meta-analysis models were utilized to combine study specific estimates and their confidence intervals (CIs) using the inverse variance technique for all outcomes. Meta-analyses were performed only when at least two studies provided comparable data for each outcome. Th results included 95% CIs and p-values. Forest plots were generated using RevMan version 5.4.1. Heterogeneity was measured using the I^2 statistic, which ranges from 0% to 100%. A p-value below 0.05 was considered indicative of statistical significance. Publication bias was evaluated through funnel plot analysis.

RESULTS

Study selection

The keyword search initially identified 991 studies. After removing duplicates and screening titles and abstracts, 12 articles were selected for full review. Following the exclusion of five irrelevant studies, data from seven studies were ultimately included. The selection process is detailed in the PRISMA flow diagram provided **(Fig. 1)**.

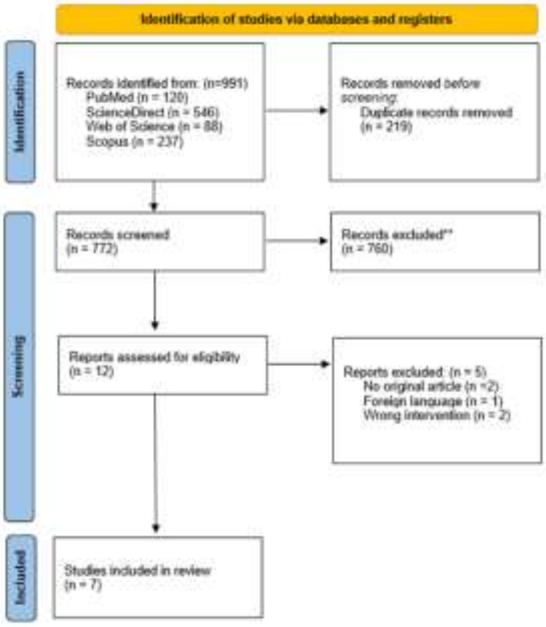


Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses flow diagram

Quality of assessment

Seven retrospective studies were appraised using the Newcastle-Ottawa Scale (NOS), which assesses eight criteria across three domains: selection of patients, comparability between groups, and outcome measurement. Studies scoring between 7 and 9 were classified as high quality, 4 to 6 as moderate quality, and 0 to 3 as low quality. Any disagreements in scoring were resolved by consensus discussion.

Study characteristics

This review included seven retrospective cohort studies involving 209 patients in the cryoablation (CA) group and 48 patients in the microwave ablation (MWA) group. The majority of studies were conducted in China, with two studies originating from Germany and the United States.

Overall survival (OS) rates refer to the time span from diagnosis or treatment initiation until death by any cause in patients with diseases such as non-small cell lung cancer. It is a primary clinical endpoint that reflects the effectiveness of treatments in prolonging a patient life. In this context is more focused in 1,2,3-years OS rates in non-small cell lung cancer patient after procedures. OS will be assessed as a percentage rate. Hospital length of stay (HLOS) indicates the total days a patient remains hospitalized and serves as an indicator of treatment costs and healthcare system efficiency. It may also reflect hospital unit performance, patient throughput, and morbidity that should be interpreted cautiously since multiple factors can affect hospitalization duration. HLOS will be assessed as a day. Adverse event is unintended physical injuries caused or worsened by medical interventions that necessitate additional monitoring, treatment, hospital admission, or result in death. In this context is more focus on after procedure adverse events after cryoablation and microwave ablation (pneumothorax, bronchopulmonary hemorrhage, pleural effusion) that reflects as a safety for patient. HLOS will be assessed as a nominal.

Table 1. Characteristics of included studies

Author	Country	Study design	Study range	Group		Age		Gender		Tumor type		Tumor site (side)		Tumor Size	
				CA	MWA	Cryo	MWA	Male	Female	Primary	Metastasis	Left	Right	CA	MWA
Li[4]	China	R	2014 - 2018	19	29	60.9±7.4	58.5±7.8	34	14	33	15	8	40	<3cm: 1.88±0.39 >3cm: 3.1±0.14	<3cm: 2.11±0.37 >3cm: 3.46±0.52
Fintelmann[24]	Germany	R	2004 - 2023	16	8	78.6±9.4	79±3.1	14	10	N/A	N/A	0	23	N/A	N/A
Das[10]	China	R	2011 - 2016	45	56			60	41	N/A	N/A	35	64	N/A	N/A
Nan[16]	China	R	2020 - 2023	42	42	66.7±11.2	65.1±11.0	44	40	N/A	N/A	N/A	N/A	N/A	N/A
Wang[12]	China	R	2023 - 2024	23	64	70.9±12.7	72.9±7.4	40	47	N/A	N/A	N/A	75	1.87±0.92	1.85±0.69
Zhang[9]	China	R	2015 - 2020	35	33	55.2±8.8	56.3±8.5	48	20	N/A	N/A	28	40	3.1 ± 0.5	2.9 ± 0.6
Wroble[21]	USA	R	2006 - 2020	29	16	65±6.1	58±9.9	21	24	7	38	N/A	N/A	N/A	N/A

***R**; Retrospective study, **CA;** Cryoablation, **MWA;** Microwave Ablation, **N/A;** Not Available*

Author	Pathology		Lung Zone		Lobe					Stage				Prior treatment		
	SCC	ADC	Central	Peripheral	Left Upper	Left Lower	Right Upper	Right Middle	Right Lower	I	II	III	IV	Chemo	Rad	Res
Li[4]	7	26	8	40	N/A	N/A	N/A	N/A	N/A	33		15		36	10	11
Fintelmann[24]	N/A	N/A	0	23	12	3	7	1	10	29	4	N/A	N/A	N/A	6	5
Das[10]	25	76	31	70	N/A	N/A	N/A	N/A	N/A	N/A	N/A	59	42	N/A	N/A	N/A
Nan[16]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	19	21	36	21	16	6	N/A
Wang[12]	N/A	77	N/A	75	30	13	30	N/A	14	81	N/A	N/A	N/A	N/A	N/A	N/A
Zhang[9]	32	36	N/A	N/A	N/A	N/A	N/A	N/A	N/A	22	30	16	N/A	31	N/A	N/A
Wroble[21]	2	7	7	31	13	14	15	1	16	N/A	N/A	N/A	N/A	N/A	N/A	N/A

***SCC;** Squamous Cell Carcinoma, **ADC;** Adenocarcinoma, **Chemo;** Chemotherapy, **Rad;** Radiation, **Res;** Resection*

Patient Characteristics

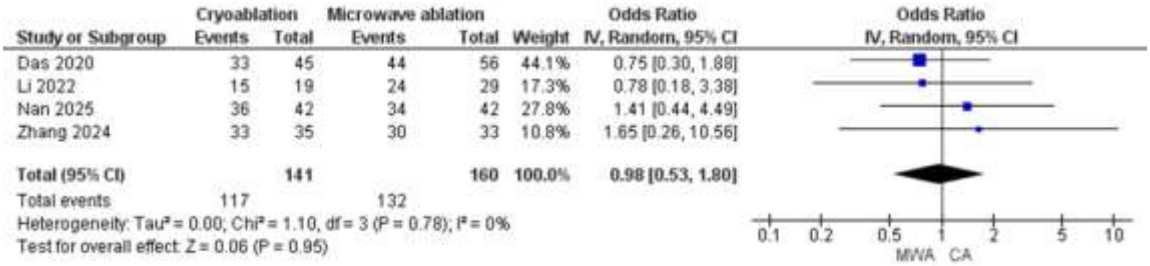
The mean age of patients in seven included studies was 68.13±11.02, with a total of 457 patients. Most patients who received treating NSCLC were male (57.1%). Only two studies differentiated the primary (n=40) and metastasis (n=53).[4,21] Based on pathology of NSCLC, adenocarcinoma (ADC) also is the most common subtype (48.57%) meanwhile squamous cell carcinoma (SCC) (14.4%). For tumor stage in NSCLC, I-II stage (52.29%) was frequently reported than III-IV stage (41.3%). The tumors were commonly located in the upper and middle lobes of the lungs (23.80%). Overall tumor size diameters are 2.43±0.86 cm.

Clinical Outcomes

Effects of intervention

1-year OS rates. Four studies[4,9,10,16] evaluated 1-year Overall Survival (OS) rates following cryoablation (CA) and microwave ablation (MWA) in patients with NSCLC. The pooled OS rates were 82.9% for CA and 82.5% for MWA. Meta-analysis using a random-effects model revealed no significant difference between the two techniques (OR = 0.98, 95% CI: 0.30–1.80, p = 0.95; I^2 = 0%).

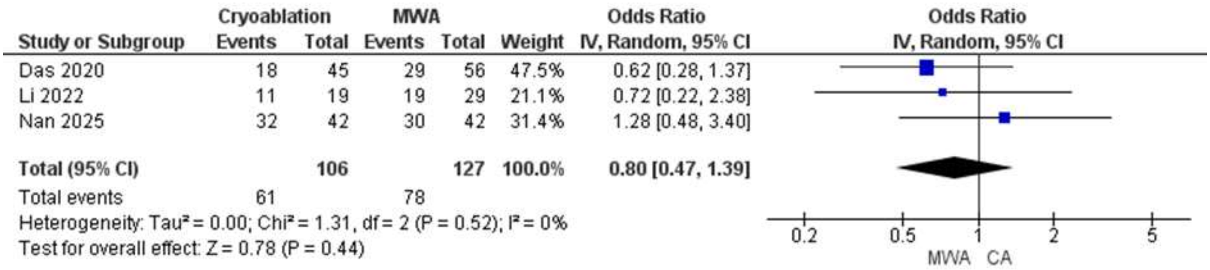
Table. 2 Forest plot of overall survival rates (OS) one year after Cryoablation (CA) vs. Microwave Ablation (MWA).



The subgroup was not significant (p= 0.95). The odd ratio (OR) described as a solid square, the horizontal lines depict the 95% confidence intervals (CIs), and the diamond represents the pooled mean difference. I-V, inverse variance

2-years OS rates. Three studies[4,10,16] evaluated 2-years year Overall Survival (OS) rates following cryoablation (CA) and microwave ablation (MWA) in patients with NSCLC. The pooled OS rates were 57.5% for CA and 61.4% for MWA. Meta-analysis using a random-effects model revealed no significant difference between the two techniques (OR = 0.80, 95% CI: 0.47–1.39, p = 0.44; I^2 = 0%).

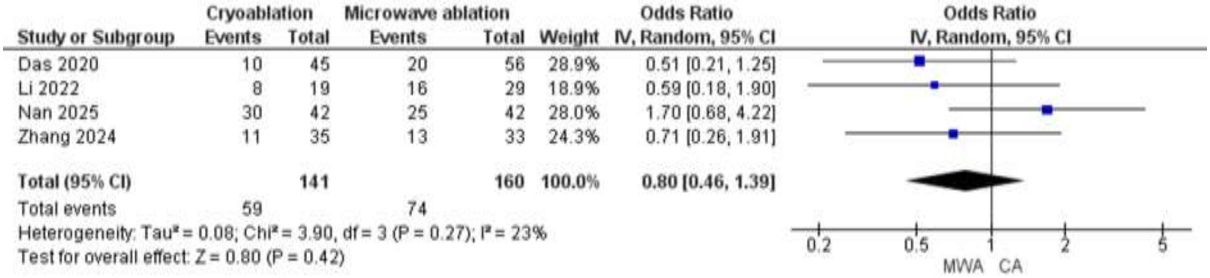
Table. 3 Forest plot of overall survival rates (OS) two years after Cryoablation (CA) vs. Microwave Ablation (MWA).



The subgroup was not significant (*p*= 0.44). The odd ratio (OR) described as a solid square, the horizontal lines depict the 95% confidence intervals (CIs), and the diamond represents the pooled mean difference. *I-V*, inverse variance

3-year OS rates. Four studies evaluated 3-years year Overall Survival (OS) rates following cryoablation (CA) and microwave ablation (MWA) in patients with NSCLC. The pooled OS rates were 41.8% for CA and 46.2% for MWA. Meta-analysis using a random-effects model revealed no significant difference between the two techniques (OR = 0.80, 95% CI: 0.46–1.39, p = 0.42; I^2 = 0%).

Table. 4 Forest plot of overall survival rates (OS) three years after Cryoablation (CA) vs. Microwave Ablation (MWA).



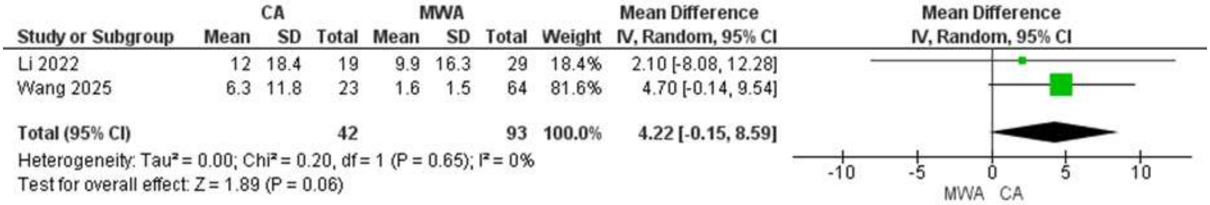
Study or Subgroup	Cryoablation Events	Cryoablation Total	Microwave ablation Events	Microwave ablation Total	Weight	Odds Ratio IV, Random, 95% CI
Das 2020	10	45	20	56	28.9%	0.51 [0.21, 1.25]
Li 2022	8	19	16	29	18.9%	0.59 [0.18, 1.90]
Nan 2025	30	42	25	42	28.0%	1.70 [0.68, 4.22]
Zhang 2024	11	35	13	33	24.3%	0.71 [0.26, 1.91]
Total (95% CI)		**141**		**160**	**100.0%**	**0.80 [0.46, 1.39]**
Total events	59		74			

Heterogeneity: $Tau^2 = 0.08$; $Chi^2 = 3.90$, df = 3 (P = 0.27); $I^2 = 23\%$
Test for overall effect: Z = 0.80 (P = 0.42)

The subgroup was not significant (p= 0.44). The odd ratio (OR) described as a solid square, the horizontal lines depict the 95% confidence intervals (CIs), and the diamond represents the pooled mean difference. *I-V*, inverse variance

Hospital Length of Stay (HLOS). Two studies reported hospital length of stay (HLOS) after cryoablation (CA) and microwave ablation (MWA) for NSCLC patients. The pooled mean difference showed that cryoablation was a longer of HLOS in 4.22 days (95% CI: –0.15 to 8.59), no statistically significant difference reported (p = 0.06).

Table. 5 Forest plot of hospital length of stay (HLOS) after Cryoablation (CA) vs. Microwave Ablation (MWA).



Study or Subgroup	CA Mean	CA SD	CA Total	MWA Mean	MWA SD	MWA Total	Weight	Mean Difference IV, Random, 95% CI
Li 2022	12	18.4	19	9.9	16.3	29	18.4%	2.10 [-8.08, 12.28]
Wang 2025	6.3	11.8	23	1.6	1.5	64	81.6%	4.70 [-0.14, 9.54]
Total (95% CI)			**42**			**93**	**100.0%**	**4.22 [-0.15, 8.59]**

Heterogeneity: $Tau^2 = 0.00$; $Chi^2 = 0.20$, df = 1 (P = 0.65); $I^2 = 0\%$
Test for overall effect: Z = 1.89 (P = 0.06)

The subgroup was not significant (p= 0.06). The odd ratio (OR) described as a solid square, the horizontal lines depict the 95% confidence intervals (CIs), and the diamond represents the pooled mean difference. *I-V*, inverse variance

Adverse events

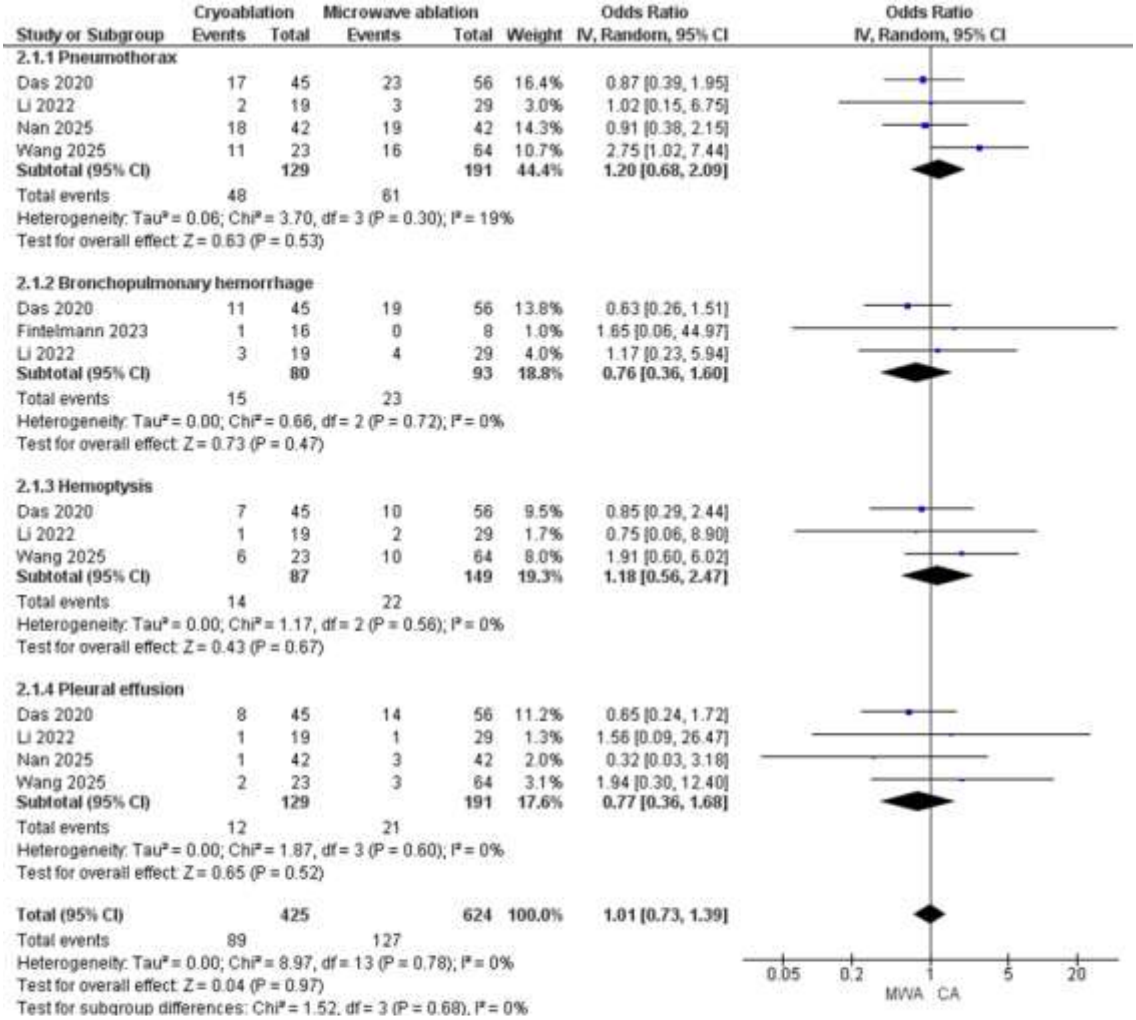
Pneumothorax. Four included studies reported clinical findings related to pneumothorax events during the procedure. The overall incidence of pneumothorax was 37.20% after CA and 31.93% after MWA. A meta-analysis using a random-effects model revealed not statistically significant for both procedure (OR 1.20, 95% CI 0.68 – 2.09, p = 0.53, I^2 = 19%) **(Fig. 6)**.

Bronchopulmonary hemorrhage. Three included studies[4,10,24] reported that bronchopulmonary hemorrhage events after the procedure were 18.75% for CA and 24.73% for MWA. Pooled analysis showed not significant difference between both procedures (OR 0.76, 95% CI 0.36 – 1.60, p = .47, I^2 = 0%).

Hemoptysis. Three included studies reported hemoptysis events were found 16.09% patients in the CA group and 14.76% MWA group. A meta-analysis showed not statistically significant differences for both procedures (OR 1.18, 95% CI 0.56 – 2.47, p = .67, I^2 = 0%).

Pleural effusion. Four included studies on pleural effusion events after treating NSCLC showed not significant differences between the CA and MWA groups (OR 0.77, 95% CI 0.36 – 1.68, p = .52, I^2 = 0%). Pleural effusion events found 9.30% for CA group and 10.99% MWA group, respectively.

Table. 6 Forest plot results of adverse events comparing Cryoablation (CA) vs Microwave Ablation (MWA) regarding pneumothorax, bronchopulmonary hemorrhage, hemoptysis, pleural effusion events.



The solid squares indicate the odd ratio (OR), the horizontal lines depict the 95% confidence intervals (CIs), and the diamond represents the overall pooled ratio. *I-V*, inverse variance

DISCUSSION

Efforts to expand the range of treatable cancers while simultaneously advancing minimally invasive techniques for tumor tissue destruction have driven the development of several novel ablative modalities. These methods are particularly designed for unresectable primary or secondary carcinomas, achieving local control by inducing in situ coagulative necrosis. Over the past two decades, several technologies have been developed for thermal ablation with the most commonly applied being cryoablation (CA), microwave ablation (MWA) and radiofrequency ablation (RFA). These approaches have gained recognition as safe, minimally invasive, and cost-effective treatment alternatives for patients who are not suitable candidates for surgery. In this review, we are more focus on comparing cryoablation and microwave ablation for treating non-small cel lung cancer (NSCLC)

Cryoablation induces tumor destruction through both direct and indirect mechanisms during cycles of freezing and thawing. Direct injury occurs at temperatures near −20 °C, where protein denaturation and membrane disruption cause irreversible cell death. Repeated freeze–thaw cycles amplify this damage by forming intracellular and extracellular ice crystals, while vascular occlusion, osmotic shifts, and edema contribute to hypoxia and coagulative necrosis. In the lung, the predominance of air in alveolar structures may hinder ice ball formation; however, this can be mitigated by an initial freeze–thaw cycle that replaces air with fluid and hemorrhage, thereby increasing local thermal conductivity and improving ablation efficacy. Meanwhile, microwave ablation generally functions within a frequency range of 915 MHz to 2.45 GHz, with 2.45 GHz being the most applied. Microwave ablation achieves tissue necrosis through rapid heating driven by dielectric hysteresis. Polar molecules such as water continuously realign with the applied microwave field, generating kinetic energy and raising tissue temperatures that can exceed 150 °C. Unlike energy modalities dependent on tissue conductivity, MWA penetrates tissues with low conductivity, including aerated lung and desiccated tissue, while the high probe-tip temperatures enhance heat diffusion and expand the ablation zone. The energy delivery allows for more rapid tissue heating and the creation of larger ablation zones, offering particular benefits in the management of larger lesions or multiple tumors.

Previous research indicated that tumor size is a key predictor of recurrence following ablation, with lesions larger than 3 cm having a higher likelihood of incomplete ablation. The cutoff point used to classify tumor as small or large differed among previous studies, as it was based on the maximum tumor size reported in each study. In a recent clinical study by Nomori et al. on early-stage NSCLC treated with cryoablation, the maximum tumor diameter was 3.5 cm, and recurrences were predominantly observed in patients whose tumor exceeded 1.8 cm in diameter. However, previous clinical studies using cryoablation treated lesions with largest diameter of less than 8 cm. MWA is a reliable method for treating malignant lung tumors smaller than 4 cm[15]. According to the recent studies, no NSCLC lesions >6 cm have been treated with MWA. This may be due to the notion that ablation of very large lesions may not be able to obtain complete tumor necrosis. One notable advantage of MWA is its ability to manage larger tumors through the simultaneous use of multiple antennae with electromagnetic microwaves produce thermal energy that causes coagulative necrosis of neoplastic cells and the surrounding parenchyma. In such cases, the initial session often results in partial tumor necrosis and appropriately selected patients, a repeat MWA procedure can be performed to enhance disease control. Thermal ablation has also shown effectiveness in patients with recurrent solitary lesions following prior local therapies (such as radiotherapy or surgery) and in those with a single lung. Nonetheless, optimal outcomes require the primary tumor to be under 3 cm in diameter and absence of nodal or distant metastases.

In a recent study reported that cryoablation achieved 2 and 3-years overall survival (OS) rates of 88% at both 2 and 3 years and for MWA at 1, 2, and 3 years were 89%, 63%, 43%, respectively, with tumors ≤3.5 cm showing more good survival outcomes compared to those >3.5 cm. Another study, with 1840 patients, reported that average overall survival (OS) rate in 1,2,3 years for CA was 86.5%, 73.5%, and 71.2% and MWA was 82.5%, 54.6%, 35.7%, respectively. Chan et al. study reporterd for the primary lung adenocarcinoma subgroup, overall survival was 83.6%, 74.9%, and 74.9%. Two prospective multi-center trials, SOLSTICE and ECLIPSE, demonstrated good local control outcomes with CA for metastatic lung cancer. In the SOLSTICE trial, involving 224 patients, OS rates were 97.6% at 1 year and 86.6% at 2 years, with local tumor control rates of 85.1% and 77.2% after the first CA. Similarly, the ECLIPSE trial reported 3- and 5-year local control rates of 87.9% and 79.2%, alongside overall survival rates of 63.2% and 46.7% in 60 patients treated with CA. Two study conducted MWA in 54 patients with primary and metastatic lung cancer, reporting overall survival rates of 98.0% at 1 year and 71.3% at 2 years suggesting that MWA is a safe, effective, repeatable option for treating primary and metastatic malignant lung cancer. All prior studies conducted similar results for present study in meta-analysis results showed OS rates in 1,2,3 years were 82.9%, 57.5%, 41.8% for CA meanwhile 82.5%, 61.4%, 46.2% for MWA, however no significant difference between both procedures that indicate both procedures are effective and viable treatment options for managing primary and metastatic lung cancer.

For patients with tumors ≤3.0 cm, there was no significant difference in OS rates between the two techniques. However, among those with tumors >3.0 cm, MWA demonstrated notably better OS than CA, likely attributable to its capacity to generate a larger ablation zone. However, MWA may be less suitable for centrally located tumors, especially those adjacent to hilar structures, major vessels, or airways, due to the heat sink effect limiting efficacy.The effectiveness of MWA decreases when the lesion size exceeds 3 cm. Consequently, larger or irregularly shaped tumors often require multipoint, multineedle, or high-energy ablation, which may lead to a higher risk of complications. In a review study reported excellent outcomes with CA in stage I NSCLC, showing 1- and 3-year overall survival rates of 100% and 63%, respectively, in a cohort of 25 patients. However, tumors larger than 3 cm demonstrated a higher risk of local progression. Similar with study, using liquid nitrogen cryoablation for T1N0M0 NSCLC, found local recurrence in 10 out of 101 patients, though no recurrences were observed in tumors smaller than 1.2 cm, suggesting that tumor size plays a critical role in local disease control. The primary tumor type, disease-free interval and having more than three lung metastases were also important influencing factors. Those factors had the greatest impact on overall survival were the presence of extrapulmonary metastases and a maximum tumor size exceeding 15 mm. Candidates for ablative therapy should present with no more than four lesions per lung and each measuring less than 3.5 cm in diameter. Additionally, percutaneous lung ablation can be considered as a salvage option for local recurrence after prior radiation therapy. Tumor size remained the strongest predictor of treatment success, with incomplete ablation more common in lesions larger than 3 cm.

A recent study reported that cryoablation achieved overall survival (OS) rates of 88% at both 2 and 3 years, while MWA yielded OS rates of 89%, 63%, and

43% at 1, 2, and 3 years, respectively, with better survival seen in tumors 3.5 cm or smaller compared to larger ones. Another large study involving 1,840 patients found that the average OS rates for cryoablation at 1, 2, and 3 years were 86.5%, 73.5%, and 71.2%, whereas for MWA they were 82.5%, 54.6%, and 35.7%. Chan et al. study reported OS rates of 83.6%, 74.9%, and 74.9% in patients with primary lung adenocarcinoma. Two multi-center prospective trials, SOLSTICE and ECLIPSE, demonstrated favorable local control with cryoablation in metastatic lung cancer. The SOLSTICE trial, including 224 patients, showed 1- and 2-year OS rates of 97.6% and 86.6%, with local tumor control rates of 85.1% and 77.2% after initial cryoablation. The ECLIPSE trial reported local control rates of 87.9% and 79.2% at 3 and 5 years, along with OS rates of 63.2% and 46.7% in 60 cryoablation-treated patients. Two studies involving 54 patients treated with MWA for primary and metastatic lung cancer reported 1- and 2-year OS rates of 98.0% and 71.3%, supporting MWA as a safe, effective, and repeatable option for these conditions. These findings align with the present meta-analysis showing 1-, 2-, and 3-year OS rates of 82.9%, 57.5%, and 41.8% for cryoablation, and 82.5%, 61.4%, and 46.2% for MWA, with no significant difference between the two, indicating both are viable treatments for primary and metastatic lung cancer.

For tumors 3.0 cm or smaller, survival outcomes did not differ significantly between cryoablation and MWA. However, for tumors larger than 3.0 cm, MWA showed superior overall survival, likely due to its ability to create a larger ablation area.[11] Despite these, MWA might be less appropriate for centrally located tumors near key hilar structures or major vessels and airways, as the heat sink effect can reduce its effectiveness. The advantages of MWA diminish with tumors exceeding 3 cm, often necessitating complex techniques such as multipoint or high-energy ablation, which may increase the risk of complications. A review reported excellent results for cryoablation in stage I NSCLC, with 1- and 3-year OS rates of 100% and 63% in a group of 25 patients; however, tumors larger than 3 cm faced higher risks of local progression. Another study using liquid nitrogen cryoablation in T1N0M0 NSCLC found local recurrence in 10 of 101 patients, with no recurrences in tumors smaller than 1.2 cm, highlighting tumor size as a key factor in local control. Additional important factors influencing survival include the primary tumor type, disease-free interval, and having more than three lung metastases. The greatest negative impact on overall survival came from extrapulmonary metastases and tumors larger than 15 mm. Suitable candidates for ablation typically have no more than four lesions per lung, each measuring less than 3.5 cm. Percutaneous lung ablation may also serve as a salvage therapy for local recurrence following radiation. Tumor size remains the strongest predictor for treatment success, with incomplete ablations occurring more frequently in tumors over 3 cm.

Abrishami et al study showed the mean hospital stay was significantly shorter with CA, averaging 1.21 days, compared with 1.90 days for MWA, highlighting a notable reduction for CA in length of hospitalization. A cross-sectional study reported CA was linked to a significantly shorter hospitalization compared with MWA, with median stays of 1 day (1–1 days) vs. 2 days (1–3 days), respectively.[44] Meanwhile in present study presented for hospital length of stay

(HLOS), CA was a longer hospitalization than MWA with averaging 4.22 days but no statistically significant reported.

In our meta-analysis, pneumothorax was the most frequently reported complication following both cryoablation (CA) and microwave ablation (MWA) for NSCLC. The pooled incidence was slightly higher in CA (37.2%) compared with MWA (31.9%), but this difference was not statistically significant (OR 1.20, 95% CI: 0.68–2.09, $p = 0.53$). Heterogeneity was low ($I^2 = 19\%$), indicating consistency among the included studies. These findings align with previous reports that pneumothorax is the predominant complication of percutaneous lung ablation. Laeseke et al. further demonstrated that ablation techniques are more prone to acute, procedure-related complications, whereas SBRT is associated with delayed radiation-induced toxicities. Liu et al. also reported pneumothorax as the most frequent complication (26.6%) after RFA and MWA, which is comparable to our observed range (31.9–37.2%). Moreover, Xie et al. identified key risk factors for pneumothorax after MWA, including emphysema (OR 16.77), low BMI (OR 0.69/kg·m^2), male sex (OR 4.65), impaired pulmonary function, multiple needle punctures (OR 5.22), tumor proximity to the pleura, longer needle pathways, higher ablation power, and larger tumor size.

Bronchopulmonary hemorrhage occurred in approximately one-fifth of patients, with no significant difference between CA and MWA (18.8% vs 24.7%; OR 0.76, 95% CI: 0.36–1.60). This event is mainly caused by needle tract trauma and thermal injury to peribronchovascular structures. Tan et al. reported a 10% incidence of pulmonary hemorrhage after MWA for colorectal pulmonary metastases, highlighting that although not uncommon, most cases were mild and manageable with conservative treatment.

Hemoptysis was reported 16.09% for CA group vs 14.76% MWA group in our analysis, no significant difference between CA and MWA group reported (OR 1.18, 95% CI: 0.56–2.47). Typically, hemoptysis results from vascular or bronchial injury within the ablation zone, particularly in centrally located tumors requiring higher ablation energy. Xu et al. findings noted a higher frequency of hemoptysis with cryoablation compared with RFA, although most cases were mild to moderate and responsive to conservative management. These data, consistent with our findings, suggest that hemoptysis is a relatively common but generally controllable complication of thermal ablation.

Pleural effusion occurred 9.30% in CA group and 10.99% MWA group, with no significant difference between both procedures (OR 0.77, 95% CI: 0.36–1.68). This complication is usually mild, self-limiting, and related to reactive pleuritis when ablating tumors adjacent to the pleura. Xu et al. found that pleural effusion was more frequent after cryoablation compared with RFA, likely due to the freeze–thaw effect provoking a stronger pleural inflammatory response.[53] Similarly, Tan et al. study reported a higher incidence of pleural effusion (17.4%) in patients undergoing MWA for colorectal pulmonary metastases, though most cases were CTCAE grade 1 and conservatively managed. Collectively, these findings indicate that while thermal ablation is associated with several procedural complications, most are mild to moderate in severity and can be effectively managed in clinical practice.

CONCLUSIONS AND RECOMMENDATIONS

Cryoablation (CA) and microwave ablation (MWA) has shown efficacy and safety due to its minimally invasiveness treatment modalities for primary and metastatic lung cancer also its effective for patient with early-advanced stage NSCLC or tumor size no exceed 3 cm that providing comparable survival outcomes and manageable complication profiles. CA may be particularly useful for smaller lesions and patients requiring precise, controlled ablation, meanwhile MWA offers advantages in treating larger tumors due to its capacity to generate broader and more uniform ablation zones. Although both techniques demonstrate effective and safety, hospitalization times may difference. Tumor size remains the key determinant of ablation success during the procedure also subsequent follow-up is equally important. The patient selection should be tailored to other tumor characteristics (primary or metastatic type, pulmonary lobe location/lung zone, single or multiple lesions, lung station etc.) and patient characteristic to optimize therapeutic outcomes.

FURTHER STUDY

This study has limitations and it is necessary to conduct further research related to the topic "Advances local ablation strategies for treating non-small cell lung cancer: A Systematic Review and Meta-Analysis". Future prospective with larger sample sizes, specific tumor size, tumor stage, pulmonary lobe site, and others are recommended to better assess durability and quality-of-life in 5-10 years later. Tumor control rate, progression rate, recurrence rates and assessments of procedural efficiency also may further guide practical adoption in the future.

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